REPEAT EXERCISE IN HEAT AND EXERTIONAL ALTERATIONS TO THERMOREGULATION (REHEAT)

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Abstract

Background: When working in extreme heat, the Australian Army refers to Work Tables that assume body core temperatures will on average peak at 38.5 °C at the end of work, and that subsequent work bouts will have equal heat gain. The current Continuous Work Table restricts personnel to two consecutive work and recovery cycles in each 24 hour period, but does not consider potential sex-based differences in core temperature or if successive bouts will result in different amounts of heat gained. We examined the sex-based differences in peak body core temperature following four work and recovery cycles in the heat.

Methodology: Fourteen males (M: 31.8 ± 7.9 yr; 178.3 ± 5.0 cm; 74.9 ± 8.0 kg, 54.4 ± 8.7 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}) and thirteen females (F: 31.5 ± 7.7 yr; 165.0 ± 6.5 cm; 58.3 ± 5.9 kg, 50.5 ± 5.9 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}) performed four successive bouts of treadmill walking in 32.5 °C Wet Bulb Globe Temperature (WBGT). The bouts alternated between 35 minutes (~550 W) and 55 minutes (~450 W), each separated by 30-min seated rest at 28 °C WBGT. Participants wore standardised military clothing including body armour and a helmet (10 kg). Women were tested on days 5-8 of their menstrual cycle. Peak heart rate (HR), rectal (T_{rec}) and 4-site mean skin temperature (T_{skin}) were compared across exercise periods. Statistical analyses were conducted using repeated measures ANOVA.

Results: Peaks in T_{rec} were significantly different between the exercise bouts (Ex1-Ex4) ($p < 0.001$), but not between males and females ($p = 0.163$). Five males and five females reached 38.5 °C by the conclusion of the fourth work bout. There was no difference in peak HR ($p = 0.422$) or peak T_{skin} ($p = 0.336$) between males or females, nor between exercise bouts (HR: $p = 0.194$) (T_{skin}: $p = 0.586$).

Conclusions: Participants on average did not meet the assumed body core temperature of 38.5 °C within four work and recovery cycles. These findings indicate the current Continuous Work Table can apply to both females (within the early phases of their menstrual cycle) and males across four work bouts.

Real World Implications: The outcomes of this study suggest that the current guidelines are appropriate for both sexes, and may inform Australian Army decision making regarding appropriate durations for up to four repeated bouts of work and rest when working in extreme heat.

Table of Contents

List of Figures

List of Tables

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: 20/12/2019

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Chapter 1: Introduction

Background

Humans are capable of working in extreme climates due to their ability to adapt to changing environments. To sustain homeostasis, a body core temperature between 36.5 °C and 37.5 °C must be maintained. Body heat is constantly generated through metabolism and muscle activity, even at rest. When exposed to extreme heat, the body must constantly dissipate heat to the surrounding environment at a rate that equals the amount of heat gained (either from the environment or by performing work, which increases metabolic heat)[1,2] in order to avoid hyperthermia and ensure thermal balance. When exposed to extreme cold, body heat must be conserved and maintained to avoid hypothermia. This balance between internal heat generation and external heat gain (in hot environments) or external heat loss (in cold environments) is constantly in flux depending on many intrinsic (e.g. fitness, body morphology, sex) and extrinsic (e.g. activity intensity, clothing, food and fluid intake) factors. Heat can be transferred either to or from the surrounding environment to maintain this balance via heat transfer pathways.

When thermal balance is disturbed such that heat gain exceeds heat loss, the excess heat will be stored, and body core temperature will rise. If the amount of heat stored reaches certain thresholds (such as 40.0 °C), a human will become hyperthermic and thermoregulation efforts will fail to sufficiently cool the body down without external intervention[3]. Such interventions can include ceasing work, seeking shade, rehydrating, cooling with fans, and applying wet towels or cooling vests. Immediate hospitalisation and deep-body cooling techniques may be required to avoid the most serious consequences of heat overexposure.

To enable work in extreme heat without the risk of heat overexposure, the Australian Army refers to a set of Work Tables which limit the duration of work that staff can perform in different climates. Work Tables are comprehensive lists of climates, work intensities, and uniforms with corresponding guidance on work duration limits[4]. These tables are designed to ensure work is stopped before there is a chance of heat-related injury. By using a Work Table, a military commander can limit the risks of overexposing staff under their supervision to hazardous environments, and therefore reduce incidence rates of heat injury in the field.

However, findings from a recent study have indicated that these limits may be too conservative, and staff may be able to work for longer periods, or perform more work bouts without putting themselves at further risk[5]. Additionally, the current Work Tables have not considered the potential for differing physiological responses to heat between male and female staff[6-11]. Evidence suggests that females can exhibit a shift in basal core temperature of up to +0.8 °C when exercising during the luteal phase of their menstrual cycle, which may put female personnel at risk when working in the heat in later phases of their menstrual cycle[11-16]. However, research has found no difference in the absolute body core temperature responses of women across the menstrual cycle compared to men when working in humid and warm conditions, though this was conducted across single bouts of exercise at fixed intensities, not repeated cycles of work and rest[17-19]. This study will investigate the effect of sex on core temperature across multiple bouts of work and rest.

Current Work Tables are based on research that has predominantly been based on findings in male participants, whereas military and occupational workplaces are steadily increasing their recruitment of female personnel. This means current Work Tables are based upon literature that has not examined thermoregulatory responses between sexes[20-22].

Purposes

The primary aims of this thesis were to investigate the effects of repeated bouts of exercise in the heat on body core temperature, and to explore any sex-based differences in these responses between males and females.

Objectives and Null Hypotheses of Research

For the primary objectives of this interventional study, the primary objectives and null hypotheses were as follows:

- To evaluate whether current Australian Army work and recovery protocols for hot environments can be increased to four consecutive work and recovery cycles without resulting in excessive heat strain in healthy adults.
    - H_0: Peak core body temperatures will be the same across all four work bouts
- To examine the sex-based differences in elevation and restoration of core temperature when working in the heat with current work and recovery protocols.
    - H_0: Core body temperature responses will be the same between male and female participants

Thesis Outline

This thesis is comprised of five chapters. Following the introduction to the general topic and an outline of the primary aims and objectives of this research project (Chapter 1), a literature review of the current body of research is presented (Chapter 2). Chapter 3 demonstrates the design and methodology of the interventional study presented in manuscript format. Chapters 4 and 5 present the results, discuss the relevant findings from this research, provide recommendations for future research, and provide research conclusions.

Chapter 2 introduces the current literature basis for this study pertaining to thermoregulation during exercise, the design and use of Work Tables in military and occupational activities, and the restoration of thermoregulation after exercise. These inform the background literature for the first primary objective of this research project. This chapter also scopes the relevant literature on sex-based differences in thermoregulation during and after exercise, the relevant phase-based changes to thermoregulation, and the impact of the menstrual cycle on thermoregulation during exercise. These findings inform the literature for the second of the primary objectives for this research project. All these findings formed the basis for the investigation undertaken as part of this thesis (Chapter 3).

Chapter 3 presents the design and methodology of the intervention used in this research project. It describes the participant selection process, the research protocol, and the analysis and calculations used for data interpretation. It outlines the investigation of core body temperature changes across four repeat bouts of exercise in the heat (n = 29). The design of this intervention is heavily informed by the findings of Chapter 2, and the results are presented in Chapter 4.

Chapter 4 summarises the results observed and the research completed throughout this thesis. It details participant biometric values, baseline physiological and perceptual measurements, and data recorded across the experimental trials. The statistically significant findings are presented in several formats. The outcomes from this section inform the discussion in Chapter 5.

Chapter 5 provides an in-depth discussion of the findings from Chapter 4, particularly on how the results of the investigation impact the primary research objectives. It also explores the limitations and generalisability associated with the research outcomes and proposes a number of areas that warrant further investigation. This section concludes the key research findings.

Chapter 2: Literature Review

Due to the extreme climates encountered at home and abroad, Australian Army personnel spend a lot of time working in the heat. Overexposure to heat can have disastrous consequences for humans, leading to significant impairment and even death. When working in extreme heat, the Australian military have a number of safeguards in place to protect the health of their personnel. This literature review introduces human body thermoregulation, current Australian Army protocols, the physiology of male and female heat loss, and the key research questions of this project.

Thermoregulation During Exercise

Whilst performing work (exercise), heat is generated in active muscles and exchanged with the surrounding environment[23]. Heat must be dissipated to prevent elevations in core temperature leading to dangerous levels of stored heat[24,25]. To maintain a safe core temperature in hot environments, the generation and exchange of heat to the body (metabolic heat load) must be balanced with heat outputs from the body to the environment[26]. Whilst working, the storage of heat develops as the sum of heat lost and heat gained[27]. By factoring heat gained or lost through heat transfer pathways and metabolic heat generation, an equation can be used to calculate the rate of heat storage (Eq.1)[1,27,28]. For a stable core temperature, heat storage (S) must equal zero (0).

$$Eq.1 \qquad S = M - W_{ex} \pm R \pm C \pm K + E$$

Where S = Rate of heat storage measured in Watts per square meter ($W \cdot m^{-2}$), M = rate of metabolic heat production ($W \cdot m^{-2}$), W_{ex} = external work performed on or by the body ($W \cdot m^{-2}$), R = heat exchange through radiation ($W \cdot m^{-2}$), C = heat exchange *through convection ($W \cdot m^{-2}$), K = heat exchange through conduction ($W \cdot m^{-2}$), and E = heat lost through evaporation ($W \cdot m^{-2}$).*

The body transfers heat through four heat transfer pathways: evaporation, conduction, radiation, and convection[25,28,29]. Evaporative cooling occurs because of the vaporisation of water at the skin surface and the transfer of water vapour to the environment, determined by air flow over the skin and absolute humidity. The vaporisation of 1g of water off the skin's surface releases 2426 J of latent heat energy, assuming 100% of the water is transferred to the environment[30,31]. This vaporisation will only occur with a sufficient water pressure gradient to enable diffusion of water from the skin to the ambient environment[27]. In hot dry conditions, there is a high water vapour pressure gradient between the skin surface and the environment, which provides a high potential for evaporative cooling. In contrast, in warm humid conditions, the low water vapour pressure gradient between the skin surface and the environment reduces the effectiveness of evaporative cooling due to the high saturation of water in the surrounding air. Without a sufficient gradient to enable water diffusion, sweat will collect on the skin surface, be wicked into clothing, or be dripped off and lose any cooling effect. Clothing also plays a role by inhibiting effectiveness of evaporative cooling, as it reduces air flow over the skin and insulates the body from convective heat exchange[32]. Evaporation is the most effective method to counter increasing internal heat storage[33-35], and, is estimated to transfer between 666 and 680 W per 1 L of sweat vaporised[27,33], depending on humidity and wind speed.

Radiation transfers heat when either the skin or a nearby radiating body has a higher temperature than the other, causing the cooler (with less heat energy) body to absorb heat[34,36]. For example, a hot halogen bulb may have a greater temperature than skin, causing the body to gain heat. When a body is exposed to sunlight, the radiant heat load upon that body arises from direct, reflected, and reradiated heat such as from shiny or white surfaces[37,38]. Convection transfers heat between a surface and a contacting mobile fluid or gas; in hot environments, convection aids internal cooling by bringing heated blood close to the skin's surface, allowing thermal transfer[21,22]. In air temperatures below ~35.0 °C skin temperature is higher than air temperature, so heat is lost by convection[38]. However, in air temperatures higher than ~35 °C skin temperature is lower than air temperature, and convection adds to the heat load. Finally, conduction transfers heat from one surface to an adjacent, cooler surface with which it is in contact, and can be responsible for up to 70% of internal heat transfer from active muscles to skin[20,36].

Heat is held in the body as a function of its mass, the mean specific heat of the body tissues, and its mean temperature[38]. The transfer of heat between the body and the environment occurs by heat flow down gradients in ambient temperature and relative humidity through independently acting physical processes[38]. As the transfer of heat is an exchange, the body can dissipate heat to the environment in order to avoid overheating, but also can gain heat from the environment (adding to the metabolic heat load). Environmental factors such as negligible air movement, high humidity and/or ambient temperature may prevent adequate heat loss[38]. The temperature gradient between the body and environment dictates which way heat will flow. If the body is hotter than the environment, the body will cool until thermal balance is achieved; however, if the environment is hotter than the body, the body will gain heat.

Physiological control centre and mechanisms to regulate body temperature

The human thermoregulatory system has been described as being more complicated than any actual technical control system[39]. It contains multiple sensors (e.g. thermoreceptors in the skin), multiple feedback loops (e.g. internal thermoreceptors feeding to the hypothalamus via afferent neurons), and multiple outputs (heat transfer pathways stimulated by efferent neurons)[40]. The heat transfer path from body core to body shell is influenced by internal (e.g. internal heat generation by exercise) and external (e.g. originating from environmental heat or cold) thermal disturbances[41]. External thermal disturbances are rapidly detected by thermoreceptors in the skin, which convey the sense of increasing heat via afferent neurons to the brain. The hypothalamus then sends impulses via efferent neurons from the central nervous system to stimulate thermoregulatory pathways. This enables the thermoregulatory system to act before thermal disturbances affect body core temperature. This “closed loop” of sensation and reaction is controlled by the autonomic nervous system and does not require a high level of central nervous system activation. It is important to note that the thermoreceptors in the skin respond to an increase in temperature as well as the rate of change of temperature[40].

Heat strain is the physiological changes that occur as the result of the presence of excessive heat in the body. Excess heat stimulates activation of thermoregulatory mechanisms via the autonomic nervous system, causing cutaneous vasodilation (dry heat exchange) and sweating (wet heat exchange) to promote heat transfer[35]. This autonomic thermoregulation is controlled by the hypothalamus, which controls different autonomic actions such as adjustment of[40]:

- Heat production by shivering
- Internal thermal resistance by vasomotion (control of skin blood flow)
- External thermal resistance by control of respiratory dry heat loss
- Water secretion and evaporation by sweating and respiratory evaporative heat loss

The body temperatures at which thermoregulatory mechanisms are stimulated are termed onset thresholds, and the subsequent increase in activation of these mechanisms per unit (°C) increase of body temperature is termed thermosensitivity. The autonomic responses may be triggered at different thresholds of body/skin temperature, depending on internal and external variables. For instance, increased respiration and skin blood flow may be stimulated at lower onset thresholds during exercise in humid heat, whereas sweating and reduced cellular water reuptake may be stimulated at lower onset thresholds during exercise in dry heat[25]. Onset thresholds can also vary depending on sex, anthropometric measures, fitness, acclimatisation, and type of work being done (load-bearing or non-load-bearing). The effectiveness of these mechanisms is influenced by several intrinsic and extrinsic factors when undertaking work in extreme environments, including hydration, acclimatization, sex, age, fitness, body fat, body size, diet, previous heat illness, alcohol, and medications[2,28,42,43].

Sweat glands are stimulated by sudomotor innervation via the sympathetic nervous system, from hypothalamic input[44]. Sudomotor innervation activates muscarinic acetylcholine receptors, which cause perspiration to occur[45-48]. To confirm the degree of hypothalamic control in sudomotor activation and to identify onset threshold of sweating in mammals, invasive studies have been conducted in Rhesus monkeys[46]. The researchers altered the temperature of the hypothalamus and skin temperature of the monkeys to stimulate a sweat response. They found that an increase in hypothalamic temperature increased sweat rate in a positive and linear fashion. However, a lower skin temperature required a higher hypothalamic temperature to stimulate a sweat response without affecting the slope of the relationship (cooler skin requires a higher core body temperature to begin sweating). This indicates that the generation of a sweat response is controlled by the integration of both skin and core body temperatures. When the monkeys rested in 38 °C environments, their skin temperature was ~37.62 °C and sweat began at a hypothalamic temp of 38.46 °C. In cooler conditions (36 °C), their skin temperature was ~36.82 °C and sweat began at a hypothalamic temperature of ~38.83 °C[46].

The onset threshold of heat loss pathways in humans has been determined through non-invasive methods, such as by monitoring core body temperature and identifying when sweat begins to form whilst exercising at a fixed rate of metabolic heat production[49-51]. A study by Poirier et al., (2016) monitored the whole-body skin temperature onset threshold and thermosensitivity of sweat responses whilst cycling at 300 W and 400 W in 35 °C and ~20% relative humidity[52]. They found that, when cycling at a fixed metabolic rate of 300 W · m^{-2}, sweating began at an onset threshold of 36.63 ± 0.18 °C, with a thermosensitivity of 512 ± 130 W · $°C^{-1}$, whereas a rate of 400 W · m^{-2} yielded an onset threshold of 37.02 ± 0.24 W · $°C^{-1}$ and a thermosensitivity of 520 ± 298 W · $°C^{-1}$ [52]. This means that onset threshold and thermosensitivity of heat loss pathways increase with intensity of exercise. These values significantly change following a 14-day heat acclimation process, as outlined by Poirier et al. (2016).

Another study by Gagnon & Kenny (2011) investigated the onset thresholds for cutaneous vasodilation and whole-body evaporative heat loss of men and women. They determined the mean body temperature onset threshold for cutaneous vasodilation whilst cycling for 90 minutes at 50% VO_{2max}, then later at a fixed rate of 500 W in 35 °C and ~12% relative humidity[53]. In the 50% VO_{2max} trial, they found no sex-based difference in the mean body temperature onset threshold of cutaneous vasodilation (males: 36.70 ± 0.09 °C vs. females: 36.76 ± 0.09 °C) and whole-body evaporative heat loss (males: 36.67 ± 0.09 °C vs. females: 36.76 ± 0.09 °C)[53]. However, they did report greater thermosensitivity of whole-body evaporative heat loss in men than women (males: 762 ± 56 W · $°C^{-1}$ vs. females: 559 ± 75 W · $°C^{-1}$)[20]. In the 500 W trial, they found no difference in onset threshold of cutaneous vasodilation (males: 36.65 ± 0.11 °C vs. females: 36.77 ± 0.08 °C) and whole-body evaporative heat loss (males: 36.61 ± 0.11 °C vs. females: 36.77 ± 0.06 °C). Like the 50% VO_{2max} trial, they reported greater thermosensitivity of whole-body evaporative heat loss in men than women (males: 795 ± 85 W · $°C^{-1}$ vs. female: 553 ± 77 W ·$°C^{-1}$)[20].

Physiological Responses to Exercise

In hot conditions, heat loss is initially facilitated by an increase in vasodilation, which increases the flow of heated blood to the skin and raises the surface skin temperature. If this heat loss pathway is insufficient to control core temperature, the body temperature will rise further and sweating begins to enable heat loss by evaporation[27,54].

Sweat release is facilitated through the body's eccrine glands, which are distributed over most of the body surface within the dermal layer. Numbers of eccrine glands vary from 1.6 to 4.0 million in an individual, and their number does not increase with age[55]. The greatest density of thermoregulation-associated glands is on the palms of the hands and soles of the feet (~600 cm^2), followed by the forehead, upper limbs, trunk, and lower limbs (~60 cm^2)[50,55-59]. It has been reported that women have a higher density and greater total number of eccrine sweat glands than men[60-62], though this has been disputed in other literature[63]. Eccrine sweat glands are not affiliated with hair follicles, and their main purpose is to assist with thermoregulation[54]. The sweat secreted from these glands is predominantly water, with traces of sodium chloride, urea, lactic acid, and potassium chloride[64].

Accurate measures of sweat production can be calculated through body mass changes (factoring in food and fluid intake), ventilated capsules (electronic sensor within a controlled capsule on the skin surface), technical absorbents (measuring change in mass of material), or iodine-impregnated paper (marks left on paper from active sweat glands)[59,65]. A maximal sweat rate can be estimated using equations and can range between 1.5 and 2.5 litres of fluid lost per hour, theoretically providing between 1000 and 1700 W of heat loss[27,54]. Men typically sweat more than women during moderate physical activity, with males sweating approximately 0.8 $L \cdot h^{-1}$ vs. approximately 0.45 $L \cdot h^{-1}$ for females[55]. Other studies have reported sweat rates of > 3 $L \cdot h^{-1}$ [66] in a highly trained male. Additional research has published an average maximum sweat rate of ~1.4 L · h^{-1} [49] amongst fit humans. However, these high sweat rates are unsustainable for a period longer than 4 - 6 hours when working under heat stress, at which a decline in the volume of sweat is observed[44,49,67,68]. The mechanism for the decline in sweat rate during sustained heat stress is not clear, though it is theorised that prolonged skin wetness can swell the tissue surrounding sweat ducts, occluding the ducts and slowing further sweat secretion[45].

Average sweat rate is reduced with age, with men and women over the age of 70 sweating less than young (average age of 35) sex matched controls[69]. Additionally, age increases the onset threshold for a whole-body sweat response by nearly 0.5 °C, with these effects being even more pronounced in older women[69].

The capacity for heat loss through sweat vaporisation far outweighs what can be realistically achieved through other heat transfer pathways[54]. For acclimatised subjects, the whole-body maximum sweat rate is approximately 20% greater than for non-acclimatised[70,71]. It has also been demonstrated recently that the rates of whole body sweat production are not impacted by relative intensity of exercise (percentage of VO_{2max}), body surface area, body mass, or core body temperature; instead, they are dependent on the evaporative heat balance requirement (E_{req}) necessitated from the environment expressed in watts[72]. This means assessments of whole body sweat rate should be undertaken under a fixed E_{req} and not any other fixed measures[72].

Interplay between environment, metabolic rate, and clothing

Compensated heat stress exists when the rate of heat loss to the environment at a higher level of strain is in balance with heat production, so that the body maintains thermal balance[27]. Uncompensated heat stress occurs when evaporative cooling requirements exceed the environment's evaporative cooling capacity (or clothing limits exposure of skin to the environment), resulting in a progressive/continuous gain to body heat storage[73,74]. Excessive heat strain (dangerously high core temperatures) can lead to dehydration, heat cramps, heat syncope, heat exhaustion, heat stroke, and heat injury[24,25,34,75,76].

Heat stress imparted on a body is a product of three factors: environmental conditions (wet-bulb globe temperature; WBGT), work intensity, and clothing[77]. Performing work generates substantial metabolic heat. As the work becomes more physically demanding, metabolic heat production increases[27,43]. Further, wearing clothing or personal protective equipment (PPE) whilst working also increases metabolic heat production and heart rate, and reduces the effectiveness of heat transfer pathways by barring heat transfer and evaporation from the skin surface[28,42,78-81]. Clothing increases the amount of mass on the body and restricts movement. Clothing that adds mass can dramatically increase metabolic work rates[82]. In addition, treadmill walking in bulky clothing can increase oxygen consumption by ~10% compared to the same exercise in light clothing carrying the same weight[80,83,84].

The heat strain imposed by clothing is a result of excess body heat storage which can be attributed to the combined effect of three factors: clothing characteristics, environmental conditions, and the level of physical activity. Two heat transfer parameters are impacted by the presence of clothing: thermal resistance (resistance to dry heat transfer by conduction, convection, and radiation, expressed as R_t in °C · m^2 / W) and evaporative resistance (resistance to evaporative heat transfer from the body to the environment, expressed as R_{et} in kPa · m^2 / W)[42]. R_t can also be expressed as clo, where 1 clo = 0.155 °C · m^2 / W [32]. Clo is widely used to represent the amount of thermal resistance clothing ensembles offer, and 1 clo equates to the amount of insulation necessary for comfort whilst sitting in a room with air movement of 0.1 m · s^{-1} at 21 °C and 50% relative humidity (or approximately one's everyday clothing)[85]. Thicker or bulkier protective garments such as coveralls have greater clo values, indicating a greater level of thermal insulation to the wearer. A standard military uniform without body armour would have a clo of 1.37 (R_{et} = 28.7 kPa · m^2 / W), and a torso and extremity ballistic protection ensemble would have a clo of up to 1.63 (R_{et} = 43.7 kPa · m^2 / W)[86].

Additionally, an increase in R_t and/or R_{et} through additional clothing reduces the rate of heat loss (due to inhibition of heat transfer pathways), and therefore may increase the rate of heat gain. However, when physical activity levels increase, greater mass on the body through clothing may have a similar or greater heat strain effect than the clothing ensemble's R_t/R_{et}[42]. Therefore, reducing R_t, R_{et} and mass can significantly alleviate heat strain imposed by clothing[80].

Exertional heat illness

Exertional heat illness is a pressing concern in civilian and military activities. Exertional heat illness presents in two forms: heat stroke and heat exhaustion. Heat stroke is a state of thermoregulatory failure and must be treated as a medical emergency. It is the most severe presentation of exertional heat illness and is associated with irreparable internal damage and a high proportion of fatalities[87-91]. Its symptoms include hot and dry skin, rapidly rising core temperature, collapse, loss of consciousness or neuropsychiatric impairment, and convulsions[92]. It can present as a moderate to severe heat illness, and is broadly characterised by organ and tissue injury associated with sustained high core body temperature (usually but not always > 40.5 °C)[75,92-94]. Heat stroke requires immediate and appropriate medical attention, including removal of the victim to a cool area and deliberate reduction of the rapidly increasing body temperature[38,95]. Without these steps, heat stroke will be fatal. Additionally, persons with a history of exertional heat illness (particularly heat stroke) are often at greater risk of recurrent heat illness during strenuous physical activity due to the disturbances to thermoregulatory, central nervous, cardiovascular, musculoskeletal, renal, and hepatic systems[95-101]. However, long-term effects are reduced markedly if proper treatment is initiated within 10 minutes of collapse[102].

Heat stroke causes tissue and cell structure swelling and degeneration, and widespread haemorrhages leading to organ congestion and failure[91]. Of all heat stroke cases in the U.S. Army, 13% are associated with renal failure[103]; a case series of heat stroke deaths in the Israeli army found renal failure in 100% of cases[89], and kidneys have been found clotted with macroscopic haemorrhage in 20% of heat stroke victims post-mortem[91]. Hepatic failure is also observed in heat stroke, due to reduced liver blood flow associated with hyperthermia[88,90,104]; 66% of Israeli army heat stroke deaths had evidence of liver damage[89]. Additionally, the effects of hyperthermia cause the central nervous system to dysfunction, resulting in respiratory alkalosis (pH approaching 6.9 – 6.8; normal pH 7.35 – 7.45[88,104]), and reduced cardiac output and falling central venous pressure (insufficient skin blood flow for thermoregulation, and organ ischemia).

Heat exhaustion is a less severe heat injury than heat stroke, but it can be a preliminary step before heat stroke. Heat exhaustion is characterised by clammy and moist skin, weakness or extreme fatigue, nausea, headache, no excessive increase in body temperature, and low blood pressure with a weak pulse. Without prompt treatment, collapse may occur. It is usually manifested by an elevated core body temperature (typically < 40.5°C) and is often associated with a high rate or volume of skin blood flow, heavy sweating, and dehydration[76,105]. Heat exhaustion most often occurs in persons whose total blood volume has been reduced due to dehydration but can also be associated with inadequate salt intake even when fluid intake is adequate[27]. Lying down in a cool place and drinking cool (10-15 °C), slightly salted water (0.1% NaCI) or an electrolyte supplement, will usually result in rapid recovery of the victim of heat exhaustion. Salt-depletion heat exhaustion may require further medical treatment under supervision.

Due to the severe nature of the consequences of heat stroke and exertional heat injury, extensive research has examined their incidence rates in several populations. In South Australia, worker deaths with heat as cause or a contributing factor were found to occur at a rate of 5.4% per annum (3.6% male and 1.8% female) in 2009[106]. In other statistics, reported cases of heat illness range from 612 cases (419 male and 193 female) per 1,000,000 (0.06%) Canadian workers from 2004 – 2010[107] to 38,392 cases (28,591 male and 9801 female) per 100,000 population per year (2.5%) U.S. emergency department admissions to hospital from 2006 – 2010[108]. In athletic populations, incidence rates of heat illness range from 0.00276% (0.00234 male and 0.0042 female) from 2005 – 2007[109] to 2.21% (1.33% male and 0.88% female) per hundred athlete exposures in 1978[110].

Person-years account for the number of people in a study and the amount of time each person spends in a study; 100 person-years contains the data of 100 people over 1 year. In the U.S Army, rates of heat illness with medical intervention range from 0.21 males and 1.31 females per 1000 person-years (1683 cases total) in 2014[111] to 1.67 males and 2.63 females per 1000 person-years (2652 cases total) in 2011[112]. In the U.S. Army, there were a recorded 37 deaths (0.3 per 1,000,000 soldier-years) due to heat illness between 1980 and 2002[103]. Stacey et al., (2016) identified 565 cases of exertional heat illness in the British Army from 2009 to 2013, with an overall incidence rate of 13.4% per year or 38 hospitalisations per 100,000 personnel[113]. Stacey et al., (2015) also reported on 389 heat illness cases in the British Army between 2007 and 2014 (4.4 per month)[114]. In the U.S Army, reported cases of heat stroke requiring medical intervention increased from 311 cases (285 male and 26 female) per 1000 person-years in 2010[115] to 417 cases (384 male and 33 female) per 1000 person-years in 2015[116]. In the French

Armed Forces, 182 personnel were hospitalised for exertional heat stroke between 2004 and 2006[117].

The incidence rates of heat illness and heat stroke are significantly greater in armed forces than in civilian and athletic populations[111]. There are many case studies and case series investigating the probable aetiology of heat-related injuries in global military personnel. For further detail on heat illness, heat stroke, and heat-related deaths, readers are encouraged to peruse Gifford et al.'s (2019) systematic review and meta-analysis on these topics[111].

Environmental factors

Several environmental factors contribute to the risk of heat illness. This can include the environmental conditions (ambient temperature, relative humidity, air motion, and amount of radiant heat from the sun[76]). In particular, environments with very high heat (e.g. > 28 °C WBGT, > 80 °F[118], > 30.1 °C[119]) tend to have higher heat-related mortality, but also typically cool climates undergoing a heat wave when people are unaccustomed to high temperature variability[120-123]. Hot and humid conditions most readily predispose people to exertional heat illnesses, where the environmental temperature is higher than the body's skin temperature and therefore heat loss is entirely dependent on evaporation (which is then impeded by high relative humidity, further increasing the risk of heat illness)[124-126]. It should be noted that the body of literature on heat illness incidence and geographical location has been found to concentrate on mid-latitude and high-income countries, and underrepresent the regions that are least able to adapt to climate-based health risks and are most likely to experience extreme heatwaves (and therefore have populations most at risk of death and illness from extreme heat)[127].

The climate of the previous day and night (high WBGT indices on the previous day with sleep in warm or non-air-conditioned locations is one of the best predictors of exertional heat illness on subsequent days of exercise[128]). Other environmental factors can include barriers to evaporative heat loss (uniforms that do not allow water vapour to pass from the skin to the environment[97,129-131]), wearing a helmet, and excessive clothing or equipment (additional clothing and layers may cause greater absorption of radiant heat and increase metabolic heat generation through added weight[76]).

Inter-individual factors

There are several inter-individual factors that influence the risk of heat illness, including overzealousness, poor physical conditioning, exercise intensity, increased body mass index, and age. Overzealous athletes and military personnel are more prone to exertional heat illness because they tend to override the normal behavioural adaptations to heat and ignore the early warning signs of heat illness[97,132]. Untrained persons (those who are unfit, overweight, or unacclimated) can rapidly reach a dangerous core temperature with less than 30 minutes of high-intensity exercise (>1000 kcal $\cdot$ h^{-1})[133,134]. Particularly, Marine Corps recruits who had a BMI of > 22 kg $\cdot$ m^{-2} and who ran 1.5 miles in over 12 minutes were found to have an eightfold increased risk of exertional heat illness during basic training than those with a BMI less than 22 kg $\cdot$ m^{-2} and who could run 1.5 miles in less than 10 minutes[134].

Another factor, exercise intensity, has the greatest influence on the rate of increase in core body temperature[133]. High-intensity exercise results in a substantial amount of metabolic heat production, which then produces a rapid rise in core body temperature[135-137]. As aerobic power (VO_{2max}) improves, the ability to withstand heat stress generally also improves[89,97,138,139]. It is important to distinguish between exercise conducted at absolute rates of metabolic heat production versus relative intensities of work. If two people with very different VO_{2max} values perform exercise at an identical rate of metabolic heat production (expressed in watts), their core temperature responses will be very similar[140]. If these people performed exercise at a relative intensity of effort (as a percentage of their VO_{2max} values), their core temperature responses will be significantly different, with the higher relative exercise intensity yielding a greater core temperature response[140].

People with an increased body mass index (and higher body fat percentage) are less efficient at dissipating heat during exercise due to their smaller surface area to body mass ratio (and thus decreased capacity to dissipate heat), and produce more metabolic heat due to their increased body mass[28,76]. People with a body mass index > 27 kg · m^{-2} are more often affected by heat exhaustion[92]. Similarly, people with greater muscle mass produce more metabolic heat and have a lower surface area to mass ratio, contributing to a decreased ability to dissipate heat[97,141].

Additionally, age can play a role in the development of heat illness. It is a consistently reported finding that military personnel under the age of 21 (and with less than one-year total service time) have the greatest incidences of heat injury[142]. Of all heat illness hospitalisations in the U.S. Army from 1980 to 2002, 40% were less than 21 years of age, and 44% of all cases had 1 year or less of military service[143]. However, these incidence rates drop significantly as length of service increases.

Intra-individual factors

There are a great many intra-individual factors which interrelate to increase the chances of exertional heat illness in military populations[144]. These include heat acclimatization, dehydration, recent illness, medications, sleep deprivation, and electrolyte imbalances. In the first of these factors, heat acclimatization, repeated heat exposure over 10 to 14 days results in physiological adaptations that enable the body to cope more effectively with thermal stressors[145-147]. The adaptations include: increases in stroke volume and sweat rate, and decreases in heart rate, core body temperature, skin temperature, and sweat salt losses[75,133,148]. The rate of acclimatization is related to aerobic conditioning and fitness; in general, a better conditioned athlete will acclimatize to the heat more quickly[76].

Dehydration magnifies the core temperature responses to exercise in temperate and hot environments, and this effect is observed with a fluid deficit of as little as 1-2% of body weight[149-153]. A person is considered "at risk" of exertional heat illness at a urine specific gravity of > 1.020 μG[96]. The magnitude of additional core temperature elevation ranges from 0.1 °C to 0.23 °C for every percentage of body weight lost[151,154-156]. During intense exercise in the heat, sweat rates can be as high as $2 \text{ L} \cdot \text{h}^{-1}$; if the fluid is not replaced, large deficits will result[129]. Water loss that is not sufficiently regained by a successive bout of work increases the risk for exertional heat illness[129,152,157,158]. In hot climates, army personnel are typically functioning at a state of moderate dehydration, unless prompted to drink[104]. Risk of exertional heat illness and heat stroke rises substantially with inadequate nutrition and hydration. Of 182 French Armed Forces heat stroke hospitalisations, 15.3% of subjects reported that they were dehydrated or fasted upon heat stroke onset[117]. Additionally, 6% of the cases reported alcohol consumption the night before, potentially contributing to dehydration the day of the event[117]. Electrolyte imbalances can present a component of risk for developing exertional heat illness[159]. These commonly arise with the use of diuretics (e.g. medications for high blood pressure, alcohol, caffeinated drinks), and can occur even in trained, acclimatized individuals who engage in regular exercise and eat a normal diet[160,161]. Most sodium and chloride losses occur through the urine, but people with high sweat rates ($>2 \text{ L} \cdot \text{h}^{-1}$) and sodium concentrations and those who are not heat acclimatized can lose significant amounts of sodium during physical activity[76].

Likewise, individuals who are currently or were recently ill are at increased risk for exertional heat illness because of fever, dehydration, or medications[97,129]. Out of 179 heat casualties during a 14-km run (over a 9 year period), 23% reported recent gastrointestinal or respiratory illness[162]. Certain medications or drugs, particularly those with a dehydrating effect or those that increase metabolic rate, also provide increased risk for exertional heat illness[163-166].

Medications that have been suggested to have an adverse effect on thermoregulation include stimulants, antihistamines, anticholinergics, and antispychotics[166]. Of 182 French Armed Forces heat stroke hospitalisations, 6% reported that they had ear, nose, and throat diseases, or viral gastroenteritis upon heat stroke onset[117]. Of 33 cases in the British Army which had traditional risk factors for exertional heat illness, 18 subjects identified intercurrent illness prior to their heat event[114].

Lastly, sleep deprivation can be a common factor in heat-related illness, especially in military contexts. In an Israeli Defence Forces case series on fatal exertional heat stroke, poor physical fitness and sleep deprivation were found to be key components in 5 out of 6 deaths to heat stroke[89]. Of 182 French Armed Forces heat stroke hospitalisations, 11.5% of subjects reported that they were sleep deprived[117]. Out of 33 cases in the British Army which had traditional risk factors for exertional heat illness, 11 subjects identified sleep deprivation prior to their heat event[114].

Heat illness in military contexts

It is accepted that the most likely contributing factors to the development of exertional heat stroke are poor physical fitness and lack of heat acclimatization[92]. So how is it that military personnel, who often are in good physical fitness and routinely have some degree of heat acclimation, have higher incidence rates of exertional heat illness and heat stroke? Whilst the U.S. military has reported a falling incidence of exertional heat illness, at the same time an increase in occurrence of life-threatening exertional heat stroke has also been found[103,142].

Most heat illness in military contexts happen during training, where local environments often are not as severe as the climate in deployment locations. This is supported by several studies indicating most military heat illness and heat stroke cases occur on local bases, and not overseas in typically hotter environments. For example, Abriat et al., (2014) found 82% of exertional heat stroke cases in the French Armed Forces occurred in metropolitan France[117]; similarly, Stacey et al., (2015) found 65.4% of exertional heat illness cases in the British Army occurred in the UK, and just under half of these cases occurred in winter[114]. In the U.S. Military, 70% of all exertional heat illness cases between 1980 and 2002 occurred within the US[103]. In the French Armed Forces, motivation was the primary intrinsic factor contributing to the onset of exertional heat stroke in 182 cases[117]. Additionally, 15.4% of the cases had previously had an episode of exertional heat stroke, meaning the victims had first-hand knowledge of the warning signs and yet continued to exercise/work[117]. In the Israeli Defence Forces fatal heat stroke case series, it was found that organisational factors largely contributed to heat stroke deaths. Six out six deaths were tied to “physical effort unmated to physical fitness”, 5 out of 6 were tied to training at the hottest hours of the day, and 4 out of 6 were tied to improper work/rest cycles[89]. The events that led to the greatest occurrence of heat illness were scheduled training activities, such as basic or assault training, followed by exercises and manoeuvres[103]. In the British Army, 62.8% of heat illness cases from 2009 to 2013 occurred during training, with only 10.6% occurring during field exercises and 6.0% during operational deployments[113].

The varied nature of military work makes predicting the length and intensity of exercise (and thus the risk of heat illness) difficult. In civilian and athletic populations, heat illness typically develops as a human overworked themselves during a standard workday or a competitive event. As an illustration of the varied work environments when working in the military that have resulted in fatal heat stroke, six cases are presented by the Israeli Defence Forces from between 1992 and 2002[89]: a recently returned soldier recovering from a leg injury for 6 weeks underwent a 5-km run with full combat gear, and lost consciousness and died of heat stroke; an elite soldier navigated 40-km in 48 hours, slept only four hours, barely ate and drank minimal water, and was found dead two hours after being directed to climb a cliff at noon; a soldier engaged in a 5-km run after 4-weeks rest and having had diarrhea two days prior, collapsed during the run and died; an overweight (BMI = 30) newly recruited (two weeks prior) soldier completed a 5-km night march with only four hours sleep, collapsed at the end of the march and died; two special forces soldiers engaged in an intensive physical training manoeuvre after being several weeks away from training, and after only four hours of sleep, both soldiers collapsed on the second day at midday within 15 minutes of each other, and both died upon arrival at the nearest hospital. Despite the fact that these were personnel who passed the fitness criteria to enter military service, the varied nature of military work placed them at substantially greater risk of developing heat stroke than in any other occupation.

There are a great many factors that expose military personnel to a greater risk of exertional heat illness than other civilian and athletic populations when working in the heat. Accordingly, substantial military research has been conducted into minimizing the risks to soldiers working in the heat, and the outcomes have established global standards for preventing overexposure to potentially hazardous environments.

Design and Use of Work-Rest Tables in Military and Occupational Activities

Quite often, military, athletic and occupational activities are undertaken in environments where the heat is so severe that humans cannot tolerate exposure for extended periods[167-170]. Additional task-specific requirements such as protective garments or intense physical activity can further diminish a human's capacity for work in hot environments. The risks of heat-related illness are particularly high in military endeavours, where ground forces may be required to undertake hard physical labour in bulky uniforms, with potentially degraded nutritional or physical status, in extreme heat[104]. In combination with military personnel's drive to successfully complete the mission, successful heat stress management during military operations is very difficult.

In conditions where military personnel will be exposed to uncompensable heat stress during work, physiological adaptations to heat (such as from acclimation or aerobic fitness) can do little to enhance performance[171-173]. Therefore, to ensure work gets completed, the options for commanders are to reduce work rates (and work for longer), or to maintain the work intensity and reduce work time (by incorporating rest breaks). The average metabolic rate of work is closely linked to tolerance of exercise when wearing protective clothing in high heat stress environments[174]. Therefore, to reduce the metabolic rate of work and increase tolerance time of exercise, the intensity of effort can be lowered, or rest periods can be introduced (creating exercise/rest cycles). The exercise/rest cycles are most commonly used in military and athletic/occupational settings to extend exercise tolerance time in high heat stress conditions[104,175,176]. However, a one-to-one ratio for exercise-to-rest does not suit all conditions, as the optimal ratio varies depending on metabolic work rate, climate (WBGT), clothing and equipment worn, hydration status, and acclimation[177,178]. Mathematical modelling can predict the most appropriate exercise/rest ratios for a given set of conditions, and these models are represented in Work Tables.

Military Work Tables

Work Tables align with evidence-based assumptions of core body temperature elevations associated with heat illness onset, to manage risk of overexposure to heat stress[179,180]. These tables are usually conservative to provide a margin of safety (expecting < 5% heat casualties), which is expected to account for variability in the core temperature responses of personnel[104]. The design of Work Tables is such that they reduce risk of heat-related injuries from overexposure to hazardous work environments. Their implementation in a military context stems from the countless number of operations which have ended with one or more personnel severely impaired after working in a high heat stress climate[144,181].

Currently, the Australian Army Work Tables assume a body core temperature elevation of 1.5 °C at the conclusion of work, from 37.0 °C to 38.5 °C[77]. The Work Tables assume that personnel will reach a body core temperature of 38.5 °C by the end of the initial work bout, and that equal heat will be gained in successive bouts of work. This limit is set as biophysical modelling indicates a substantially greater risk of heat injury when operating at body temperatures over 38.5 °C[179,180]. At a core body temperature of 38.5 °C, 20% of working personnel indicate volitional exhaustion, whereas such fatigue rarely occurs at temperatures lower than 38.5 °C[168,169,182]. Although 38.5 °C is the assumed core temperature at cessation of exercise, normal inter-individual heat gain variations of ± 0.2 – 0.4 °C can occur, meaning personnel can finish work anywhere between 38.0 – 39.0 °C[183-185]. Some individuals may even see core temperatures greater than 39.0 °C due to innate variability. Therefore, work limits must be set to minimise risk of harm to all troops including individual variability.

For example, a Work Table might indicate that, for a soldier wearing standard body armour and operating at a metabolic heat production of 300 W in 32 °C WBGT, work should be limited to 20 minutes with a rest of 40 minutes afterwards, repeated for up to five hours total. The Australian Army use two Work Tables – one designed to advise on work and rest cycles per hour, for up to 5 hours (Work-Rest Table), and one designed for longer, continuous, bouts of work (continuous Work Table), after which a Recovery Table is used to determine the required rest period before a second bout of work can be conducted. Which table to use is at the discretion of command personnel, depending on the task required. The Work Table enables many repeat bouts of exercise at a shorter duration with a rest specified according to exercise intensity. However, the continuous Work Table allows for only two repeat bouts of work, each separated by a rest bout (the duration of which is controlled by WBGT), after which no more work can be done in that day.

There is some evidence to suggest current Work Tables in the Australian Army are too conservative, to the point where personnel are finishing work substantially below the expected 38.5 °C core temperature[77]. Additionally, there is evidence to show that aerobically trained individuals are capable and comfortable working at core temperatures in excess of 38.5 °C[186-188]. This implies ground forces can continue to work for greater lengths of time than are currently recommended by Australian Army Work Tables. Although the Work Tables have been in use for a number of years, recent research has indicated that a core body temperature in excess of 38.5 °C may not impede performance and can be tolerated for extended periods without causing physiological damage[186-192]. A study by Ely et al., (2009) found no differences in running velocity in 17 competitive runners when running at a core body temperature > 40 °C than when running at < 40 °C[186]. Older research by Christenen & Ruhling (1980) found core temperatures to fluctuate between 38.9 – 39.1 °C in a female distance runner completing a marathon in cool air temperatures[189], though this was with a sample of one woman. Similarly, Maron et al., (1977) found core temperature to plateau between 38.9 – 41.9 °C in two male distance runners completing a marathon in cool conditions[190]. A more recent study by Veltmeijer et al., (2014) found that 15% of 227 recreational runners developed a core body temperature ≥ 40 °C after 15-km running in 11 °C, with no difference in race times compared to cooler runners[191]. Byrne et al., (2006) found that, out of 18 heat acclimatized male soldiers completing a 21-km road race in 26.5° C WBGT, all runners completed with peak body temperatures > 39 °C, with ten > 40 °C and two > 41 °C, and were asymptomatic of heat illness[192]. In military research, a study by Nolte et al., (2011) had 18 males marching for 25-km carrying 26kg in 28.8 °C WBGT; they found six individuals had body core temperatures between 39.0 – 40.3 °C, with all individuals asymptomatic for heat illness and all 18 males completing the march[187]. Lee et al., (2010) found that, out of 31 male soldiers completing a 21-km road race in 26.4 °C dry bulb and 81% relative humidity, 24 runners achieved core temperatures > 39.0 °C, with seventeen ≥ 39.5 °C, and ten ≥ 40.0 °C, with no significant difference found in running speed between the hotter and cooler groups[188]. A recent paper by Hunt et al., (2016) investigated heat strain in 37 male soldiers completing a 10-km march carrying 41.8 ± 3.6 kg in 23.1 ± 1.8 °C WBGT; out of 28 non-heat-exhaustion-symptomatic soldiers, five did not complete the march and had core temperatures of > 39.0 °C, though these five reported similar heat-related symptoms to the remainder who completed the march[77].

The results of these studies are in contradiction with the current Australian Army Work Table limits, which would have expected participants to present with symptoms of heat injury at these core body temperatures. This implies there is a potential for Australian Army personnel to continue work beyond what is currently permitted. The current Continuous Work Tables assume core temperature at the end of the initial bout of work to be approximately 38.5 °C, and for an equal amount of heat to be gained in subsequent work bouts, leading to a progressively higher core temperature. This cutoff is set as, when an average Australian Army soldier reached a body core temperature of 38.5 °C, normal inter-individual variation of ± 0.2 – 0.4 °C would allow for the majority of individuals to complete work in the 38.0 – 39.0 °C range, with approximately 5% exceeding 39.0 °C[77]. Currently, it is anticipated that an equal amount of heat will be gained in each subsequent bout. This means a core temperature gain of +1 °C in the first bout is expected to be matched by a gain of +1 °C in subsequent bouts. Likewise, Continuous Work Tables assume an equal amount of heat will be lost in subsequent rest periods. They expect a core temperature reduction of –0.5 °C in the first rest to be matched by a loss of –0.5 °C in subsequent bouts. However, evidence indicates both patterns may not hold true. Recent research suggests that core temperature elevations are highest in the first work bout and heat losses are lowest in the first rest, whereas elevations are lowest in the final bout and losses are greatest in the final rest[5,53,193,194].

These findings suggest that the previously assumed association between core body temperature elevation and heat-related symptoms should be re-examined for the purposes of determining the optimal exercise-to-rest ratio for work productivity and personnel safety. Accordingly, the restrictive nature of the current Work Table of the Australian Army has been called into question, with attention being directed to whether the total number of work bouts could be increased without substantially increasing the risk of heat-related injury[77]. Additionally, the research base of the current Work Tables does not make considerations for sex-based differences in thermoregulation. This is particularly of relevance as military settings currently do not consider sex as a potential factor in heat illness incidence rates during work in the heat, despite evidence to the contrary[53].

Restoration of Thermoregulation after Exercise

After completion of work in a heated environment, heat loss responses in the body are abruptly ceased as the heat production stimulus is removed, and two main changes to the thermoregulatory mechanism occur. Firstly, the body sees a period of hypotension[195,196]. This hypotension stems from the rapidly reduced cardiac output without an equally rapid reduction in peripheral resistance (as blood pressure is a factor of cardiac output and peripheral resistance). Secondly, sweating is rapidly ceased[197]. This is thought to occur as an attempt to avoid unnecessary water loss through sweating. These post-exercise changes limit the body's ability to lose heat stored from exercise[195,198]. This elevation of core body temperature above resting levels can be sustained for up to 90 minutes after completion of exercise[5,199,200]. The duration required to lose heat gained during exercise typically must be longer than the period of exercise, as evidence shows only 30 – 50% of this heat is lost during a rest of the same duration (1:1)[5,199].

The Work Tables utilised in the military are constructed from evidence-based assumptions regarding the risk of heat related illness corresponding to an elevation of core body temperature[75,77]. Military work limits assume an elevation in body core temperature up to 38.5 °C is attained at the end of each work bout[77]. However, there exists a disparity between the Continuous Work Table and current literature regarding sufficient periods of rest. The allocated rest component of these tables may not be of sufficient duration to return to pre-work baseline measures, potentially increasing the risk of heat-related injury with each subsequent bout[5,25,199]. However, the total heat gained in subsequent exercise bouts may not be identical to initial work bouts and this will be addressed later.

Several studies have investigated the prolonged elevation in core temperature after a single bout of exercise in the heat. Gagnon (2012) conducted two studies: in the first, 16 males completed 30 minutes of cycling at 70% of their VO_{2max} in 42 °C and recovered for 60 minutes in 30 °C, and their core body temperature measured at the end of the recovery was elevated by an average of +0.6 °C[201]. In the second, the same 16 males completed 120 minutes of cycling at a fixed intensity of 120 W in 42 °C and 20% relative humidity; they recovered for 90 minutes in the same environment, and their end core body temperature was elevated by an average of +1.2 °C[201]. Similarly, Kenny et al. (1997) completed two studies. In the first, five men completed 18 minutes of treadmill running at 75% VO_{2max} in 24 °C and 20% relative humidity[202]. They recovered for 20 minutes in the same environment, and their end core body temperature was elevated by an average of +0.7 °C[202]. They used the same group of males treadmill running (at the same intensity) and recovering for the same periods of time in 29 °C and 50% relative humidity, and found their end core temperature was +0.6 °C[202]. Another study by Gagnon et al. (2011) assessed 10 males cycling at 130 W for 60 minutes in 35 °C and 20% relative humidity and recovered for 60 minutes at 25 °C and 20% relative humidity[53]. The participants finished rest with an average end core temperature of +0.4 °C. Kenny (2008) completed another study in which 6 males and 2 females cycled for 60 minutes at 70 W in 30 °C and 30% relative humidity[199]. They recovered for the same duration in the same conditions, and participants' end core temperature was elevated by an average of +0.2 °C[199]. Finally, Vargas et al. (2018) studied 6 males and 6 females cycling for 60 minutes at 66 W in 24 °C and 43% relative humidity; they recovered for the same duration in the same conditions, and their end core temperature was elevated by +0.2 °C on average[203].

On the whole, these studies link the cessation of enhanced heat transfer post-exercise to significantly elevated core temperatures and post-exercise hypotension for an extended duration after a relatively short bout of exercise[5,196,197,199,201,204]. This has led to the assumption that the elevation in core temperature is consistent in successive exercise bouts, and combined with the elevated core temperature during recovery, the core temperature at the end of the next bout of work would be much higher. This assumption forms the rationale behind this research project. This would lead to excessively high temperatures after only a few work-rest cycles. Whilst these findings are significant, the studies they came from were interested in single bouts of exercise, not repeat bouts.

Although the core temperature does not rapidly return to a baseline after a single work-rest cycle, recent research has indicated that the body is better able to lose heat in subsequent exercise bouts, and therefore core temperature does not reach progressively higher peaks. Kaciuba-Uscilko et al. (1992) studied 10 males completing 4 cycles of 30 minutes work / 30 minutes rest whilst cycling at 50% VO_{2max} in 22 °C and 60% relative humidity[194]. They recovered in the same environment and noted core temperature elevations between +0.6 °C and +0.7 °C above baseline at the end of each rest period, despite peak core temperatures being elevated further with each successive bout[194]. Kenny et al. (2009) studied six males and four females, who cycled at 500 W of metabolic heat production in 30 °C and 30% relative humidity, completing three cycles of 30 minutes work / 15 minutes rest[5]. The participants recovered in the same environment, and their core temperatures were still elevated by between +0.2 °C and +0.5 °C at end of rest[5]. However, whilst their core temperatures reached greater peaks in each bout, they lost more heat in each successive work bout. Gagnon et al. (2011) completed two studies, in which 10 men cycled at 130 W in 35 °C and 20% relative humidity and recovered in the same environment[53]. In the first study, the men completed three cycles of 20 minutes work / 20 minutes rest, and core body temperatures at end of rest measured between +0.4 °C and +0.5 °C; in the second study, the men completed six cycles of 10 minutes work / 10 minutes rest, and their temperatures measured between +0.2 °C and +0.3 °C at end of rest[53]. Similarly, although participants core temperatures reached greater peaks during exercise, each bout of work saw an increase in the rate of heat loss. Lastly, Smith (2013) observed 10 men walking at 47% VO_{2max} on a treadmill in 21 °C and 58% relative humidity[193]. The participants completed three work rest cycles: the first cycle was 20 minutes work / 10 minutes rest, and the subsequent two cycles were 20 minutes work / 20 minutes rest in the same conditions. The participants' core body temperatures at end of rest varied between +0.7 °C and +0.9 °C, and again, during work their core temperatures reached higher values, but their rates of heat loss were increased successively[193].

This published evidence demonstrates a reduction in the increase of core temperature in successive exercise bouts. These results stemmed from a greater rate of increase in whole-body heat loss for a similar rate of heat production in the subsequent exercise bouts, in addition to increased thermoeffector responses (sweat rate, skin blood flow, heart rate). Other studies regarding heat storage and loss during intermittent exercise have reported similar alterations to thermoregulation whilst exercising and at rest, namely increases in the absolute rates of heat loss in each successive bout of work and rest after the first[41,135,167]. Therefore, the assumption of increased risk due to a progressive elevation in core temperature is inaccurate and unnecessarily limiting, indicating that more than 2 successive bouts of work in the heat may be possible without an excessive increase in core temperature.

Additionally, the current work-rest protocols do not consider the differing physiological responses to heat between male and female staff. Current work-rest tables are built on research that has predominantly been based on findings in male participants (as is evident in paragraphs above), whereas military and occupational workplaces are steadily increasing their recruitment of female personnel. This means current Work Tables are based upon literature that does not reflect potentially different thermoregulatory responses between sexes[20-22].

Sex-Based Differences in Thermoregulation During and After Exercise

Characteristics of the female body which may affect thermal stress-strain relationships include hormone levels, anthropometric factors, and body composition. Hormonal variations throughout the menstrual cycle may lead to increased core temperatures at rest and during exercise. Anthropometric factors may make it harder for women to dissipate generated heat during exercise. Body composition variations may cause women to metabolically generate more heat whilst exercising at a similar intensity to men.

Physiology of the menstrual cycle

Menstruation is the cyclic, orderly sloughing of the uterine lining that occurs as a result of hormonal interactions in females[205]. It is a complex, coordinated sequence of events involving the hypothalamus, anterior pituitary gland, ovary, and endometrium[206]. It can easily be perturbed by environmental factors such as stress, extreme exercise, eating disorders, and obesity.

The physiology underlying this process begins in the hypothalamus. The hypothalamus secretes gonadotropin-release hormone (GnRH), which stimulates the anterior pituitary gland to secrete both follicle-stimulating hormone (FSH) and luteinizing hormone (LH)[205,206]. The levels and timing of secretion of each gonadotropin is influenced by GnRH, feedback from sex steroid hormones, and other autocrine and paracrine factors. These gonadotropins stimulate the ovary to produce the steroid hormones estrogen or progesterone, as well as several key autocrine, paracrine, and endocrine peptides. Although estrogen and progesterone have some feedback at the level of the hypothalamus, the more dynamic feedback occurs at the level of the anterior pituitary gland.

Normal ovulatory menstrual cycles occur at regular intervals (21 – 35 days between) and last for < 7 days[205,207,208]. The ovarian cycle consists of the follicular phase, ovulation, and the luteal phase, whereas the uterine cycle is divided into menstruation, the proliferative phase, and the secretory phase. In ovarian cycling, the first day of the menstrual bleed is considered day 1[206]. During the menstrual phase (typically days 1 – 7), the uterine endometrium undergoes changes and is sloughed off because of low estrogen (E_2) levels. This is a component of the ovarian follicular phase (typically up to day 11), which is mainly controlled by the hormone estradiol. Towards the end of the follicular phase, levels of LH and FSH from the anterior pituitary gland rise, as do levels of E_2 (which initiate the formation of a new layer of endometrium in the uterus). As E_2 levels peak, a surge in LH and FSH is noted (lasting for 24 – 36 hours), and results in a release of an oocyte from the ovary. Upon ovulation, estrogen levels deplete.

After menstruation has completed and the follicular phase has ended, ovulation begins (typically days 12 to 17). This is the most fertile phase, wherein the oocyte descends to the uterus ready for fertilization. During this phase, E_2 levels drop whilst progesterone (P_4) levels begin to rise, beginning the luteal phase.

The luteal phase represents the latter phase of the ovarian cycle (typically days 18 – 28) and is mainly associated with P_4 and core body temperature, as these measures are higher during this phase than in other phases of the cycle. E_2 also partially rises as an effect of cellular changes within the ovaries. Approximately halfway through the luteal phase E_2 and P_4 levels will fall, causing increased levels of FSH in preparation for the next cycle. Continued drops in E_2 and P_4 trigger the end of the luteal phase, beginning menstruation and the beginning of the next cycle.

Phase-Based Thermoregulation Changes

As a result of the menstrual cycle, basal core temperature has been found to shift upwards by an average of 0.3 °C at rest during the luteal phase (compared to the midfollicular phase), and this difference can increase up to 0.8 °C during exercise[11-16]. Elevated P_4 levels and changes in E_2-to-P_4 ratios within the luteal phase of the menstrual cycle are linked to this elevation in the thermoregulatory set point[209-211]. This elevated core body temperature resets at the onset of menstruation, remaining at this temperature throughout the follicular phase[211]. A short temperature dip in the late-follicular phase (just prior to the luteal phase elevation) has been reported, but was only observed in between 10% and 50% of menstrual cycles recorded[10,212].

There are further measurable physiological differences in thermal responses of women over the course of the menstrual cycle. Heart rate in the midluteal phase has been found to be on average ~10 beats per minute greater than in the midfollicular phase[11]. Subjective responses such as rating of perceived exertion are significantly greater when exercising in the midluteal phase compared to exercise in the midfollicular phase[11]. Additionally, some authors have reported that sweat onset is delayed during the postovulatory phase of the menstrual cycle[14,61,213], while others find no change[15,62,214-216]; still more report a greater sweat rate during the mid-luteal phase[7].

It has been reported that thermosensitivity for sweating and cutaneous vasodilation is increased in the midluteal phase of the menstrual cycle during resting heat exposure, as well as during exercise[8,217]. Evidence from Gagnon & Kenny (2011) indicates that the thermosensitivity of whole-body evaporative heat loss response (whilst cycling at a fixed intensity of 500 W) is significantly greater in men than women (795 ± 85 W · $°C^{-1}$ vs. 553 ± 77 W · $°C^{-1}$), but there is no significant difference in onset thresholds for sudomotor stimulation (whole-body heat loss) or cutaneous vasodilation[20]. Therefore, women demonstrate a lower whole-body sudomotor activation at fixed rates of metabolic heat production (in non-load bearing exercise) than men, due to the lower thermosensitivity of the response[20]. This agrees with previous research indicating that females typically sweat less than males (30 – 40% less)[47,218] during weight-bearing exercise at a fixed external workload[19,219-221] and at fixed percentages of maximum oxygen consumption[17,18,222-224].

When exercising in the heat, previous studies across the menstrual cycle have found no changes in female cardiovascular responses (heart rate and/or VO_2) at 20%[225], 30%[9], and 60%[226] VO_{2max}. The major limiting factor when working in the heat is expected to be the elevated core temperature during the luteal phase. Only one previous study has examined the effect of possible thermoregulatory changes over the menstrual cycle on exercise time to exhaustion in the heat, where they found a longer time to exhaustion in the early-follicular phase during light intensity intermittent exercise[225]. This study was undertaken in uncompensable heat, and the authors reported the expected higher core temperate for the participants in the mid-luteal phase of the menstrual cycle at the start of exercise. They also found that there was no difference over the menstrual cycle for the rate of increase of the core temperature during exercise and at exhaustion. Because the participants' starting core temperature was lower in the mid-follicular phase and increased at the same rate as in the mid-luteal phase, it took a longer time to reach a critical core temperature at exhaustion. Therefore, it can be assumed that any exercise undertaken in uncompensable heat conditions will be shorter in duration in the luteal phase than the follicular, due to the heightened starting core temperature.

On the whole, research seems to agree that there is no change in thermosensitivity or overall heat tolerance over the menstrual cycle[22,211]. However, the alteration to resting body temperature during the luteal phase may result in increased thermoregulatory and cardiovascular strain and a decrease in prolonged exercise performance[211]. It is important to note that thermoregulatory differences between men and women arise largely from morphological variations, and not specifically from physiological differences due to sex. Body morphology can vary through body composition, body surface area, body mass, and the ratio of surface area to mass (SA/m). The SA/m ratio in particular has been found to explain 10-48% of individual thermoeffector variance between men and women exercising in compensable conditions, with sex only accounting for 5% of this variation[3,227]. For example, when performing non-weight bearing activities (such as cycling at an absolute exercise intensity) in warm/humid and hot/dry conditions, a high mass and high surface area, resulting in a low SA/m ratio, leads to lower core temperatures responses and lower heat strain[228].

Body composition

Body composition describes the relative ratios of fat and fat-free mass making up a body. When referring to the heat gain differences between lean and fat tissues, specific heat is used. Specific heat describes the amount of heat required to raise the temperature of 1 gram of a substance by 1 °C. The specific heat of adipose tissues (fat) is 0.4 $\text{Kcal} \cdot g^{-1} \cdot {}^{\circ}C^{-1}$, whereas the specific heat of lean tissues (muscle, bone, and water) is higher at 0.8 $\text{Kcal} \cdot g^{1} \cdot {}^{\circ}C^{-1}$ [229]. Therefore, as fat has a higher capacity for heat than lean tissue, when two individuals with equal mass are exposed to an equal amount of heat stress, the person with a greater amount of fat mass will have a larger core temperature increase. However, these observations have only been made between groups of very lean (< 11% body fat) and obese (> 30% body fat) people[230].

Women typically have a higher percentage body fat than men (21.9 – 29.5% vs. 10.9 – 22.3%)[231], which affects their responses to both cold and heat[22]. It is understood that a "healthy" woman will have roughly 6 – 7% more body fat than a "healthy" male matched for other anthropometric factors, though some female elite athletes can be as lean as their male counterparts[231]. This inherent sex difference can be visualised as Behnke's concept of minimal weight, which approximates solely lean mass in men, but is larger in women due to "essential fat" stored in mammary tissue and elsewhere[232]. Additionally, women tend to have greatest fat stored over the leg (gluteal-femoral region), whereas men have fat stored over the posterolateral trunk (visceral depot)[69,233,234].

A higher fat content also indirectly contributes to increased heat generation when exercising in the heat, as the weight of fat tissue contributes to the metabolic cost of lifting and moving the body[26,60]. Therefore, as body fat percentage increases, heat stress upon the body becomes more difficult to sufficiently manage (due to increased metabolic heat generation), and the internal heat strain load will increase. As women may typically present with slightly more essential body fat than men, it can be expected that women will see greater core temperature increases when exercising in the heat than men.

Body surface area

The dimensions of the body surface have an important effect on whole-body heat exchange, as the absolute rates of heat transfer through evaporation, convection and radiation will be greatest in people with the greatest total body surface area. Since attainment of heat balance relies upon an equalization of heat production with an equivalent heat loss, individuals with larger surface area will be able to sustain a higher rate of heat production while still remaining in heat balance due to their larger heat loss potential[36]. Smaller individuals with a smaller body surface area will therefore have a relatively limited ability to dissipate heat, and an impaired ability to safely regulate core temperature at high ambient temperatures or during exercise. Additionally, a smaller body surface area will result in a reduced ability to dissipate heat via evaporation when compared to a larger body surface area. The same rate of whole-body sweat production over a smaller body surface area will result in higher local sweat rates, reducing sweating efficiency and the total amount of heat transferred[224].

A larger body size (measured in m^2) results in a lower body surface area to mass ratio, as there is a relatively smaller increase in body surface area for any given increase in body mass. Therefore rates of heat exchange per unit of mass are higher in lighter individuals when working in high ambient temperatures than for heavier people[235]. A person with a smaller surface area to mass ratio will see a lower rate of heat storage for an equivalent metabolic heat load and will result in a smaller core temperature change [36,236]. As women are generally smaller than men and have a 10 – 12% greater SA/m ratio, they will typically show a greater rate of heat storage during an equal amount of metabolic heat generation[22]. This is due to the rapid heat gain enabled by a high SA/m ratio when exercising in extreme heat, which is poorly tolerated by small persons due to their low thermal mass[237,238]

Body mass

Body mass serves two roles in heat exchange: first, the mass is the body's internal heat sink and contributes to thermal inertia; second, the energy cost of weight-bearing exercise is greater in people with larger body mass, increasing metabolic heat production[239]. In weight-bearing activities (such as running at a fixed speed), a person with a higher mass will generate a greater metabolic rate than someone with less mass at the same intensity of effort. This is especially pronounced whilst running in humid/warm conditions where heat loss pathways are already maximally activated[236]. The implication of this is that heavier runners need to exercise at lower speeds to match the same metabolic work rate as lighter runners in humid conditions[240].

On average, women have less body mass than men (avg. 21.5 kg · m^{-2} vs. 24.5 kg · m^{-2}) due to their smaller body sizes[241]. Additionally, research indicates that obese individuals tend to have a lower density of sweat glands compared to leaner individuals, as the fixed number of sweat glands are spread over a larger area with a larger body size[58]. Therefore, as women typically have lower body mass and smaller body sizes than men, body size differences will result in females generating less heat compared to men during exercise in the heat.

Given the significant number of intrinsic and extrinsic factors contributing to exertional heat illness, risk mitigation techniques must be employed when working in extreme heat. The Australian Army Work Tables provide durations of work and rest to commanders when conducting exercises in the heat, but the appropriateness of these durations has not been assessed between sexes, nor along a longer-duration work day.

Summary

Currently, the Australia Army Instruction dictates that no more than 2 consecutive bouts of fixed duration and rest (set by Continuous Work Tables) are to be performed per 24-hour period under specific environmental conditions. This limitation may hamper the effectiveness of ground forces who are limited to a few hours of work per day in hot conditions. However, this limitation is based on the assumption that sequential bouts of work will result in the same amount of heat being gained in each bout. However, recent research has found that subsequent bouts of exercise result in reduced amounts of heat gained in each repeat bout after the first. Additionally, the tables have been developed using data specific to males, and the work and rest durations have not been checked with females. This research project will assess the current continuous Work Tables and investigate whether the current work limits may be increased without increasing personal risk.

Research Questions and Implications

1. To evaluate whether current Australian Army work and recovery protocols for hot environments can be increased to four consecutive work and recovery cycles without resulting in excessive heat strain in healthy adults
2. To examine the sex-based differences in elevation and restoration of core temperature when working in the heat with current work and recovery protocols.

This research project may inform the Australian Defence Forces and other occupational groups who work in hot environments on strategies to manage work and recovery durations over the work day. It will also assist in ensuring current work and rest durations are appropriate for males and females when working in the heat.

Chapter 3: Research Design

Methodology and Research Design

Participants

After ethical approval from the Human Research Ethics Committee (Queensland University of Technology) (Appendix A), a sample of 14 males and 15 females between 18 and 45 years of age were recruited for this study. Prior to commencement of the study all participants completed a health screening questionnaire (Appendix B) and provided signed informed consent. Contraindications for participation included any cardiovascular disease or injury, previous musculoskeletal injury that would impede exercise performance (as identified by a health screening questionnaire), current medications that may impact their ability to thermoregulate, current pregnancy, or a BMI below 18.5 kg · m^{-2} or above 32.9 kg · m^{-2} (following Australian Army entry criteria)[1]. Female participants were eligible if they were using combined monophasic (not biphasic or triphasic) oral contraceptive methods, or could self-report a regular menstrual cycle for at least the previous 6 months[6]. Participants were screened with a treadmill VO_{2peak} assessment to ensure they met the minimum aerobic capacity criteria for entry into the Australian Army, which is a VO_{2max} of >38.1 mL · kg^{-1} · min^{-1}. Priority selection was given to participants with a VO_{2peak} above 45.0 mL · kg^{-1} · min^{-1} to more closely reflect the fitness levels of Australian Army Infantry personnel.

Height was measured with a stadiometer to the nearest 5mm, with shoes removed and participants instructed to stand fully upright with full inhalation. Nude weight was measured

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[1] https://www.defencejobs.gov.au/joining/can-i-join/health-and-fitness

to the nearest 50 grams using digital scales (Wedderburn BWB-600, Tanita Corporation, Tokyo, Japan).

Research Protocol

Participants attended a total of three sessions: a screening and VO_{2peak} assessment, an experimental trial session, and a body composition session. The VO_{2peak} session was conducted a minimum of 24 hours before the experimental trial session, and the body composition was conducted within one month after the experimental trial.

Screening and assessment of aerobic capacity

During the screening sessions, participants were screened for eligibility into the study by completing a pre-exercise health screening tool (Appendix B). The participants' height and clothed weight were measured, and a chest strap heart rate monitor was attached (Polar Team^2, Polar Electro, Kempele, Finland). Aerobic fitness was measured using an incremental test to exhaustion on a motorised treadmill (StairMaster ClubTrack 2100 Treadmill, Nautilus Health & Fitness Group, Louisville, USA). The participants undertook a 5-minute treadmill warmup at a self-selected intensity, and verbally confirmed they were ready to begin the VO_{2peak} test. Expired gas measures were obtained using a metabolic cart (Parvo Medics TrueOne 2400, Parvo Medics, East Sandy, USA) connected to a two-way T-shape non-rebreathing valve (Model 2700, Hans-Rudolph, Shawnee, USA) and oro-nasal mask (Model 7450 Silicone V2, Hans-Rudolph, Shawnee, USA). Concurrent measurement of metabolic energy expenditure utilised a 6 L fluted mixed box within the calorimeter. Concentrations of oxygen (O_2) were measured using a paramagnetic gas analyser (error of ± 0.1%), and carbon dioxide (CO_2) were measured using an infrared gas analyser (error of ± 0.1%) within the Parvo Medics system. Prior to each session the gas analysers were calibrated using gas mixtures of 4% CO_2 and 17%

O_2, and the pneumotach was calibrated using a 3 L syringe (error of ± 3%). Metabolic energy expenditure was calculated from minute averaged values for VO_2 and Respiratory Exchange Ratios (RER)[242]. Participants began the VO_{2peak} test at 1% incline and a speed correlating to 6-8/20 on a Borg Rating of Perceived Exertion (RPE) scale[243]. Each minute, the treadmill speed was increased by 1 $km \cdot h^{-1}$ until participants indicated they were running at 16-18/20 RPE. The incline was then increased by 1% per minute until participants reached their perceived maximum effort and ceased exercising. Expired gas analysis yielded the participants' highest minute averaged VO_2 during the maximal effort, which was recorded as their VO_{2peak}. If their measured VO_{2peak} met the entry requirements to the Australian army ($>38.1\ mL \cdot kg^{-1} \cdot min^{-1}$), they were deemed eligible to continue with the study. Participants who did not meet this threshold were not able to continue with the study.

Body composition

During the body composition sessions, participants had their height and clothed weight measured, and their body composition assessed using a fan beam Dual-Energy X-ray Absorptiometry (DXA) (Lunar Prodigy, GE Healthcare Lunar, Madison, USA) and analysed using dedicated software (encore, version 9, GE Healthcare Lunar, Madison, USA). Participants attended the scanning session hydrated and rested (no exercise the afternoon before and the morning of the scan). The scans were conducted by a qualified and accredited DXA operator. All scans were conducted within one month of the experimental trial date. The DXA scanner provided assessments of participants' fat mass (error ± 0.3%) and fat-free mass (error ± 2.5%)[244].

Experimental Trial

In preparation for the test, participants did not engage in exercise, ingest caffeine or alcohol 24 hours prior to testing, and were instructed to consume at least 40 $mL \cdot kg^{-1}$ body mass of water over the 24 hours before the trial. They were asked to consume a light meal and 500 mL of water 2 hours prior to arriving at the laboratory. Pre-trial hydration status was confirmed by urine specific gravity (USG) (PAL 10s, ATAGO, Tokyo, Japan) of <1.020[245]. If participants provided a sample >1.020 they were given an additional 500 mL of tap water, which was consumed 30 minutes before commencing the trial. The average USG was 1.011 ± 0.005, and only two participants required an additional 500 mL of water before beginning exercise.

At the beginning of the experimental trial, participants were reminded of the trial procedures and verbal consent to continue was obtained. The trials were conducted between December and March (Summer) to account for seasonal variations in core temperature and acclimatisation, and all trials began between 7am and 9am to control for circadian core temperature variations. Participants provided a urine sample for hydration assessment. Once adequate hydration was determined, participants undertook a nude weight in a private lockable room and self-inserted the rectal thermistor to a depth of 12 cm, as marked with tape on the probe. They then re-clothed, and a chest strap heart rate monitor and four skin temperature sensor thermocrons were attached.

Female participants undertook the trial between days 5 and 8 of their regular menstrual cycle, with day 1 being the beginning of menses. This date range was chosen as days 5 to 8 is when females have a hormonal status most similar to males, and enables analysis of core temperature variations based on morphological differences between sexes. Female participants self-reported a regular menstrual cycle and predicted the appropriate date range for attendance.

During work, participants wore the Multi-Cam Uniform of the Australian Army (total thermal insulation I_T: 1.36 clo), their own shoes, and an Australian Army helmet and vest (Body Armour covering 3299.5 cm^2) totalling 10kg of weight. The helmet and vest were removed during rest periods (resulting in a clo of 1.36 during rest), and participants were instructed to remain seated for the duration of the rest period. Please refer to Figure 1 for a timeline of the experimental trial.

At the beginning of the trial, participants remained seated for a 20-minute baseline period[246] in a thermoneutral environment (24.0 ± 1.3 °C, 56 ± 9% relative humidity, <0.1 $\mathrm{m \cdot s^{-1}}$ air speed) whilst resting measures were taken. Thereafter participants entered an environmental chamber to start the experimental trial. The work and rest periods, and environmental conditions, were determined in consultation with army stakeholders, and in accordance with the Army Standing Instruction Continuous Army Work Table, and corresponded to Heavy work (> 500W) for 35 minutes and Moderate work (350 - 500W) for 55 minutes. From this, the corresponding work-rest environments were selected to simulate real world training.

The experimental trial was conducted in an environmental chamber (dimensions 4 x 3 x 2.5m; length, width, height) alternating between 32.5 °C WBGT (Air temperature: 38.8 ± 0.2 °C; Relative humidity: 55 ± 1%; Wind speed: 1.5 $\mathrm{m \cdot s^{-1}}$) during work and 28 °C WBGT (Air temperature: 32.0 ± 1.1 °C; Relative humidity: 60 ± 6%; Wind speed: 0.5 $\mathrm{m \cdot s^{-1}}$) during rest.

Ambient air temperature, relative humidity and Wet-Bulb Globe Temperature (WBGT) were measured with a digital weather station (3M QuestTEMP 36, 3M, St. Paul, USA) recording at 1-minute intervals. WBGT was calculated using equation 1[27]. Wind speed was measured with a digital anemometer (Kestrel Pocket Weather 4000, Nielsen-Kellerman, Pennsylvania, USA) once during each work period.

$$Eq. 1 \qquad WBGT = 0.7T_{wet-bulb} + 0.2T_{globe\ thermometer} + 0.1T_{dry-bulb}$$

Four consecutive work bouts were conducted on a motorised treadmill, alternating between 5.9 $\mathrm{km \cdot h^{-1}}$ and 1% incline, with 10kg load (567 ± 143 W) and 4.5 $\mathrm{km \cdot h^{-1}}$ and 1% incline, with 10kg load (439 ± 109 W). The wattages calculated correspond to “hard” and “moderate” work in the Army Standing Instruction as calculated by the Pandolf Load Carriage equation (Eq.2), assuming an average Australian Army soldier (82 kg) and a terrain factor of 1.0[247]:

$$Eq.2 \qquad M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + n(W + L)(1.5V^2 + 0.35VG)$$

Where M = metabolic rate, watts; W = subject weight, kg; L = load carried, kg; V = speed of walking, $m \cdot s^{-1}$*; G = grade, %; n = terrain factor (n = 1.0 for treadmill).*

Participants were able to eat and drink freely during the trial, and the researchers verbally encouraged participants to remain hydrated by drinking water and an electrolyte drink regularly throughout the trial. Nutritionally appropriate food was provided in each rest period to assist with fluid retention and to prevent fatigue. The available foods were recommended by an accredited sports dietician to replenish carbohydrates and ensure adequate energy throughout the trials, and included vegemite sandwiches, muesli and fruit bars, healthy wraps, and fresh fruit. Although these foods are not a replication of a standard Army diet, this was done to control for food and fluid-based alterations to thermoregulation (such as progressive dehydration) and premature fatigue due to glycogen depletion.

All fluids and foods provided to and consumed by participants were weighed on a digital scale (Propert 5 kg Slimline Glass Digital Kitchen Scale, McGloins-Supertex, Sydney, Australia). Participants' clothed body mass was measured at the end of each exercise period throughout the experimental trial session using a digital scale (Wedderburn BWB-600, Tanita Corporation, Tokyo, Japan).

The work bout was ceased if participants' heart rate exceeded 90% of the measured maximum obtained during the VO_{2peak} screening session, if their core body temperature exceeded 39.0 °C as per ISO 9886:2004[248] and ACSM[92] policy, or if they showed signs of heat-related illness.

Participants were then allowed to cease the trial completely if they wished, or to continue with the next work bout after the 30-minute rest period. If a participants' body core temperature exceeded 38.5 °C at any point in time, all their data (including biometric values and hydration measurements) were stored separate to the participants who did not exceed 38.5 °C for later comparison. As the Work Tables assume that, on average, a core temperature of 38.5 °C will be reached at the conclusion of work, it is important to ascertain whether any physiological variables will be strong predictors of exceeding this threshold.

At the end of the trial, participants provided a final nude weight and were permitted to leave. The pre and post nude weights were combined with the monitored food and fluid intake to estimate sweat losses throughout the trial.

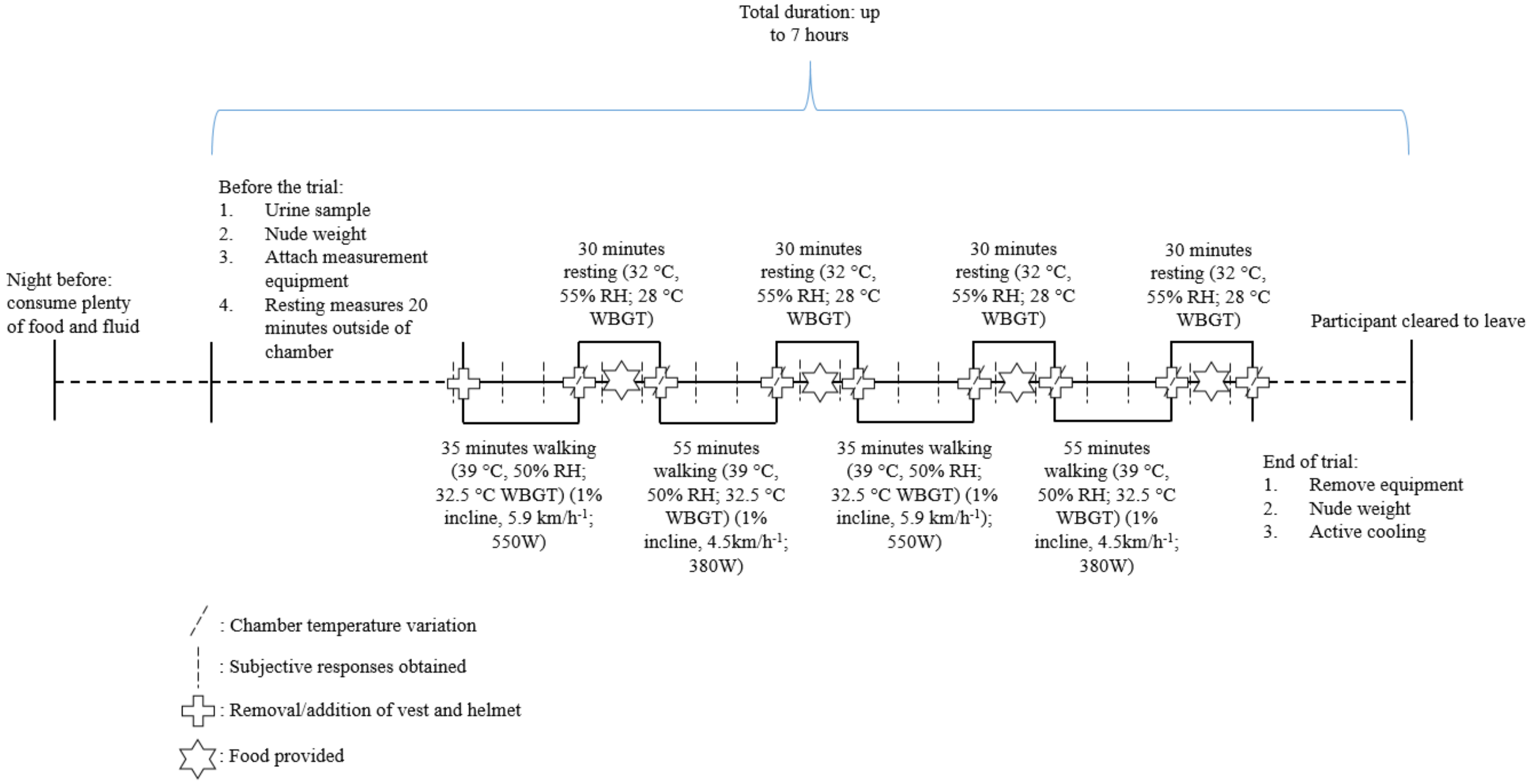

Figure 1: Timeline of experimental trial session

Data Collection

Physiological measurements

Core body temperature was estimated from rectal temperature (T_{rec}) using a thermistor (YSI 400, DeRoyal, Knox, USA) self-inserted 12cm beyond the anal sphincter (following American Society for Testing Material Standard F2668-16[249]) and recorded using a data logger (Squirrel 2020 series, Grant Instruments, Cambridge, UK) which was programmed to log every five seconds. Samples were averaged per minute and analysed at the end of work and rest bouts. The change in core body temperature, from rest to peak, as well as peak to lowest during rest, was calculated.

Mean skin temperature (T_{skin}) was estimated using from four sites (neck, right scapula, back of left hand, front of right shin) wireless iButton thermocrons (DS1922L-F50 iButtons, Maxim Integrated, San Jose, USA) attached to four sites using a single piece of adhesive tape (Premium Sports Tape, AllCare, Kumeu, New Zealand). iButtons were programmed before data collection to log every 6-seconds at a resolution of 0.0625 °C via USB to a computer (DS9490R USB Port Adapter, DS1402D-DR8 Blue Dot Receptor, Maxim Integrated, USA). T_{skin} was calculated according to ISO 9886:2004 (Eq.3)[248]:

$$Eq.3 \qquad T_{skin} = 0.28T_{neck} + 0.28T_{scapula} + 0.16T_{hand} + 0.28T_{shin}$$

Cumulative heat strain index (CHSI) was measured from minute-averaged heart rate and core temperature values. It provides a numerical value describing the total amount of cumulative heat strain a body undergoes, by comparing physiological measurements during work to baseline.

CHSI was calculated using the following (Eq.4)[250]:

$$Eq.4 \qquad CHSI = (\sum_{0}^{t} hb - f_{c0} * t) * 10^{-3} * (\int_{0}^{t} T_{rec} * dt - T_{rec0} * t)$$

Where hb = heart beats, f_{c0} *= initial lowest heart rate (bpm),* T_{rec} *= rectal temperature,* T_{rec0} *= baseline rectal temperature (ºC) and t = time (min) from the onset of measurement.*

Sweat loss was calculated from changes in body mass by adding the participants' initial nude mass and fluid and food intakes, and subtracting their outputs and final nude mass, all in kilograms.

Body surface area (BSA) was calculated using the following (Eq.5)[251]:

$$Eq.5 \qquad BSA = 0.007184 * (Weight^{0.425} * Height^{0.725})$$

Metabolic work rate was measured once over three minutes approximately halfway through each exercise and rest bouts, using a metabolic cart (Parvo Medics TrueOne 2400, Parvo Medics, East Sandy, USA) connected to a two-way T-shape non-rebreathing valve (Model 2700, Hans-Rudolph, Shawnee, USA) and oro-nasal mask (Model 7450 Silicone V2, Hans-Rudolph, Shawnee, USA).

Metabolic heat production was calculated using the following formula (Eq.6)[242]:

$$Eq.6 \qquad Heat\ production\ (W) = \left(352 * (0.23 * RER + 0.77) * \left(\frac{VO_2}{1.84}\right)\right) * 1.84$$

Where RER = respiratory exchange ratio, and VO_2 *is measured in* $L \cdot min^{-1}$

Physiological strain index (PSI) was measured continuously as a factor of core temperature and heart rate. It describes physiological response to exercise on a scale from 0 to 10. Minute-averaged core temperature and heart rate values were utilised to calculate PSI using the following (Eq.7)[252]:

$$Eq.7 \quad PSI = 5 * (T_{rect} - T_{rec0}) * (39.5 - T_{rec0})^{-1} + 5 * (HR_t - HR_0) * (180 - HR_0)^{-1}$$

Where T_{rect} = rectal temperature at specific time point, T_{rec0} = rectal temperature at baseline, HR_t = heart rate at specific time point, and HR_0 = heart rate at baseline

Perceptual measurements

Perceived intensity of exercise was measured using Borg's Rating of Perceived Exertion scale where 6 represents "no effort" and 20 indicates "maximum effort"[243]. Thermal sensation was measured using a modified scale where 1 represented "unbearably cold", 7 "neutral", and 13 "unbearably hot"[253]. Thermal comfort was similarly measured on a modified scale where 1 represented "comfortable" and 5 "extremely uncomfortable"[253]. Both thermal sensation and comfort were measured at 20-minute intervals during moderate work bouts, and 15 minute intervals during rest and hard work bouts.

Analysis

The data is presented as means ± standard deviation unless otherwise stated. Group biometric differences (age, height, body mass, body mass index, surface area to body mass ratio, VO_{2peak}, body fat percentage, and body surface area) between males and females were assessed by independent samples t-test. Participants who exceeded the 38.5°C core temperature threshold had their data compared to that of the participants who did not exceed this threshold via independent samples t-tests. The primary data collected for analyses were T_{rec}, HR, and T_{skin}. Two-way repeated-measures analysis of variance (ANOVA) was used to assess the difference in T_{rec}, HR, and T_{skin} between the sexes, and across the work and rest bouts.

T_{rec} absolute peaks, troughs (minimums), end of bout maximums, gains and losses, rates of change and time delay from end of bout to absolute maximums were compared using two-way repeated measures ANOVA across all four exercise bouts (Ex1-Ex4) and between sexes. T_{rec} values were comparable between all four bouts as each bout was assumed to reach a T_{rec} value of 38.5 °C irrespective of duration and intensity, based on the Army Work Tables.

T_{skin} and HR absolute peaks, gains (difference between minimum values at rest and maximum values during the subsequent work bout) and losses (difference between maximum values during work and minimum values during the subsequent rest bout) were compared using two-way repeated measures ANOVA between exercise bouts of the same intensity (Ex1/Ex3, Ex2/Ex4) and between sexes. T_{skin} and HR values were only comparable between bouts of the same intensity as the duration and intensity of work significantly affected these measurements. The within-subjects levels were Ex1-Ex4, R1-4, with a between-subjects factor of Sex. All data were analysed using SPSS (SPSS version 25.0, SPSS Inc., Chicago, USA). All variables were tested for normality by Shapiro-Wilks tests, and where the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied to adjust degrees of freedom and increase critical values of the F-ratio. Statistical significance of the two-way repeated-measures ANOVA was set to $P < 0.05$.

A retrospective (post hoc) power calculation using G*Power 3.1.9.4 software was performed in order to determine if the experiment was sufficiently powered. For sex-based differences in core temperature, heart rate, and skin temperature, over the four exercise periods, the effect size f was calculated using Cohen's d to be 0.51 with α set at 0.05 and a total sample size of 27. Within G*Power, an F test ANOVA: Repeated measures, within-between interaction was performed, resulting in a Critical F of 2.717. This project was sufficiently powered with the number of participants recruited.

For differences between bouts for core temperature, heart rate, and skin temperature, the effect size f was calculated using Cohen's d to be 0.852 with α set at 0.05. Within G*Power, an F Test ANOVA: Repeated measures within factors was performed, resulting in a Critical F of 2.717.

Chapter 4: Results

Summary of Sessions

Fourteen men and fifteen women participated in the trial. One female was stopped at the end of the second work bout due to technical issues with the environmental chamber and was unable to re-attend later to complete the trial. Another female suffered an unexpected adverse event where she briefly stumbled on the treadmill 21 minutes into the second work bout, and the trial was ceased for her safety (Appendix C). It was later determined that this participant had an underlying illness when she attended the experimental trial session. For core temperature measurements, if a participant did not complete a work bout to its full duration, that participant's data was excluded from the repeated measures analysis of variance. Therefore n = 14 men and 13 women for T_{rec}, HR and T_{skin}. One female participant was included with a VO_{2peak} value of 39.5 mL · kg^{-1} · min^{-1}. This participant was included in the study as her VO_{2peak} assessment was likely not a true maximal effort, with a reported maximal RPE of 15/20 ("maximal" > 18/20) and an RER value of 1.03 ("maximal" > 1.10), and she likely has a greater aerobic capacity than was observed in this assessment.

Statistically significant differences were found in the biometric and anthropometric values between the men and women in this trial (Tables 1 and 2). As recorded from the aerobic fitness and body composition sessions, the men and women differed in height ($t = -5.940$, $p < 0.001$), body mass ($t = -6.118$, $p < 0.001$), BMI ($t = -4.044$, $p < 0.001$), body surface area to mass ratio ($t = -5.264$, $p < 0.001$), body fat percentage ($t = 2.798$, $p = 0.010$), and BSA ($t = -8.219$, $p < 0.001$). The participants also differed in several variables during the experimental trial: pre-trial nude weight ($t = -7.762$, $p < 0.001$), post-trial nude weight ($t = -7.519$, $p = 0.000$), fluid intake ($t = -2.382$, $p = 0.025$), sweat rate ($t = -2.132$, $p = 0.043$), and absolute sweat losses ($t = -2.132$, $p = 0.043$).

Table 1: Participant biometrics

	Men (n = 14)	**Women (n = 13)**	**p-Value**
Age (Years)	31.8 ± 7.9	31.5 ± 7.7	0.935
Height (cm)	178.3 ± 5.0	165.0 ± 6.5	**< 0.001**
Body mass (kg)	74.93 ± 7.96	58.31 ± 5.91	**< 0.001**
BMI (kg · m^{-2})	24.1 ± 2.1	21.2 ± 1.6	**< 0.001**
SA/m (cm^{2} · kg^{-1})	256.6 ± 12.7	282.9 ± 13.1	**< 0.001**
VO$_{2peak}$ (mL · kg^{-1} · min^{-1})	54.39 ± 8.69	50.49 ± 5.86	0.186
Body fat (%)	17.65 ± 6.94	25.00 ± 6.65	**0.010**
BSA (m^{2})	1.9 ± 0.9	1.6 ± 0.1	**< 0.001**

BMI = body mass index, BSA = body surface area, SA/m = surface area to mass ratio

Table 2: Participant hydration measurements during trial

	Men	**Women**	**p-Value**
USG	1.012 ± 0.005	1.012 ± 0.005	0.917
Nude weight (pre)	76.91 ± 6.33	58.45 ± 6.00	**< 0.001**
Nude weight (post)	77.13 ± 6.68	58.41 ± 6.22	**< 0.001**
Fluid intake (kg)	3.88 ± 1.12	2.93 ± 0.93	**0.025**
Food intake (kg)	0.48 ± 0.30	0.51 ± 0.39	0.832
Outputs (kg)	0.51 ± 0.16	0.53 ± 0.40	0.927
Sweat rate (kg · hr^{-1})	0.79 ± 0.25	0.62 ± 0.12	**0.043**
Relative sweat loss (g · kg^{-1})	0.053 ± 0.017	0.054 ± 0.013	0.812
Absolute sweat loss (kg)	3.94 ± 1.25	3.12 ± 0.62	**0.043**

USG = urine specific gravity

The wattage generated by the participants in the "moderate" and "heavy" work bouts accurately represented the intensity of work described in the Australian Army Work Tables. The participants generated an average of 439 ± 109 W during the "moderate" work bouts (expected range of 350 – 500 W, calculated by the Pandolf Load Carriage), and 567 ± 143 W during the "hard" work bouts (expected range > 500 W). There were no significant differences in the absolute (men: 136.62 ± 51.3 W vs. women: 112.81 ± 56.16 W, p = 0.631) or relative metabolic work rates (men: 1.79 ± 0.70 W · kg^{-1} vs. women: 1.93 ± 0.87 W · kg^{-1}, p = 0.270) of the men and women during the baseline measurements, although there were differences in the additional load carried as a percentage of body mass (t = 6.228, p < 0.001), and the percentage of body surface area covered by body armour (t = 8.101, p < 0.001). There were no significant differences in any other physiological or perceptual measurement during the baseline resting period (Table 3).

Table 3: Baseline physiological and perceptual measurements

	Men	**Women**	**p-Value**
T_{rec} (°C)	37.01 ± 0.27	37.04 ± 0.25	0.816
Heart rate (bpm)	64.7 ± 9.3	60.5 ± 12.0	0.326
T_{skin} (°C)	33.7 ± 0.8	32.7 ± 0.5	0.683
PSI (0-10)	1.4 ± 0.9	0.9 ± 0.7	0.137
Thermal Comfort (1-5)	1	1	0.623
Thermal Sensation (6-13)	7 ± 1	7 ± 1	0.563
Rating of Perceived Exertion (6-20)	6	6	0.345
Load carried relative to mass (%)	14 ± 1	17 ± 2	**< 0.001**
BSA covered by body armour (%)	17 ± 1	20 ± 1	**< 0.001**
Menstrual cycle day	-	7 ± 1	-

PSI = physiological strain index

Physiological Strain During Work

Core temperature thresholds

Over the whole trial, ten participants (five males and five females) experienced a T_{rec} above 38.5 °C, 35% of 29 participants (Figure 2). Of those ten, two males experienced a T_{rec} above 39.0 °C, 7% of 29 participants. Participants who were observed to be approaching the 39.0 °C threshold were instructed to cease work when they reached 38.9 °C; they immediately began the next rest period and all 39.0 °C core temperature peaks were reached whilst at rest.

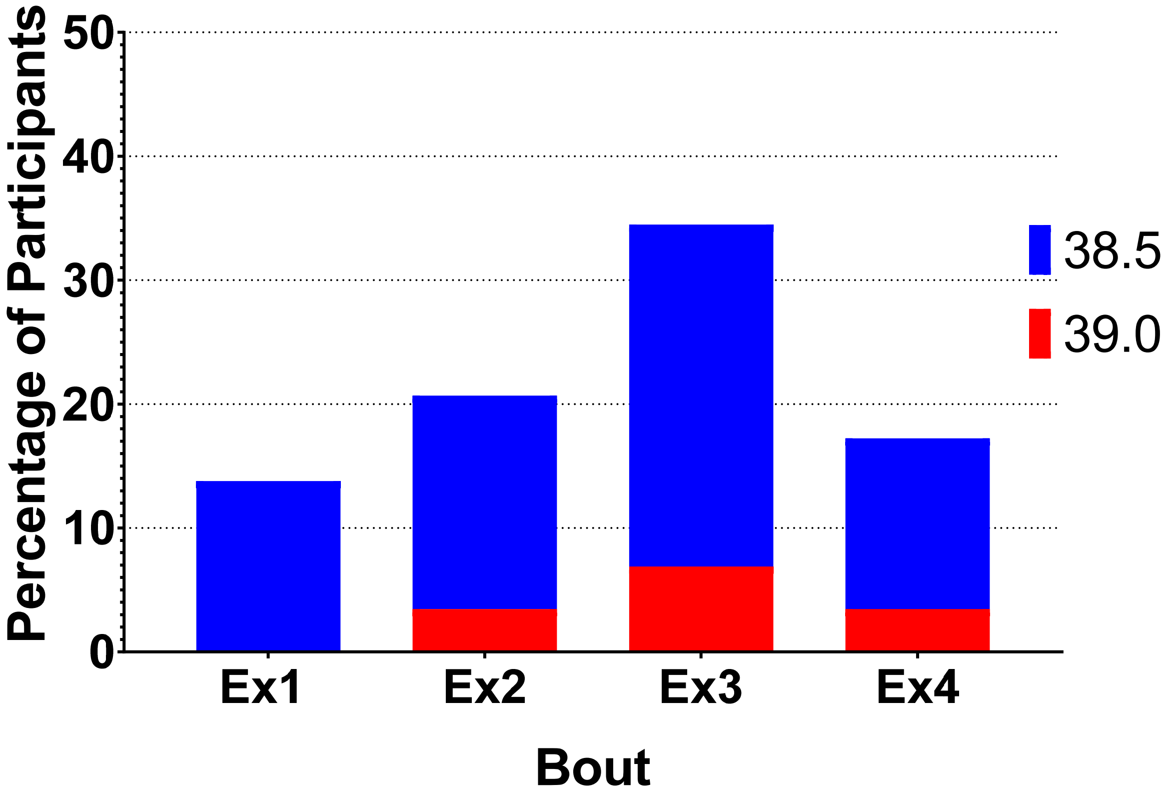

Figure 2: Percentage of participants with core temperatures at or above threshold values

No significant differences were observed in any biometric, anthropometric, or physiological variable between the participants that reached and exceeded a core temperature of 38.5 °C and those who did not before the trial or at rest (Table 4).

Table 4: Physiological measurements between high responders and non during baseline

	< 38.5 °C (n = 19)	> 38.5 °C (n = 10)	p-Value
Age (Years)	32.7 ± 7.2	29.2 ± 7.8	0.239
Height (cm)	171.0 ± 7.3	173.3 ± 11.2	0.566
Body mass (kg)	65.05 ± 11.11	68.00 ± 11.54	0.508
BMI (kg · m^{-2})	22.4 ± 3.0	22.8 ± 1.5	0.648
SA/m (cm^2 · kg^{-1})	271.8 ± 21.0	266.6 ± 15.5	0.470
VO_{2peak} (mL · kg^{-1} · min^{-1})	51.89 ± 6.61	55.16 ± 10.00	0.299
Body fat (%)	22.35 ± 7.75	19.49 ± 8.10	0.361
BSA (m^2)	1.78 ± 0.18	1.71 ± 0.20	0.692
USG	1.012 ± 0.005	1.011 ± 0.005	0.516
Nude weight (pre)	66.16 ± 11.83	68.97 ± 11.13	0.541
Nude weight (post)	66.23 ± 12.19	69.07 ± 11.20	0.545
Fluid intake (kg)	3.15 ± 1.22	3.56 ± 1.15	0.390
Food intake (kg)	0.50 ± 0.37	0.45 ± 0.31	0.710
Outputs (kg)	0.43 ± 0.25	0.76 ± 0.42	0.081
Sweat rate (kg · hr^{-1})	0.66 ± 0.21	0.72 ± 0.27	0.525
Relative sweat loss (g · kg^{-1})	0.052 ± 0.017	0.052 ± 0.016	0.894
Absolute sweat loss (kg)	3.50 ± 0.91	3.61 ± 1.34	0.811
Load carried relative to mass (%)	15.8 ± 2.7	15.1 ± 2.5	0.489
BSA covered by body armour (%)	18.7 ± 1.9	18.4 ± 2.1	0.726
T_{rec} (°C)	36.97 ± 0.24	37.10 ± 0.26	0.213
Heart rate (bpm)	62 ± 12	63 ± 9	0.914
T_{skin} (°C)	32.5 ± 0.5	33.0 ± 0.7	0.095
PSI (0-10)	1.0 ± 0.6	1.0 ± 0.8	0.435
Thermal Comfort (1-5)	1	1	0.974
Thermal Sensation (6-13)	7 ± 1	7 ± 1	0.082
Rating of Perceived Exertion (6-20)	6 + 1	6 + 0	0.478

Core temperature

Peaks in T_{rec} were significantly different between the four work bouts (Greenhouse F = 12.284, $p < 0.001$, effect size 0.898 (Table 5) (Figure 3-4). Pairwise comparisons of all bouts indicate that T_{rec} peaks in work bouts 1, 2 and 4 were significantly lower than work bout 3. Positive T_{rec} rates of change were significantly greater in work bout 1 than bout 3 (Greenhouse F = 14.662, $p = 0.001$), but were not different between work bouts 2 and 4 (Greenhouse F = 0.045, $p = 0.834$) (Table 5). Positive T_{rec} changes (absolute gains) were significantly different between all four work bouts (Greenhouse F = 39.227, $p < 0.001$). Lengths of time from the end of work to peak body core temperatures were not significantly different across all four work bouts (F = 1.042, $p = 0.387$) (Table 5).

Across all four work bouts, there were no significant differences in peak T_{rec} values between men and women (F = 2.071, $p = 0.163$, effect size 0.869), sex and positive changes in T_{rec} (F = 0.677, $p = 0.418$), nor sex and lengths of time from the end of work to peak body core temperatures (F = 0.752, $p = 0.404$). There was no interaction between sex and positive T_{rec} rates of changes between bouts 1 and 3 (F = 0.200, $p = 0.658$), nor between bouts 2 and 4 (F = 0.594, $p = 0.448$) (Table 5).

Table 5: Trec measurements during work

	Ex1	**Ex2**	**Ex3**	**Ex4**
Absolute peak values (° C)				
Men	38.20 ± 0.32	38.36 ± 0.34	38.49 ± 0.43*	38.33 ± 0.42
Women	38.05 ± 0.40	38.09 ± 0.34	38.33 ± 0.38*	38.15 ± 0.35
Core temperature changes from previous bout (° C)				
Men	1.19 ± 0.23	0.85 ± 0.31	0.71 ± 0.25	0.48 ± 0.19
Women	1.01 ± 0.29	0.65 ± 0.27	0.76 ± 0.25	0.57 ± 0.16
Time from end of work bout to peak T_{rec} (minutes)				
Men	7.11 ± 3.92	6.34 ± 4.21	8.00 ± 5.29	5.56 ± 2.92
Women	5.50 ± 1.73	4.75 ± 2.63	6.50 ± 1.29	4.75 ± 2.22
Rate of change (° C · min^{-1})				
Men	0.0332 ± 0.0090	0.0126 ± 0.0052	0.0216 ± 0.0103	0.0097 ± 0.0051
Women	0.0314 ± 0.0128	0.0069 ± 0.0053	0.0223 ± 0.0103	0.0117 ± 0.0054

* Significantly different to all other bouts ($p < 0.001$)

Core temperature changes calculated from rest bout minimum to subsequent work maximum

Rates of change calculated across 10-minute sample during minutes 15-25 in Ex1/Ex3, minutes 30-40 in Ex2/Ex4

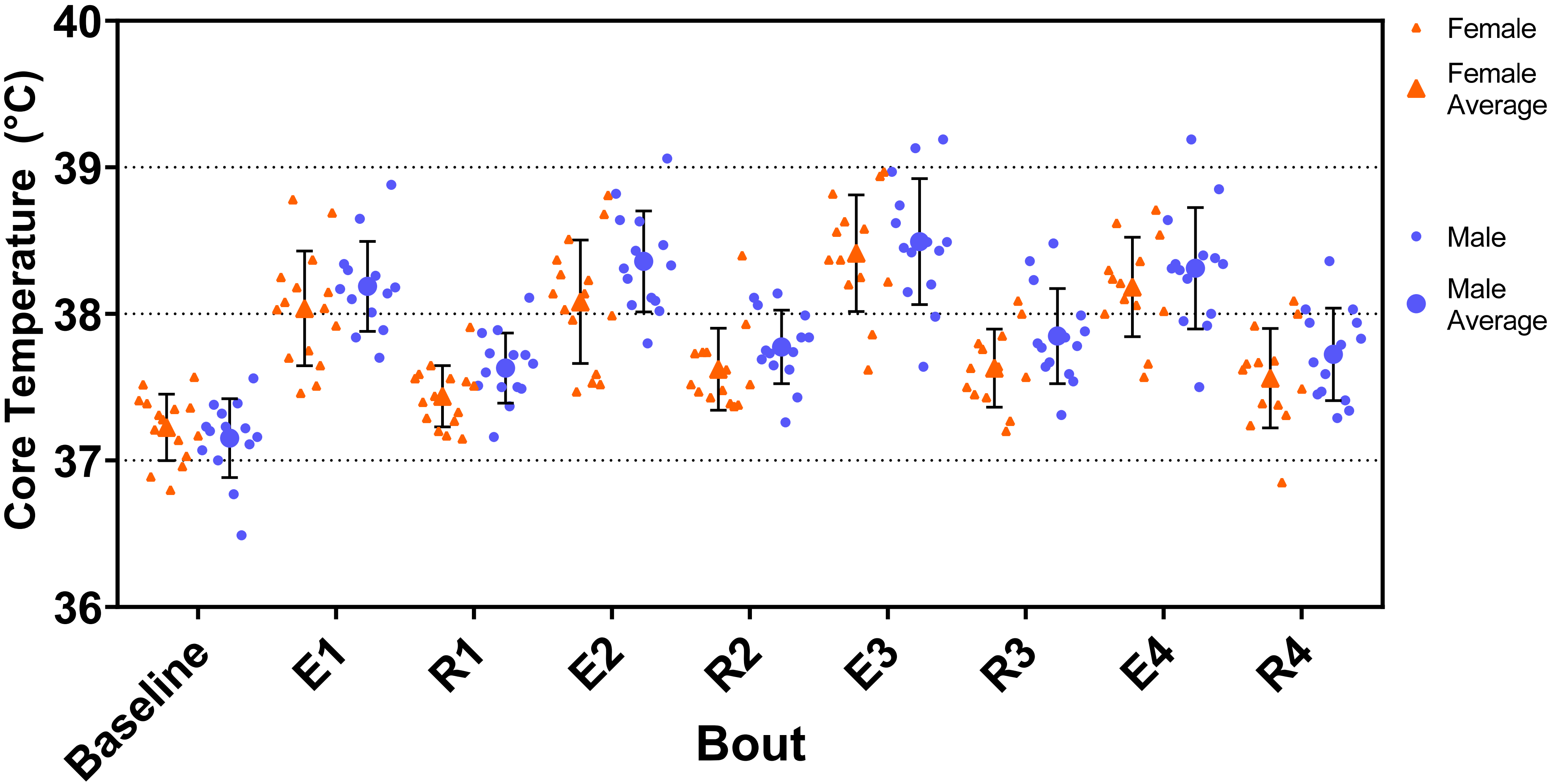

Figure 3: Minimum and maximum T_{rec} values for all participants in all work and rest periods

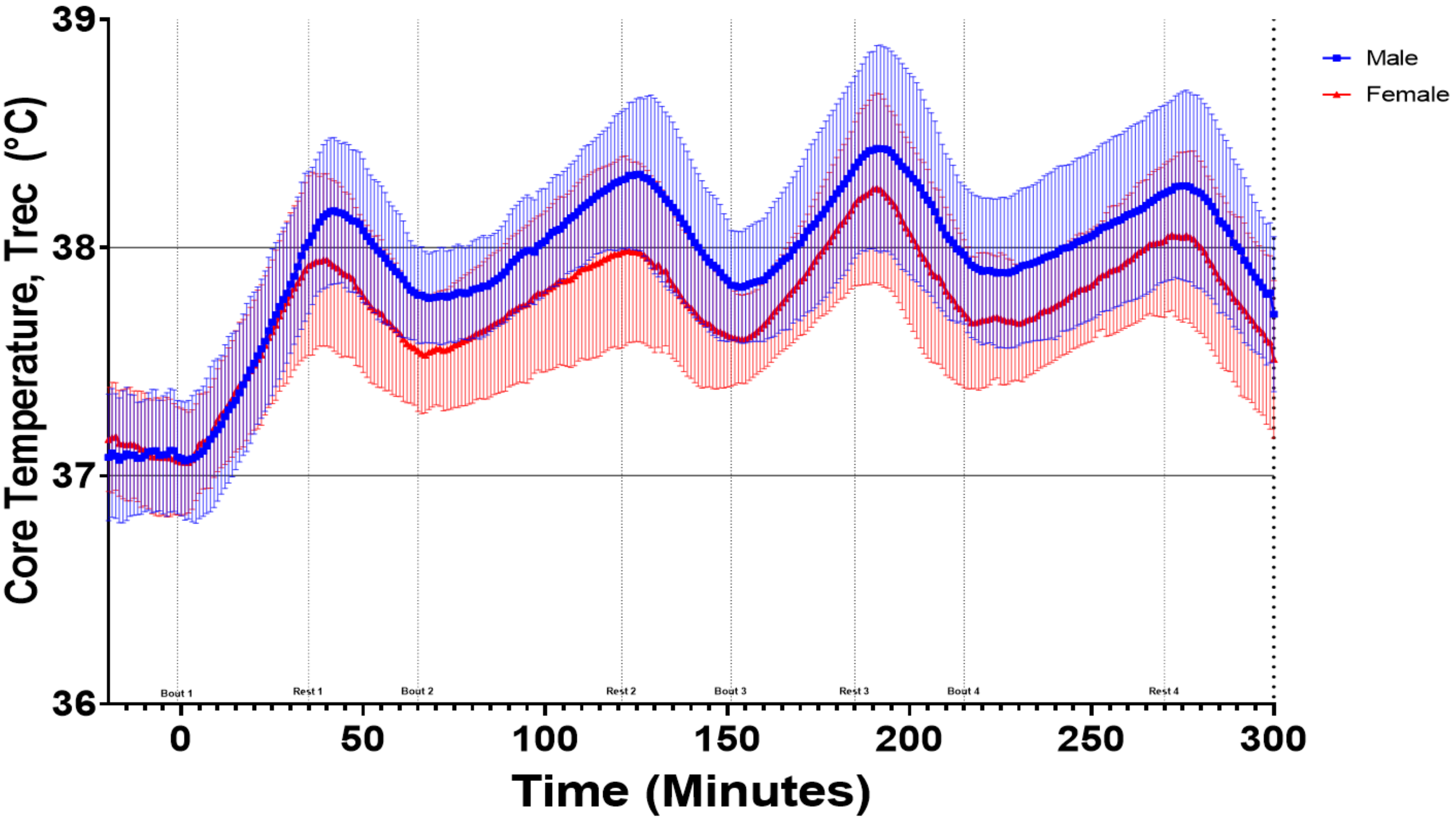

Figure 4: Minute-by-minute plotting of mean Trec temperatures of males and females across all exercise and rest bouts

Heart rate

A significant difference was observed in peak HR, with bout 3 being greater than bout 1 ("heavy" work) (Greenhouse F = 24.172, $p < 0.001$, effect size 0.616), but no difference was observed between bouts 2 and 4 ("moderate" work) (Greenhouse F = 1.783, p = 0.194, effect size 0.525) (Table 6) (Figure 5-6). Positive HR changes (absolute gains) were significantly greater in bout 1 than bout 3 (Greenhouse F = 5.915, p = 0.023), and greater in bout 2 than bout 4 (Greenhouse F = 18.697, $p < 0.001$) (Table 6).

There were no significant differences in peak HR values between men and women in bouts 1 and 3 ("heavy" work) (F = 0.3, p = 0.588, effect size 0.558), nor between bouts 2 and 4 ("moderate" work) (F = 0.551, p = 0.465, effect size 0.579). There were no significant interactions observed between bouts 1 and 3 ("heavy" work) and sex for positive changes in HR (F = 0.009, p = 0.926), nor between bouts 2 and 4 (F = 0.123, p = 0.728) (Table 6).

Table 6: Heart rate measurements during work

	Ex1	**Ex2**	**Ex3**	**Ex4**
Absolute peak values (BPM)				
Men	138.0 ± 19.6	134.1 ± 19.1	148.4 ± 22.2	134.6 ± 21.1
Women	135.5 ± 21.6	127.4 ± 19.3	142.3 ± 19.3	130.4 ± 18.1
Heart rate changes from previous bout (BPM)				
Men	73.3 ± 14.2	58.5 ± 14.4	68.0 ± 13.5	47.9 ± 10.4
Women	75.0 ± 17.8	57.3 ± 11.8	70.0 ± 9.3	52.1 ± 9.3

Heart rate changes calculated from rest bout minimum to subsequent work maximum

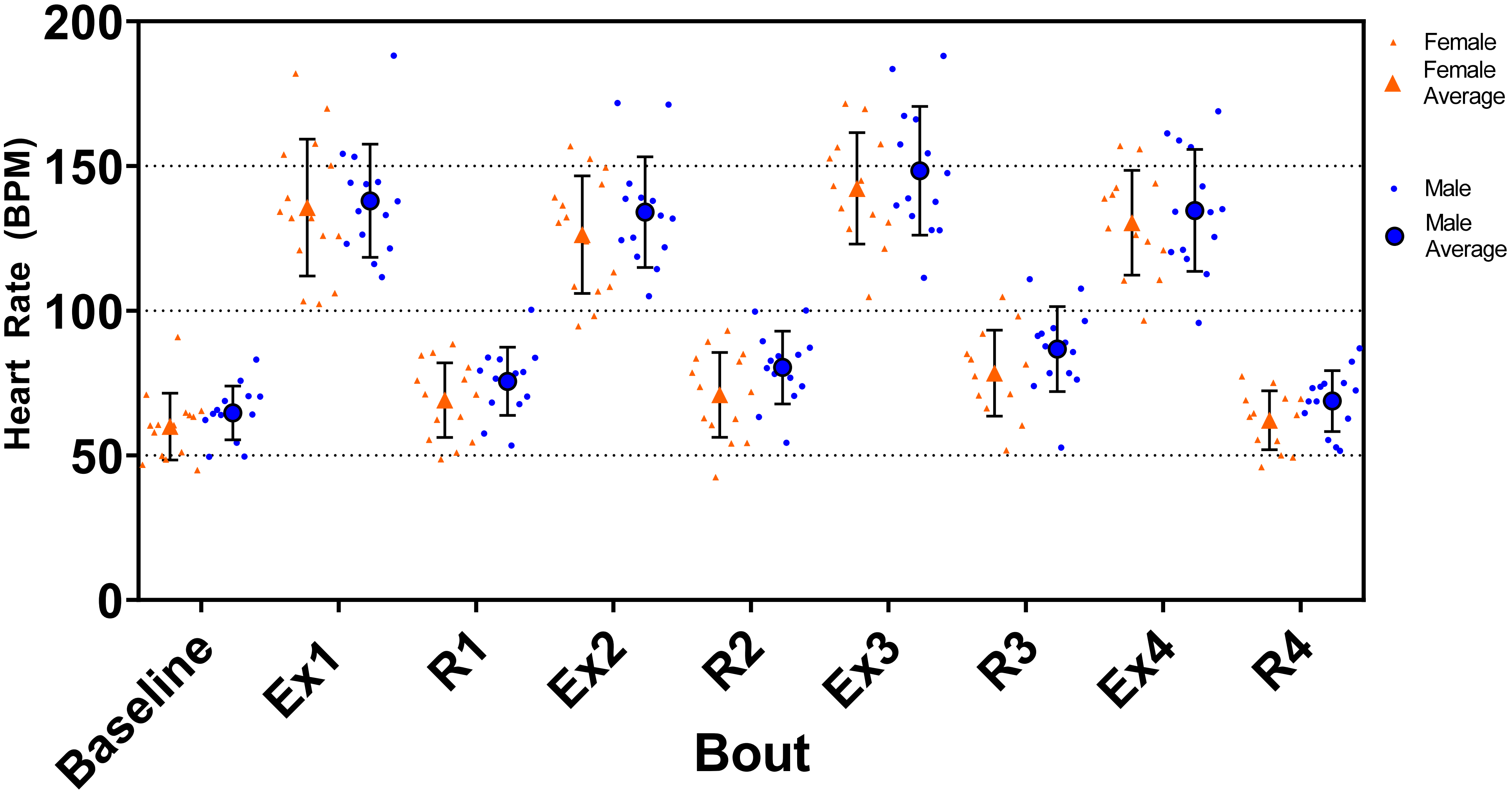

Figure 5: Minimum and maximum heart rate values for all participants in all work and rest periods

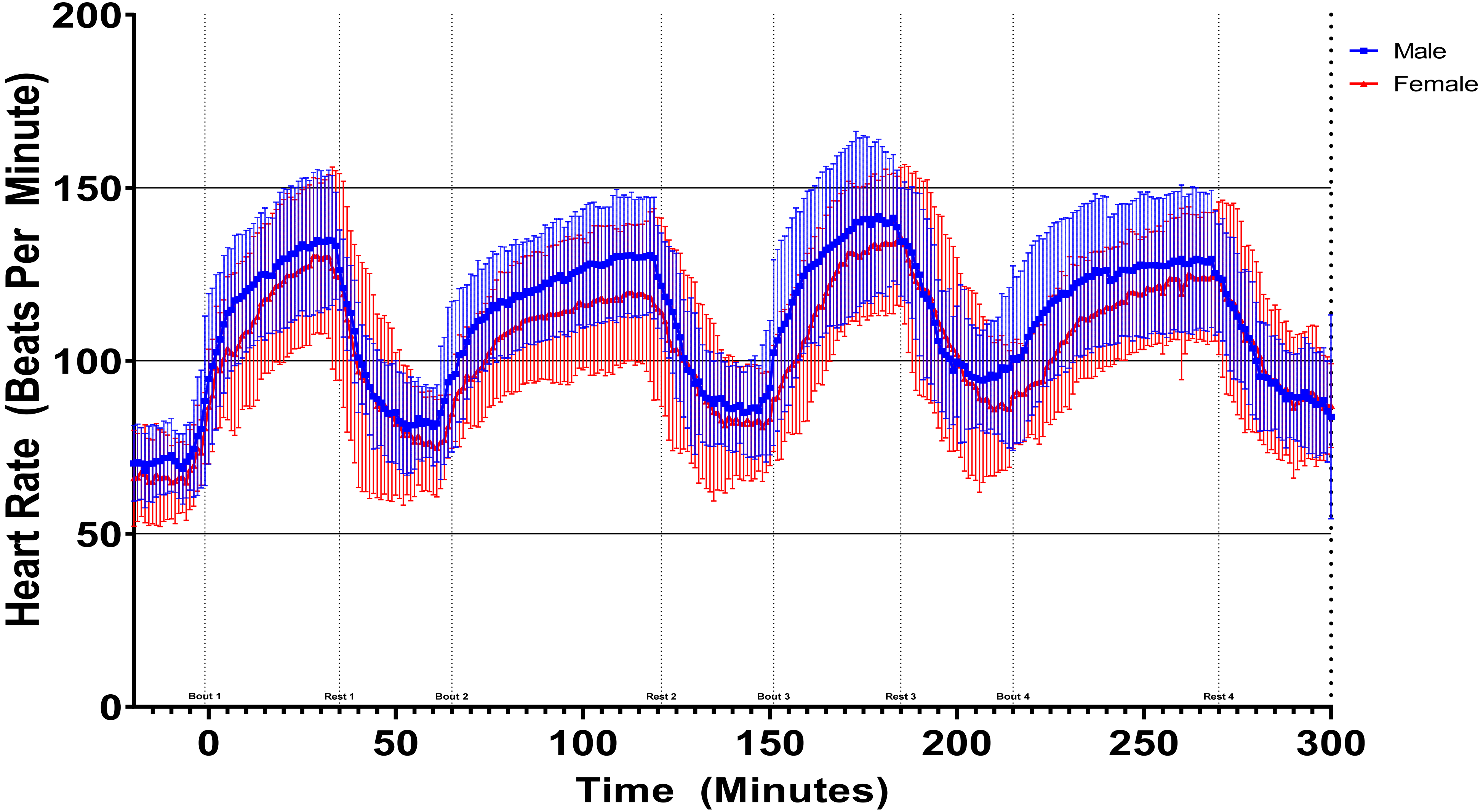

Figure 6**:** Minute-by-minute plotting of mean heart rates of males and females across all exercise and rest bouts

Skin temperature

A significant difference was observed in peak T_{skin}, with bout 1 being greater than bout 3 (“heavy” work) (Greenhouse F = 16.286, p < 0.001, effect size 0.657), but not between bouts 2 and 4 (“moderate” work) (Greenhouse F = 0.586, p = 0.451, effect size 0.556) (Table 7) (Figure 7-8). Positive T_{skin} changes (absolute gains) were significantly greater in bout 1 than bout 3, (Greenhouse F = 10.459, p = 0.003), but not different between bouts 2 and 4 (Greenhouse F = 4.217, p = 0.051).

There were no significant differences in peak T_{skin} values between men and women in bouts 1 and 3 (“heavy” work) (F = 0.314, p = 0.581, effect size 0.553), nor between bouts 2 and 4 (“moderate” work) (F = 1.671, p = 0.208, effect size 0.610). No significant interaction was found between sex and positive changes in T_{skin} between bouts 1 and 3 (F = 0.931, p = 0.344), nor between bouts 2 and 4 (F = 0.050, p = 0.825).

Table 7: T_{skin} measurements during work

	Ex1	Ex2	Ex3	Ex4
Absolute peak values (° C)				
Men	36.8 ± 0.6	36.5 ± 0.5	36.4 ± 0.6	36.4 ± 0.6
Women	36.8 ± 0.4	36.7 ± 0.4	36.6 ± 0.5	36.6 ± 0.5
Skin temperature changes from previous bout (° C)				
Men	4.1 ± 0.7	3.0 ± 0.8	3.4 ± 0.3	3.5 ± 0.4
Women	4.1 ± 0.4	3.1 ± 0.6	3.7 ± 0.9	3.3 ± 0.8

Skin temperature changes calculated from rest bout minimum to subsequent work maximum

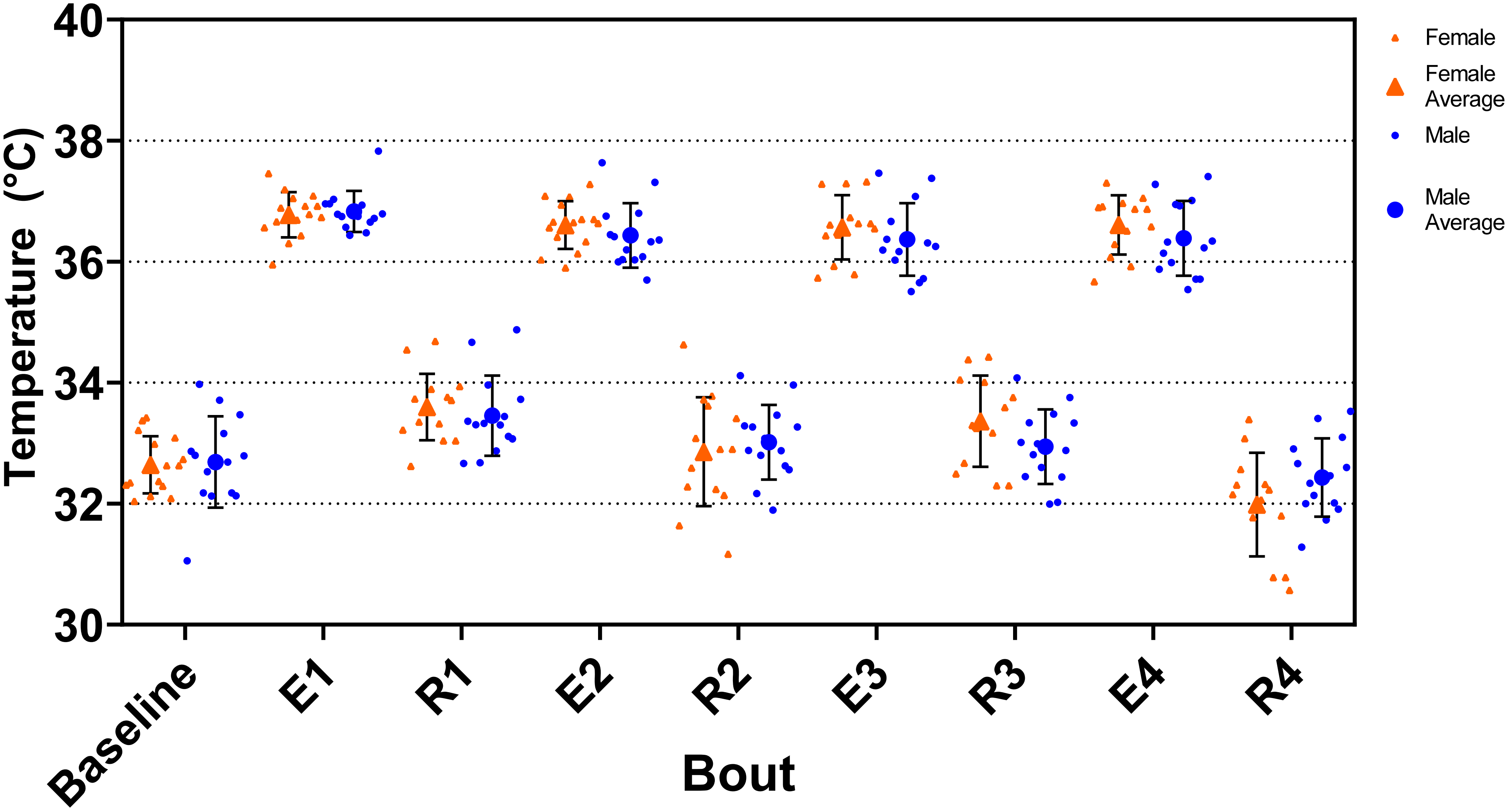

Figure 7: Minimum and maximum Tskin values for all participants in all work and rest period

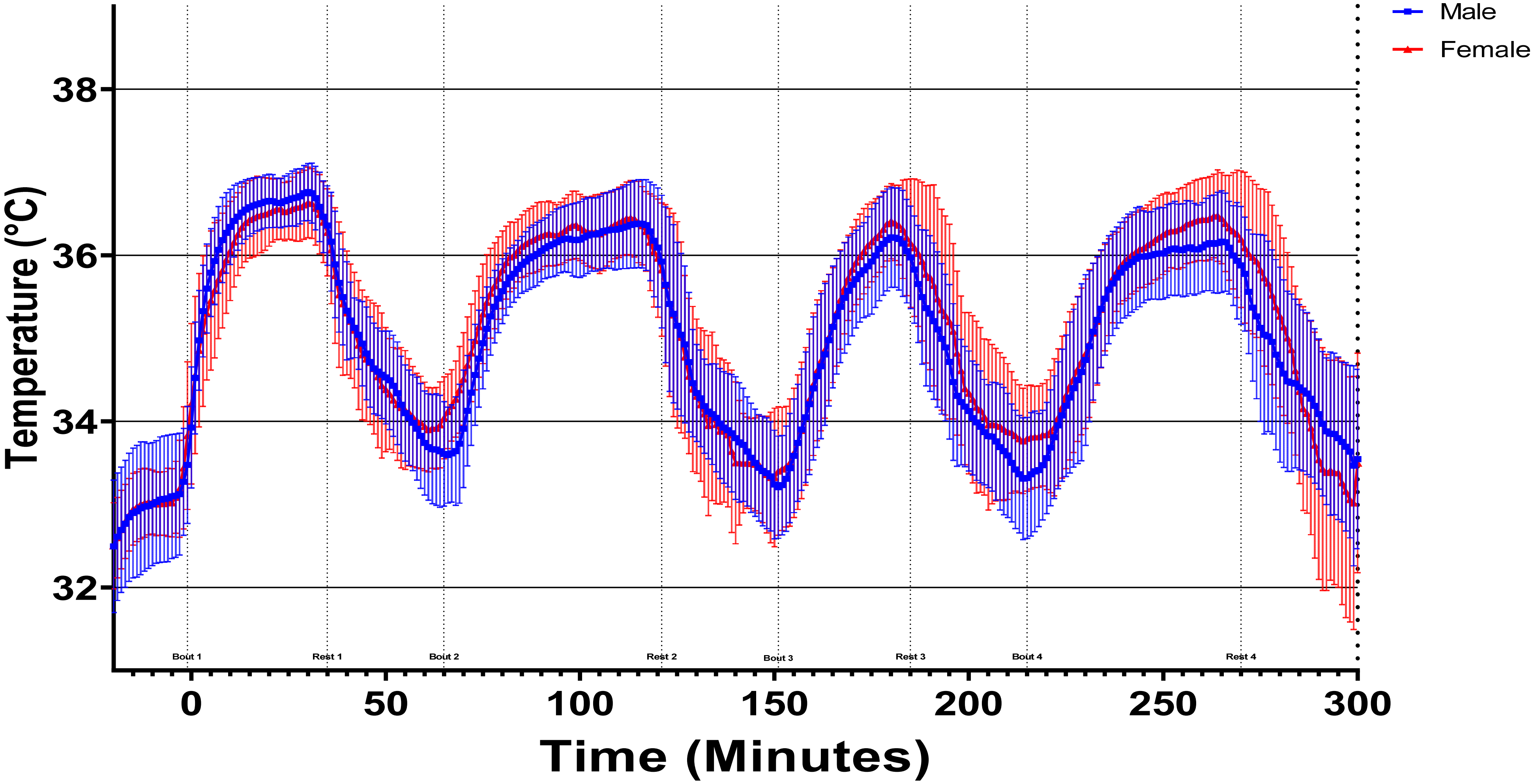

Figure 8: Minute-by-minute plotting of mean Tskin temperatures of males and females across all exercise and rest bouts

Additional measurements

Bout 3 was significantly greater than bout 1 (“heavy” work) for maximum PSI values (Greenhouse F = 32.569, $p < 0.001$) (Figure 9) and ratings of perceived exertion (Greenhouse F = 4.698, p = 0.04) (Table 8). There was no significant difference between sexes for bouts 1 and 3 maximum PSI values (F = 0.839, p = 0.369), nor ratings of perceived exertion (F = 0.265, p = 0.611) (Table 8).There were no significant differences between bouts 1 and 3 (“heavy” work) for relative metabolic heat production (Greenhouse F = 0.025, p = 0.876) (Figure 10) or absolute metabolic heat production (F = 0.051, p = 0.824). There was no significant interaction between sexes for bouts 1 and 3 for relative metabolic heat production values (F = 0.274, p = 0.274), but men displayed significantly greater absolute metabolic heat production than women in bouts 1 and 3 (F = 6.881, p = 0.015).

Bout 4 resulted in significantly greater ratings of perceived exertion than bout 2 (“moderate” work) (Greenhouse F = 9.412, p = 0.05), but no difference was observed between sexes for bouts 2 and 4 (F = 0.257, p = 0.616) (Table 8).There were no significant differences between bouts 2 and 4 (“moderate” work) for maximum PSI values (F = 0.226, p = 0.638), relative metabolic heat production (Greenhouse F = 0.458, p = 0.505), nor absolute metabolic heat production (F = 1.045, p = 0.317) (Table 8). There was no significant interaction found between sexes for bouts 2 and 4 maximum PSI values (F = 3.102, p = 0.090), nor relative metabolic heat production (F = 0.614, p = 0.441), but men displayed significantly greater absolute metabolic heat production than women in bouts 2 and 4 (F = 6.556, p = 0.017) (Table 8).

There were no significant differences across all four work bouts for thermal comfort (F = 0.563, p = 0.641), nor thermal sensation (F = 1.498, p = 0.222, nor between sex and all four work bouts for thermal comfort (F = 0.106, p = 0.748) or thermal sensation (F = 0.408, p = 0.529)

(Table 8).There was no significant difference between men and women and CHSI results (p = 0.673) across the experimental trial (Figure 11).

Table 8: Additional measurements made during work bouts

	Ex1	**Ex2**	**Ex3**	**Ex4**
Maximum Physiological Strain Index (PSI) (0 – 10)				
Men	5.1 ± 0.9	5.5 ± 1.1	6.2 ± 1.5	5.4 ± 1.3
Women	4.7 ± 1.6	4.4 ± 1.4	5.7 ± 1.4	4.7 ± 1.2
Relative Metabolic Heat Production (W · kg^{-1})				
Men	7.93 ± 1.39	5.95 ± 0.94	8.01 ± 2.55	6.33 ± 1.78
Women	8.75 ± 1.48	6.72 ± 0.71	8.57 ± 1.37	6.70 ± 1.32
Absolute Metabolic Heat Production (W)				
Men	603.17 ± 117.71	452.69 ± 78.33	652.44 ± 75.24	512.33 ± 73.03
Women	506.20 ± 76.04	390.62 ± 52.54	499.65 ± 96.38	392.44 ± 91.46
Thermal Comfort (1-5)				
Men	2.3 ± 1.0	2.2 ± 1.0	2.3 ± 0.9	2.4 ± 0.8
Women	2.6 ± 0.7	2.5 ± 0.7	2.4 ± 0.8	2.3 ± 0.7
Thermal Sensation (6-13)				
Men	9.4 ± 0.9	9.2 ± 0.9	9.4 ± 0.9	9.5 ± 0.9
Women	9.2 ± 0.9	9.1 ± 1.2	9.5 ± 1.0	9.2 ± 0.5
Rating of Perceived Exertion (6-20)				
Men	11.3 ± 2.6	10.5 ± 2.8	11.2 ± 3.0	11.6 ± 2.6
Women	11.7 ± 2.5	11.6 ± 2.6	12.2 ± 2.4	11.8 ± 2.3

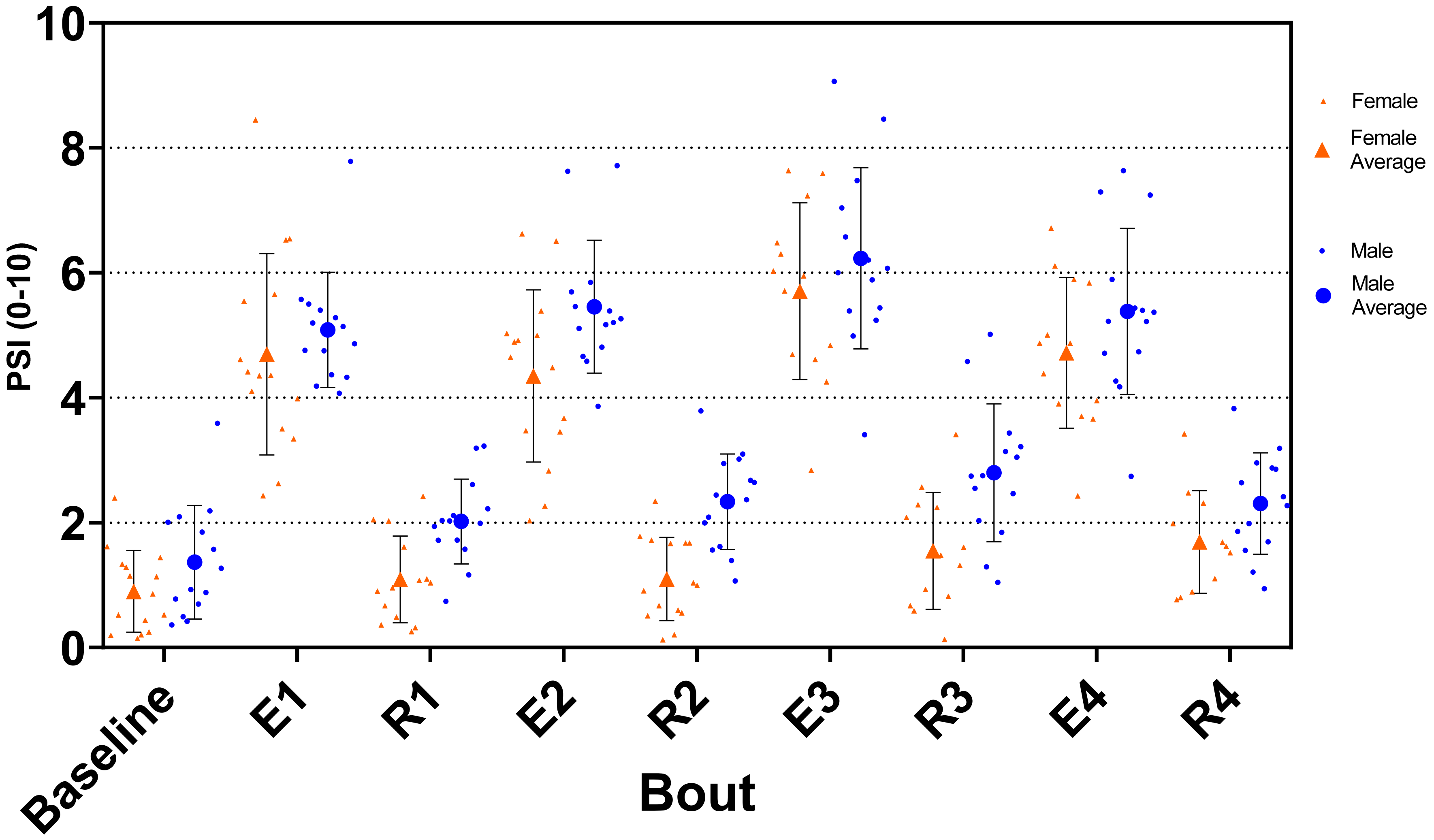

Figure 9: Minimum and maximum PSI values for all participants in all work and rest periods

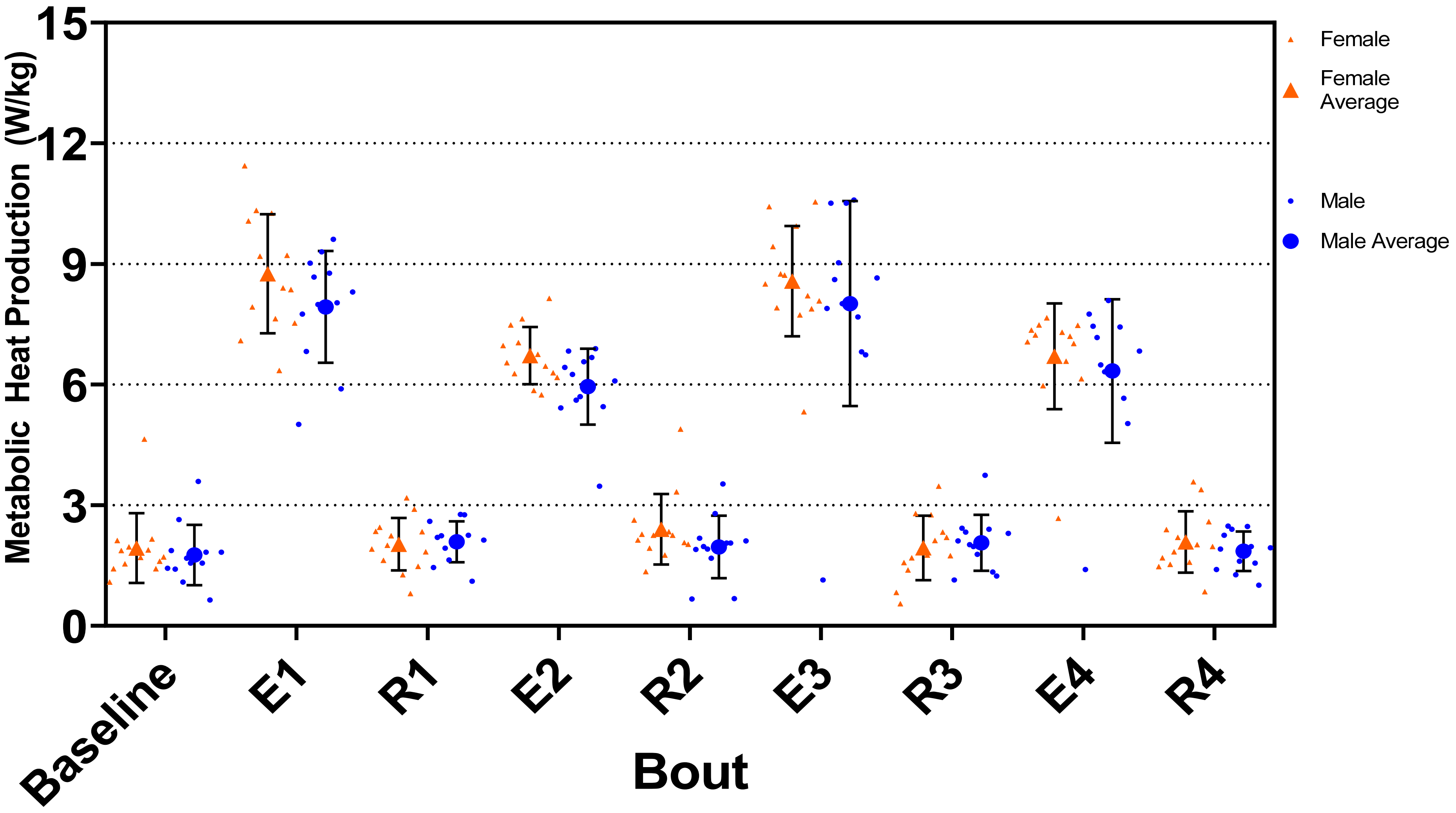

Figure 10: Metabolic heat production per kilogram body mass values for all participants in all work and rest periods

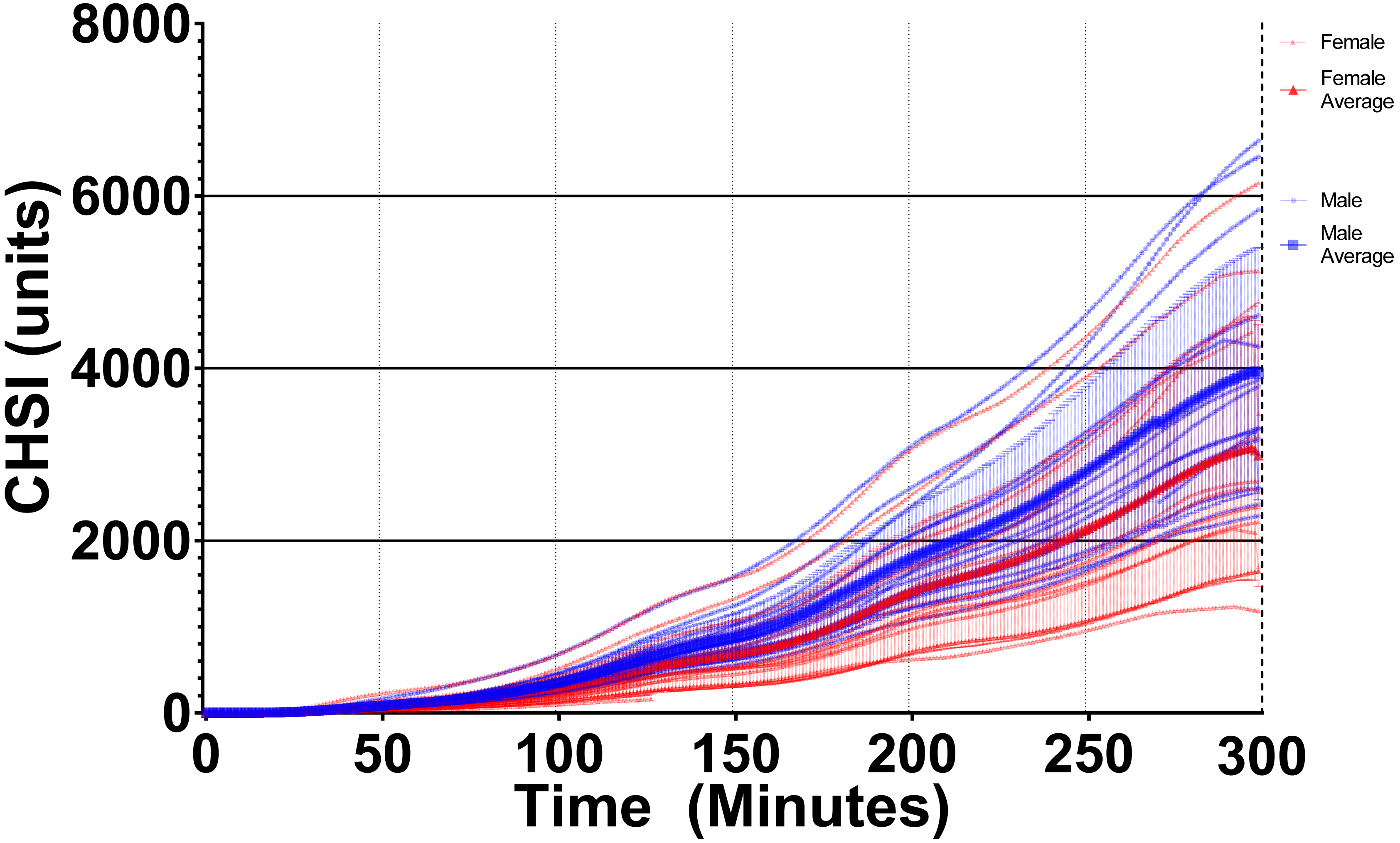

Figure 11: Minute-by-minute plotting of cumulative heat strain index of males and females across experimental trial

Physiological Strain During Rest

Core temperature

Across all rest periods (but not baseline), there were significant differences in minimum T_{rec} values (Greenhouse F = 9.120, p = 0.001) (Table 9). Pairwise comparisons of all rest bouts indicate that T_{rec} minimum was significantly lower in bout 1 than in bouts 2, 3 and 4 ($p < 0.05$), but bouts 2 and 3 T_{rec} minimums were not significantly different from bout 4 (p = 1.0) (Table 9).

Negative T_{rec} changes (measured work peak to subsequent rest minimum) were significantly different between all rest bouts (Greenhouse F = 5.179, p = 0.003). Negative T_{rec} rates of change were not significantly different across rest bouts (F = 2.005, p = 0.121) (Table 9).

There was a significant difference observed between sexes, with men having higher minimum core temperature values than women during rest (F = 4.621, p = 0.041). No difference was observed between sexes for T_{rec} changes (F = 0.005, p = 0.947), nor between sexes for T_{rec} rates of change during rest (F = 0.350, p = 0.559) (Table 9).

Table 9: Trec measurements during rest

	R1	R2	R3	R4
Absolute minimum values (° C)				
Men	37.51 ± 0.28*	37.78 ± 0.24	37.85 ± 0.33	37.76 ± 0.31
Women	37.44 ± 0.21*	37.56 ± 0.18	37.58 ± 0.25	37.57 ± 0.35
Core temperature changes (° C)				
Men	-0.69 ± 0.18	-0.58 ± 0.19	-0.64 ± 0.22	-0.56 ± 0.21
Women	-0.61 ± 0.25	-0.53 ± 0.24	-0.75 ± 0.22	-0.58 ± 0.22
Rate of change (° C · min^{-1})				
Men	-0.0171 ± 0.0083	-0.0220 ± 0.0129	-0.0207 ± 0.0141	-0.0234 ± 0.0184
Women	-0.0185 ± 0.0115	-0.0254 ± 0.0168	-0.0274 ± 0.0490	-0.0238 ± 0.0181

* Significantly different from other bouts ($P < 0.05$)
Core temperature changes calculated from work bout maximum to subsequent rest minimum
Rate of change calculated across final 10 minutes during rest

Heart rate

Each rest period was significantly different in minimum HR values (Greenhouse F = 19.345, p = 0.001) and negative HR deltas (absolute losses) to each other rest period (Greenhouse F = 10.376, p = 0.001) (Table 10). There were no significant differences observed between sexes for HR troughs at rest (F = 3.264, p = 0.083), nor between sexes for negative HR deltas (F = 0.221, p = 0.642).

Table 10: Heart rate measurements during rest

	R1	R2	R3	R4
Absolute minimum values (BPM)				
Men	75.6 ± 11.8	80.4 ± 12.6	86.7 ± 14.7	68.8 ± 10.5
Women	70.1 ± 12.4	72.2 ± 13.0	78.4 ± 14.9	62.1 ± 10.1
Heart rate changes from previous bout (BPM)				
Men	-62.4 ± 13.5	-53.7 ± 10.5	-61.6 ± 10.5	-65.9 ± 24.3
Women	-65.4 ± 12.1	-55.1 ± 9.6	-63.9 ± 8.6	-68.3 ± 20.2

Heart rate changes calculated from work bout maximum to subsequent rest minimum

Skin temperature

Each rest period was significantly different for minimum T_{skin} values (Greenhouse F = 24.584, $p < 0.001$) and negative T_{skin} changes (absolute losses) to each other rest period (Greenhouse F = 17.502, $p < 0.001$) (Table 11). There were no significant differences observed between sexes for T_{skin} troughs at rest (F = 0.006, p = 0.938), nor between sexes for negative T_{skin} rates of change (F = 1.129, p = 0.298).

Table 11: Tskin measurements during rest

	R1	R2	R3	R4
Absolute minimum values (°C)				
Men	33.5 ± 0.7	33.0 ± 0.6	32.9 ± 0.6	32.4 ± 0.6
Women	33.6 ± 0.6	32.9 ± 0.9	33.4 ± 0.8	32.0 ± 0.9
Skin temperature changes from previous bout (°C)				
Men	-3.4 ± 0.6	-3.4 ± 0.3	-3.4 ± 0.3	-4.0 ± 0.7
Women	-3.2 ± 0.5	-3.8 ± 0.9	-3.2 ± 0.7	-4.6 ± 1.0

Skin temperature changes calculated from work bout maximum to subsequent rest minimum

Additional Measurements (Table 12)

There were no significant differences observed across all four rest bouts for minimum PSI values (Greenhouse F = 7.533, p = 0.001), minimum relative heat production values (Greenhouse F = 0.659, p = 0.528), minimum absolute heat production values (Greenhouse F = 0.594, p = 0.576), thermal comfort responses (Greenhouse F = 0.304, p = 0.749), thermal sensation responses (Greenhouse F = 0.517, p = 0.613), nor RPE (F = 0.172, p = 0.915).

There were no significant interactions observed between sex and rest relative metabolic heat production values (F = 0.035, p = 0.853), thermal comfort responses (F = 0.1.715, p = 0.202), thermal sensation responses (F = 1.056, p = 0.314), nor RPE values (F = 0.162, p = 0.69).

A significant interaction was observed between sexes for rest minimum PSI means (F = 10.062, p = 0.004), with men displaying greater PSI minimums than women across all rest periods. Similarly, men displayed greater absolute metabolic heat production than women across all rest periods (F = 5.072, p = 0.033).

Table 12: Additional measurements made during rest periods

	R1	R2	R3	R4
Physiological Strain Index (0-10)				
Men	2.0 ± 0.7	2.3 ± 0.8	2.8 ± 1.1	2.3 ± 0.8
Women	1.1 ± 0.7	1.1 ± 0.7	1.6 ± 0.9	1.7 ± 0.8
Relative Metabolic Heat Production (W/kg)				
Men	2.23 ± 0.59	2.04 ± 0.72	2.21 ± 0.85	1.93 ± 0.58
Women	2.05 ± 0.78	2.41 ± 0.95	1.97 ± 0.87	2.10 ± 0.82
Absolute Metabolic Heat Produced (W)				
Men	162.82 ± 44.67	160.84 ± 48.92	174.21 ± 63.25	148.42 ± 39.36
Women	103.54 ± 58.02	121.57 ± 69.49	97.13 ± 59.24	105.92 ± 63.21
Thermal Comfort (1-5)				
Men	1.3 ± 0.5	1.2 ± 0.5	1.3 ± 0.6	1.3 ± 0.4
Women	1.2 ± 0.5	1.2 ± 0.5	1.1 ± 0.3	1.1 ± 0.2
Thermal Sensation (6-13)				
Men	7.5 ± 1.1	7.1 ± 1.2	7.3 ± 1.3	7.1 ± 1.0
Women	7.1 ± 1.1	7.1 ± 1.0	6.8 ± 1.0	7.0 ± 0.9
Rating of Perceived Exertion (6-20)				
Men	6.3 ± 0.6	6.2 ± 0.4	6.4 ± 0.7	6.4 ± 1.3
Women	6.6 ± 1.4	6.4 ± 0.6	6.4 ± 1.1	6.3 ± 0.6

Chapter 5: Discussion

The aim of this research project was to evaluate the current continuous work table protocols as specified for the Australian Army, and to determine if the limitations set on repeated work bouts may be increased without increasing the risk of excessive heat strain to personnel. It also evaluated the sex-based differences when undertaking work according to the current work-table protocols and determined if there were any variations between male and female participants completing the increased total work.

It was hypothesised that both men and women would be able to complete an increased total duration of work that is currently recommended by the continuous Work Table without an increased risk of heat illness, and that no major physiological differences would be observed between men and women throughout the trials.

The key findings of this study include: (1) the work duration limits can be substantially increased without further increases in body core temperature response and risk of heat illness; (2) women within days 5 – 8 of their menstrual cycle and men exhibit no sex-based differences in core body temperature response to repeat bouts of exercise in the heat. These findings agree with our hypothesis, namely that the number of work bouts following the Australian Army Work Table may be increased and that these tables need not have specific divisions for males vs. females.

Work Tables & Repeat Exercise

The current Australian Army Continuous Work Tables are designed with the expectation that a majority of personnel operating as per recommended work-rest ratios will reach a body core temperature of 38.5 °C by the conclusion of each work bout. This threshold accounts for individual variation in core temperature responses between ± 0.2 – 0.4 °C, expecting approximately 5% of personnel to potentially reach core temperatures up to 39.0 °C by completion of work[77]. This expectation accounts for the understanding that 5% of personnel will present with heat exhaustion symptoms at core temperatures > 38.5 °C and a gradually increased risk of heat stroke when > 39.0 °C. The continuous Work Table allows for two consecutive bouts of work with a specified rest period in between, per twenty-four hours.

Core temperature elevations & risk of heat stroke (T_{rec} > 39.0 °C)

This study monitored core temperature elevations of 29 individuals with comparable fitness and body composition status to Australian Army personnel operating in the heat[254,255]. These individuals followed the current Australian Army continuous Work Table in 32.5 °C WBGT conditions for four consecutive bouts of work, twice the current limitation. It was assumed that most participants would meet a body core temperature of 38.5 °C at the end of each work period; however, this was not seen in this study, as only 35% of 29 participants reached 38.5 °C at any time during the trials. Of the 35%, five were males and five were females, and all these participants had exceeded 38.5 °C by conclusion of the third work bout. Only 7% of participants (two males) reached and exceeded 39.0 °C at any point during the experimental trial (Figure 2). This agrees with the expectation that approximately 5% of personnel will reach up to 39.0 °C by completion of work following the current Work Tables[77].

The first male exceeded 39.0 °C twice during his trial: five minutes into the third rest bout, and 53 minutes into the fourth work bout. He reached a peak core temperature of 39.13 °C 15 minutes into the third rest bout, and a peak of 39.19 °C 11 minutes into the fourth rest bout. This participant reported no symptoms of heat illness and was reporting thermal comfort and thermal sensations within normal ranges in both instances. It is important to note that this participant consumed the least amount of fluid of all men across the experimental trial (average 3.88 ± 1.12 kg). Across the four work bouts he lost a cumulative 3.75 kg of fluid to sweat (totalling 5% of body weight) and replenished 2.21 kg of fluid (totalling 3% of body weight) and was therefore likely partially dehydrated (2% difference in fluid out vs. fluid in). This participant was a current serving member of the Australian Defence Force as a field medic, and had previously served several years stationed in Darwin, Australia. It is likely that his low fluid intake is a trained habit from his experience in the field. Additionally, this participant achieved the highest VO_{2peak} assessment at 72.3 $mL \cdot kg^{-1} \cdot min^{-1}$, which theoretically should have correlated to a reduced heat gain during the experimental trial, though the opposite was observed. He had a body fat percentage of 13.5% and a BMI of 22.4. The exact reason for this participant exceeding 39.0 °C despite being well trained and experienced with operating in the height is not known, though it is likely that his limited fluid intake played a major component.

The second male also exceeded 39.0 °C twice during his trial: six minutes into the second rest bout, and three minutes into the third rest bout. He reached a peak core temperature of 39.06 °C eight minutes into the second rest bout, and a peak of 39.19 °C five minutes into the third rest bout. Similarly, nil heat illness symptoms were reported by this participant, and he always expressed thermal comfort and thermal sensations within normal ranges. In an opposite direction to the other male participant exceeding 39.0 °C, the second male consumed the second highest volume of fluid (5.63 kg of fluid), though his VO_{2peak} was more modest at 51.0 $mL \cdot kg^{-1} \cdot min^{-1}$. He had a body fat percentage of 23.9% and a BMI of 26.2. It is unknown why these two participants with dissimilar body morphology and fluid intake both exceeded a core temperature of 39.0 °C, and this may warrant further research to protect the wide variety of personnel in the Australian Army. This unknown factor or factors are also discussed elsewhere in literature, wherein no significant differences are found in the individual characteristics of participants with high core temperature responses and those with normal responses[77,256,257]

Of the participants who completed the trial (n = 27), 66% did not exceed the assumed thermal threshold of 38.5 °C at any point during the trial, even after performing double the current recommended number of work bouts by the continuous Work Table. There were no statistical differences in the participants who reached or exceeded 38.5 °C at any point in time and those who did not (Table 4). It is worth noting that the participants recruited for this study represented a highly aerobically trained sample of people, who likely have some degree of heat acclimation from exercising during the recent Brisbane, QLD summer. Any heat acclimation resulting from recent training in a hot environment would correspond with lower core and skin temperatures and heart rates at rest and during exercise in the heat, increased sweat rates, and reduced RPE and thermal sensation responses[258]. This implies that fit males and females may be able to work for greater lengths of time than are currently permitted by Australian Army Work Tables.

Of all participants that reached or exceeded a core body temperature of 38.5 °C at any point during the experimental trial (n = 10), none reported any symptoms of heat illness. Of the participants that reached and exceeded a core body temperature of 39.0 °C (n = 2), neither of them reported any symptoms of heat illness.

Since the tables assume an average person reaches 38.5 °C at the conclusion of each work bout, it was expected that 50% of our participants would reach that value. However, this was not observed in our participants. This is likely because our VO_{2max} criteria provided a sample of relatively fit participants who are similar in aerobic fitness (measured by VO_{2max}) to

Australian Army personnel. Research indicates that as aerobic fitness increases, tolerance to heat stress improves similarly, and people with greater VO_{2max} values show lower elevations in body core temperature for a standard absolute work intensity[89,97,138,139].

Additionally, participants on average did not exhibit equal amounts of heat gained in subsequent bouts of exercise. In fact, participants exhibited gradual reductions in the total amount of heat gained during exercise in each subsequent bout after the first. This agrees with previous research reporting that the absolute heat gain in repeat bouts of exercise is greatest in the first work bout and lowest in the final work bout[5,53,193,194]. From this literature, it is speculated that the cumulative heat gain is reduced in successive work bouts due to "priming" of the heat loss pathways in each bout after the first. With each consecutive bout of work, the body is more readily able to dissipate generated metabolic heat, and short-term adaptations to efficiency of work reduce the total amount of metabolic heat generated. This priming is presented as a shorter duration for onset of skin vasodilation and sweat secretion in each successive bout of work, enabling heat transfer from an earlier point of time in later work bouts[5].

The change in core body temperature between each exercise bout was significantly different, with less heat being gained in each subsequent bout after the first, and the amount of heat lost in each rest bout being significantly different after the first. This substantiates the claim of a gradual reduction in the heat gained in subsequent exercise bouts and a fluctuation in the amount of heat lost in subsequent rest periods[5,53,193,194]. Between this finding of reductions in absolute heat gain, and the previous finding of reductions in relative heat gain, it can be suggested that the current Australian Army Work Table may be able to be revised to enable more bouts of work. These findings suggest that the number of work bouts within the Australian Army Work Tables may be revised without substantially increasing the risk of heat-related injury.

Cardiovascular strain and risk of heat exhaustion

In this study, peak heart rate measurements between exercise bouts one and three ("heavy" work) were significantly different, with bout three resulting in a higher heart rate than bout one (Table 6). However, this difference was not observed between exercise bouts two and four ("moderate" work), with both bouts resulting in similar peak heart rates. It is speculated that the greater heart rate peak for bout three was due to accumulation of heat from the two prior bouts of exercise, whereas the heart rate peak in bout one was recorded after 20 minutes of exercise in the heat subsequent to 30 minutes of seated rest.

It is hypothesized that the greater heart rate peaks observed in later work bouts result from the cardiovascular strain imposed by an increased core temperature, combined with continued exercise in the heat. This finding is similar to other heart rate patterns reported in literature, where significantly greater peak heart rates are observed in successive bouts of work and can be termed as cardiovascular "drift"[193,194,259], though other studies have failed to report any increase in peak heart rate over repeat bouts of work[5]. This "drift" presents with increased cardiovascular strain over repeat bouts of work, as the heart must increase cardiac output to combat rising core body temperatures (through increased skin blood flow and reduced peripheral resistance), whilst still providing oxygenated blood to the working muscles[193]. A greater heart rate in bout 3 was likely observed as a consequence of cardiovascular drift, as it was another "hard" work bout (with substantial physiological demand) with an elevated core body temperature at onset (another significant physiological demand).

This increased cardiovascular strain of working at a high intensity in the heat and the thermoregulatory requirements of a substantially elevated core temperature can potentially increase the risk of heat exhaustion over the course of several successive work bouts[260]. This is pertinent as demands for blood flow between the active muscles and the skin can result in a competition for available cardiac output, especially when combined with the effects of dehydration and hyperthermia[214]. We observed participants in the third (“hard”) work bout reaching greater core temperatures and heart rates than in any of the other bouts (despite fluid replacement and heat dissipation during the rest intervals), likely as an effect of this competition for cardiac output. This matches findings reported in literature wherein greater peak heart rate and core temperature values are found in successive bouts of work, theoretically arising from a “slow drift upwards” in physiological variables over repeated bouts of work at the same relative intensity[194]. This drift upwards was also reflected in the PSI values obtained during the third bout of work, which were greater than those reached in the other bouts. Therefore, in military training, consideration should be given to the intensities of successive work bouts relative to the work done immediately before to avoid excessive increases in the risk of heat illness. Commanders devising whole-day repeated drills may consider the ordering of work tasks to avoid excess accumulation of heat, such as alternating heavy workloads with light workloads or rest.

Maximum changes in heart rate between exercise bouts of the same intensity (bout 1 to bout 3 / bout 2 to bout 4) were significantly different throughout the experimental trial. This is likely to have occurred as participants’ heart rates did not return to a baseline when at rest, as part of their bodies’ process to continue dissipating heat gained from the previous work bout (in line with literature-based expectations[193,194,259]). Therefore, participants began each subsequent bout at a higher heart rate than the previous. Although the peak HR values were significantly higher in bout 3 than bout 1 (but not different between bouts 2 and 4), the absolute changes in HR likely stemmed from the increase in heart rate at each onset of work not matching the increase in peak HR during work. This implies that other variables that are commonly found to impact HR relative and absolute values may have been present, such as fatigue[198,261], hydration status[151,152,168], and time of day[262]. However, our participants were instructed to attend well rested and without exercise in the 24 hours prior, were assessed for adequate hydration through USG, and all began the trial between 7am and 9am. This suggests that other uncontrolled variables may have affected the results, such as genetics and training history[263]. These unknowns present a potential area for future investigation.

Skin temperature findings

Peaks in T_{skin} were significantly different between exercise bouts 1 and 3 (despite both bouts being of the same intensity and in the same climate) but not between exercise bouts 2 and 4 (Table 7). This finding is interesting as the climate between all four exercise bouts was identical, and the only varied factor was alternating intensities of work bouts. The significant reduction in absolute skin temperature gain between exercise bouts 1 and 3 implies an initial spike in average skin temperature at onset of exercise; however, after this primary stimulation, greater skin temperature loss is likely observed due to the priming of heat loss pathways[3]. This finding of lowered skin temperature in successive bouts of work in the same climate is also reported in other literature, though the absolute peak values vary[5,53]. It is likely that we reported greater absolute peak skin temperature values due to the microclimate created by the uniform worn, encapsulating the thermocrons and dramatically increasing skin temperature compared to other studies with skin that is open to air flow. The uniform worn covered a substantial percentage of the available skin surface area to dissipate heat from, hampering effectiveness of sweat evaporation (particularly as the microclimate within the uniform can reach high levels of humidity, further reducing potential for sweat evaporation) and local cooling through conduction, convection and radiation[36,42,264,265]. As the trial uniform also comprised of an impermeable vest covering between 14 – 17% of body surface area, it is likely that the high skin temperatures observed in our study arose from the thermoregulatory restrictions of the clothing[266]. The values obtained in this study are appropriate for an encapsulating ensemble with helmet and vest, as athletic garments can yield skin temperatures between 33 °C[267] and 36 °C[268] during exercise (depending on the ambient environment) and protective garments can result in mean skin measurements above 36 °C[269] very rapidly during exercise in the heat.

Sex-Based Differences

The experimental design appropriately simulated work according to the current Australian Army continuous Work Table, with participants completing up to twice the current prescribed work duration limits. As previously mentioned, characteristics which may affect the thermal stress-strain relationships within the female body include hormone levels, anthropometric factors, and body composition.

Anthropometry and body composition linked variations

It is understood that women will typically present with a greater percentage of body fat, smaller body size, less body mass, and a smaller surface area to mass ratio than men[6,15,212,216,218]. These anthropometric and morphological variations are known to cause women to generate more heat and find it harder to dissipate stored heat whilst performing exercise than men performing the same work[270].

The women in our study had, on average, a significantly greater body fat percentage, greater body surface area to mass ratio, smaller body size, smaller body mass, smaller body surface area, and lower BMI than our male participants (Table 1). Additionally, the female participants had lower sweat rates and absolute sweat losses, and the body armour and helmet worn weighed a greater percentage of their body mass and covered a greater percentage of their body surface area than the male participants (Table 2). As anthropometric characteristics have been classified as key factors influencing performance during exercise in the heat, it is likely that these variables will have impacted our primary physiological measurements[271-273].

The body surface area to mass ratios of the participants in our study are equivalent to those reported in similar literature (males: 256.6 ± 12.7 $cm^2 \cdot kg^{-1}$, females: 282.9 ± 13.1 $cm^2 \cdot kg^{-1}$; literature reported males between 258.9 ± 6.5 $cm^2 \cdot kg^{-1}$ and 272.0 ± 4.0 $cm^2 \cdot kg^{-1}$, females between 276.0 ± 19.0 $cm^2 \cdot kg^{-1}$ and 290.4 ± 7.4 $cm^2 \cdot kg^{-1}$)[224,228,273,274]. It is well documented that a large body surface area, large mass and lower body surface area to mass ratio provides an "advantage" in hot dry and humid warm climates, particularly when comparing groups completing work at the same relative intensity[275]. As the males in our study had larger body surface areas, larger mass and lower body surface area to mass ratios than the females, their morphological advantages would theoretically enable a more rapid dissipation of stored body heat (and therefore reduced core temperature peaks) during the experimental trial[228]. However, this was not seen, as there were no differences in peak core temperatures throughout the work bouts between the men and women. Though the core temperature of our male participants may numerically appear greater than that of the female participants, it is likely that this stems from the significantly greater absolute rates of metabolic heat production observed in men than women across all four work bouts (20% greater in bouts 1 and 3, 19% greater in bouts 2 and 4; Table 8). Therefore, the visually lower core temperatures of the women in our study are more likely due to the metabolic rate difference than the body surface area to mass ratio difference. This assumption is substantiated in the literature, wherein core temperature variations between women controlled for the menstrual cycle and men exercising in the heat can be explained by metabolic rate differences, rather than anthropometric variation[228,273]. Additionally, this greater metabolic heat generation by the male participants may contribute to why we saw two males (but no females) exceed a core temperature of 39.0 °C.

Menstrual cycle linked variations

It is important to note that these results were taken from female participants who were exercised only during days 5 – 8 of their menstrual cycles. All other days of the menstrual cycle were excluded from this study. It is anticipated that the heart rate would likely be increased later in the menstrual cycle, by about ~10 beats per minute in the midluteal phase[11]. This increase in heart rate responses across all work and rest bouts could theoretically enable greater heat loss through increased peripheral blood flow, but this would likely have minimal functional impact[9,211,225].

There is evidence indicating no differences in absolute body core temperature responses of women across the menstrual cycle when working in humid heat (after acclimation) compared to men[17-19]; however, this conflicts with evidence that basal core temperatures can shift up to +0.8 °C when exercising during the luteal phase[11-16]. If the latter observations are correct, then the same absolute increase in heat gain during exercise may put female personnel at risk later in the menstrual cycle when their core temperature at onset is higher[11-16]. However, the research supporting that healthy and active women are not disadvantaged when working in the heat compared to men is substantial, and supports our recommendation that the current Work Tables need not be divided based on sex[16]. It is important to note that this body of literature is within single bout, steady state work and does not investigate repeated work and cumulative heat strain at various times across the menstrual cycle. While no difference was observed during this trial with women at days 5 – 8 of their menstrual cycles, future work into repeated bouts at different stages of the menstrual cycle needs to be investigated.

Other Points of Interest

Metabolic heat production

It is important to note that the absolute amounts of metabolic heat generated by participants in this trial was matched to expected metabolic heat generation for “moderate” (439 W) and “heavy” (567 W) work following current Work Table guidelines. No differences were observed in metabolic heat production across the pairs of exercise bouts of the same intensity

(Table 8). This is in line with literature-based expectations, as each work bout is designed to result in a core body temperature of 38.5 °C[77]. Therefore, absolute intensities of effort as measured by gas sampling should present similar findings across all exercise bouts.

Rate of change

Positive T_{rec} rates of change were significantly different between exercise bouts 1 and 3, but not between exercise bouts 2 and 4 (Table 5). This is likely to have been observed as the first work bout initiated the heat loss pathways, which were then already active from onset of subsequent work bouts. This is similar to responses reported elsewhere, where the reduction in total change in body heat (less total heat gained) was due to a greater rate of increase in whole-body heat loss for a similar rate of heat production in the later bouts relative to the earlier bouts[5,194]. The greater rate of change in core temperature we observed in later bouts in this study matches the findings in other investigations during intermittent exercise in the heat, where the rate of heat loss increases with successive bouts of work[276,277]. A similar protocol to this project found a significant reduction in the "thermal inertia" (response time for thermoregulatory pathways to effectively manage growing heat storage) over repeat bouts of work, specifically lowering response time from 12.3 ± 2.3 min in the first work bout, to 7.2 ± 1.6 min in the second, and 7.1 ± 1.6 min in the third work bouts as measured through whole-body calorimetry[5]. It is reported that this likely arises from a more rapid onset of local sweating[278] and skin vasodilation[279] in successive bouts of work, in addition to alterations to other nonthermal skin blood flow and sweat response factors[280].

Rectal temperature is typically observed to be slow to respond to changes in core temperature, though not significantly different from other core temperature measurement methods (gastrointestinal pill or oesophageal thermistor)[281,282]. The rates of change during work bouts observed in this study were similar to those reported in other literature for submaximal to intense exercise (between 0.001 ± 0.006 °C · min^{-1} and 0.033 ± 0.011 °C · min^{-1}; expected ~0.018 °C · min^{-1})[281,283]. The rates of change during rest are also similar to those reported elsewhere for core temperatures during recovery from exercise (between -0.017 ± 0.011 °C · min^{-1} and -0.024 ± 0.020 °C · min^{-1}; expected between -0.010 ± 0.003 °C · min^{-1} and -0.029 ± 0.028 °C · min^{-1})[282,284]. As the participants wore a standardised Australian Army uniform including a long-sleeve shirt, trousers, and running shoes, it could be expected that heat loss at rest would be attenuated. However, as the uniforms were mostly saturated with sweat after the first work bout, the damp uniform enabled heat transfer to the environment via conduction and evaporation within expected ranges.

Sweat loss

Total sweat losses were estimated by adding food and fluid inputs, then subtracting any outputs and the difference in pre-trial and post-trial nude weight (Table 2). These values were then divided across the five hours of the trial to provide sweat loss per hour values. We observed a significant difference in the total volume of sweat secreted per hour between the men and women in our trial, with male participants closely matching expectations and the female participants sweating slightly more than expected (men: 0.79 ± 0.25 kg · hr^{-1}; expected ~0.8 kg · hr^{-1}, women: 0.59 ± 0.16 kg · hr^{-1}; expected ~ 0.45 kg · hr^{-1}) [19,55,219-221]. It has been reported that trained men and women sweat more than untrained men and women, and that trained men tend to sweat more than trained women[224]. As our sample represented a highly aerobically fit group of men and women (of appropriate fitness to match Australian Army Infantry personnel), these values are likely to mimic real-world sweat losses in the field.

There was also a significant difference in the amount of fluid consumed by the men and women in this trial (men: 3.88 ± 1.12 kg, women: 2.75 ± 1.02 kg). All participants replenished at least 80% of the fluids lost to sweat throughout work and rest bouts, and no participant became dehydrated during each bout (>2% body weight loss). This volume of fluid replaced is feasible for soldiers, as Australian Army personnel typically carry ~10 kg of fluid when in the field[285].

Limitations and Generalisability

The females recruited for this study were limited to a specific set of reproductive and contraceptive criteria and were exercised only in a short window (days 5 – 8) of their menstrual cycle. The potential for variations in the observed core temperature results was not investigated at later points in their cycles. The females for this study participated during the limited menstrual cycle window to reduce the potential impact of menstrual cycle-related effects on body core temperature; this window was chosen as the 5 – 8 day period is when females have a hormonal status most similar to males, and this enabled the researchers to more appropriately assess core temperature variations stemming from morphological differences. Further investigation is required to understand the potential impacts of different phases of the menstrual cycle on core temperature during intermittent exercise in the heat.

Unfortunately, the study was not able to utilize the most accurate version of the current Australian Army personnel uniform, as participants were instructed to wear their own comfortable running shoes and carried less load than is typically expected. A standard Australian Army member is expected to wear standard issue combat boots (an additional 2 kg), in addition to an approximately 40 kg load comprised of ammunition and tools, food and water supplies, clothing, and personal possessions. The participants in this study only carried an additional 10 kg of weight within a ballistic vest and helmet. The combat boots were not worn in this study due to the range of sizes required, the discomfort associated with new and unworn leather shoes, and the participants' comfort when wearing unfamiliar and potentially uncomfortable walking boots for an extended period. Wearing combat boots increases metabolic work rate due to the increased weight at the end of the limb, reducing mechanical efficiency and therefore forcing the body to work harder[286]. The full combat load was not simulated as participants were not expected to be experienced in carrying heavy loads, and this lack of adaptation was feared to cause overexertion and affect key physiological measurements. In an ideal scenario, a similar study would be performed on Australian Army personnel with access to their own broken-in combat boots and with experience in carrying the required load. However, it is important to note that internal absolute metabolic heat production rates were appropriately matched in this study to relevant "moderate" and "heavy" metabolic rates stipulated in the Work Tables. The "moderate" work category assumes a metabolic heat generation of between 350 W and 500 W, and participants in this trial averaged an absolute metabolic heat generation of 439 W during the "moderate" work bouts. The "heavy" work category assumes a metabolic rate greater than 500 W, and participants in this trial averaged an absolute metabolic heat generation of 567 W during the "heavy" work bouts. Therefore, even though our participants did not complete the trial in the most correct military uniform of the Australian Army regarding weight and boots, the metabolic heat production was appropriate to apply our findings to the current Work Tables.

Furthermore, the activities undertaken in this study were at a fixed wattage whilst conducting work on a motorised treadmill. The current Australian Army Work Tables provide recommendations for a wide range of work activities and is not specific to walking alone. Although this study was completed with walking only, army staff regularly engage in other tasks limited by the Work Tables, such as trench digging, engagement manoeuvres, training exercises, and so forth. All of these tasks elicit different metabolic heat generation, and therefore the findings from this study may not accurately represent heat gain potential across all such activities.

The foods and fluids selected for this trial were not in direct mimicry of standard fare for Australian Army personnel in the field. This was done to control for any diet-based variations in core temperature, such as from the thermic effect of high-protein foods[287] or the increase in heat gain from dehydration. It is likely that, in the field, Army personnel would have limited access to nutritionally appropriate foods and fluids, and therefore the findings from this study may not accurately represent the hydration and nutrition status during military activities.

Future Research Directions

There is a lack of high-quality research into core temperature variations over repeat bouts of exercise in females across the whole menstrual cycle. Future studies would ideally not limit female recruitment by reproductive and contraceptive criteria, and also would exercise the women across all days of the menstrual cycle. Additionally, future studies would recruit specifically military personnel who had access to their own broken-in combat boots and with experience in carrying the required load to simulate real-world military situations.

Conclusions

The key objectives for this study were: 1) To evaluate whether current Australian Army work-rest protocols for hot environments can be increased to 4 consecutive work-rest cycles without resulting in excessive heat strain in healthy adults; and 2) To examine the sex-based differences in elevation and restoration of core temperature when working in the heat with current work-rest protocols. Our findings concluded that peak core temperatures were significantly different across all four work bouts, though core temperatures on average did not exceed 38.5 °C. We also concluded that there were no significant differences in core temperature responses between the male and female participants in this trial. These results suggest that the current continuous Work Table of the Australian Army are appropriate for both sexes, and may inform Australian Army decision making regarding appropriate durations for up to four repeated bouts of work and rest and working in extreme heat.

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Appendices

Appendix A Human Research Ethical Approval

Dear Dr Andrew Hunt and Mr Christopher Anderson

Ethics Category: Human - Committee
UHREC Reference number: 1800000438
Dates of approval: 1/08/2018 to 1/08/2019
Project title: Repeat Exercise in Heat
and Exertional Alterations to Thermoregulation (REHEAT)

Thank you for submitting the above research project for ethics review.
This project was considered at a recent meeting by the Queensland University of Technology (QUT) Human Research Ethics Committee (UHREC).

I am pleased to advise you that the above research project meets the requirements of the National Statement on Ethical Conduct in Human Research
(2007) and ethical approval for this research project has been granted.

Please find attached the Research Governance Checklist.
Please ensure you address any items you identify as relevant to your research project.

Note:
If additional sites are engaged prior to the commencement of, or during the research project, the Chief Investigator (CI) / Project Supervisor (PS) is required to notify UHREC. Notification of withdrawn sites should also be provided to the UHREC in a timely fashion.

The approved documents include:

ETH_REHEAT_HREA_Output-Form_1-08-2018
ETH_REHEAT_HREA_Project-Protocol_1-08-2018
ETH_REHEAT_Email-Recruit_1-08-2018
ETH_REHEAT_Flyer-Recruit_1-08-2018
ETH_REHEAT_Information-Sheet_1-08-2018
ETH_REHEAT_Consent-Form_1-08-2018
ETH_REHEAT_MRIWalletAlert_1-08-2018
ETH_REHEAT_Screening-Tool_ESSA_1-08-2018

Approval of this project from UHREC is valid as per the dates above, subject to the following conditions being met:

< The CI/PS will immediately report anything that might warrant review
of ethical approval of the project.

< The CI/PS will notify the UHREC of any event that requires a
modification to the protocol or other project documents and submit any required amendments in accordance with the instructions provided by the UHREC. These instructions can be found at http://www.orei.qut.edu.au/human/.

< The CI/PS will submit any necessary reports related to the safety of

research participants in accordance with UHREC policy and procedures.
These instructions can be found at http://www.orei.qut.edu.au/human/.

< The CI/PS will report to the UHREC annually in the specified format
and notify the UHREC when the project is completed at all sites.

< The CI/PS will notify the UHREC if the project is discontinued at a
participating site before the expected completion date, with reasons provided.

< The CI/PS will notify the UHREC of any plan to extend the duration of
the project past the approval period listed above and will submit any associated required documentation. Instructions for obtaining an extension of approval can be found at http://www.orei.qut.edu.au/human/.

< The CI/PS will notify the UHREC of his or her inability to continue
as CI/PS including the name of and contact information for a replacement.

This email constitutes ethics approval only.
If appropriate, please ensure the appropriate authorisations are obtained from the institutions, organisations or agencies involved in the project and/or where the research will be conducted.

The UHREC Terms of Reference, Standard Operating Procedures, membership and standard forms are available from:
http://www.orei.qut.edu.au/human/manage/conditions.jsp.

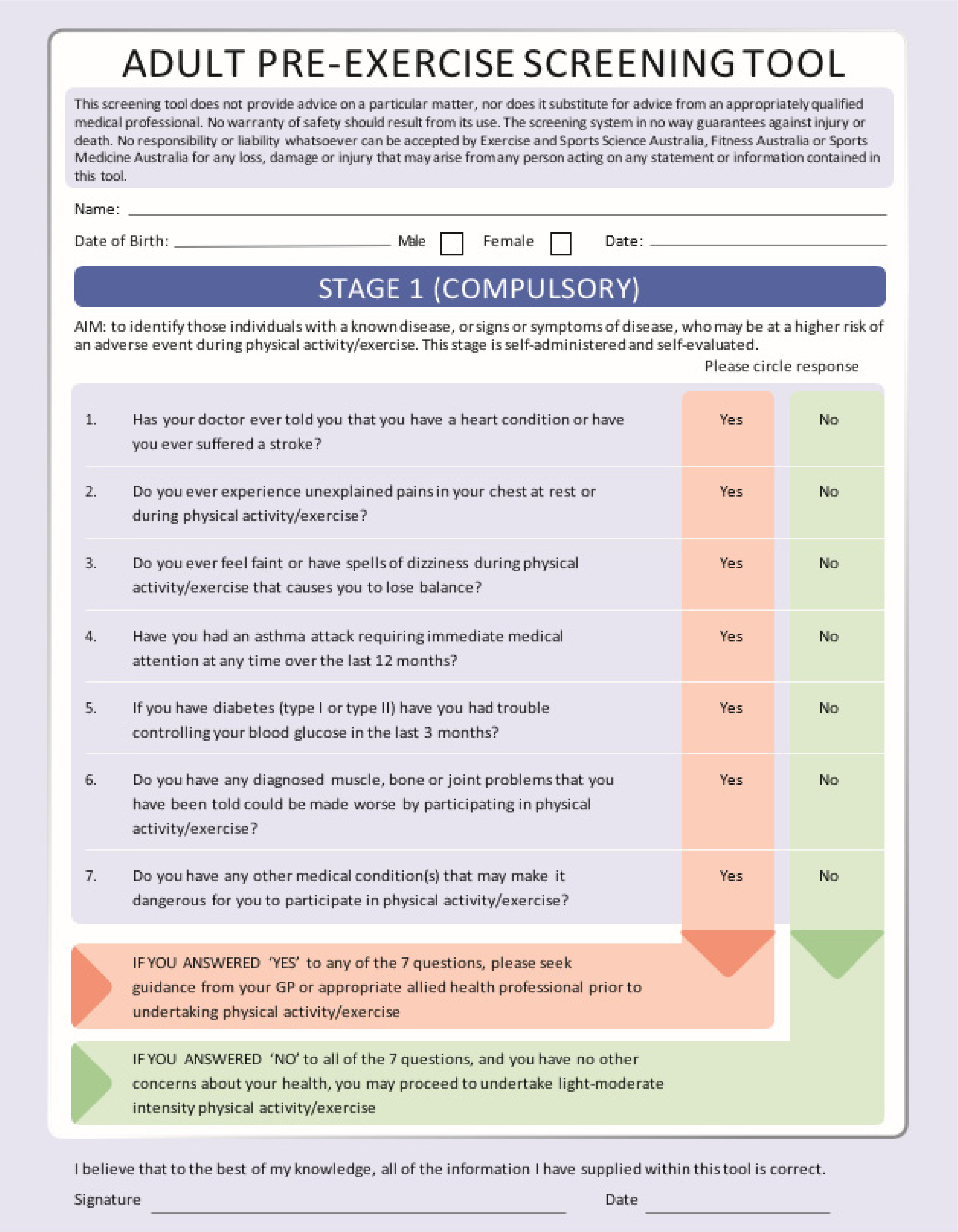
Should you have any queries about the UHREC's consideration of your project please contact the Research Ethics Advisory Team on 07 3138 5123 or email humanethics@qut.edu.au.

The UHREC wishes you every success in your research.

Research Ethics Advisory Team, Office of Research Ethics & Integrity
on behalf of the Chair, UHREC
Level 4 | 88 Musk Avenue | Kelvin Grove
+61 7 3138 5123 | humanethics@qut.edu.au

The UHREC is constituted and operates in accordance with the National Statement on Ethical Conduct in Human Research (2007) and registered by the National Health and Medical Research Council (# EC00171).

Appendix B ESSA Pre-Exercise Screening Tool



ADULT PRE-EXERCISE SCREENING TOOL

This screening tool does not provide advice on a particular matter, nor does it substitute for advice from an appropriately qualified medical professional. No warranty of safety should result from its use. The screening system in no way guarantees against injury or death. No responsibility or liability whatsoever can be accepted by Exercise and Sports Science Australia, Fitness Australia or Sports Medicine Australia for any loss, damage or injury that may arise from any person acting on any statement or information contained in this tool.

Name: ____________________

Date of Birth: ____________ Male ☐ Female ☐ Date: ____________

STAGE 1 (COMPULSORY)

AIM: to identify those individuals with a known disease, or signs or symptoms of disease, who may be at a higher risk of an adverse event during physical activity/exercise. This stage is self-administered and self-evaluated.

Please circle response

1.	Has your doctor ever told you that you have a heart condition or have you ever suffered a stroke?	Yes	No
2.	Do you ever experience unexplained pains in your chest at rest or during physical activity/exercise?	Yes	No
3.	Do you ever feel faint or have spells of dizziness during physical activity/exercise that causes you to lose balance?	Yes	No
4.	Have you had an asthma attack requiring immediate medical attention at any time over the last 12 months?	Yes	No
5.	If you have diabetes (type I or type II) have you had trouble controlling your blood glucose in the last 3 months?	Yes	No
6.	Do you have any diagnosed muscle, bone or joint problems that you have been told could be made worse by participating in physical activity/exercise?	Yes	No
7.	Do you have any other medical condition(s) that may make it dangerous for you to participate in physical activity/exercise?	Yes	No

IF YOU ANSWERED 'YES' to any of the 7 questions, please seek guidance from your GP or appropriate allied health professional prior to undertaking physical activity/exercise

IF YOU ANSWERED 'NO' to all of the 7 questions, and you have no other concerns about your health, you may proceed to undertake light-moderate intensity physical activity/exercise

I believe that to the best of my knowledge, all of the information I have supplied within this tool is correct.

Signature ____________________ Date ____________

Appendix C Adverse Event Report

Dear Dr Andrew Hunt

Ethics Number: 1800000438
Clearance Until: 1/08/2019
Ethics Category: Human

This email is to advise that your adverse event submission has been reviewed by the Chair, University Human Research Ethics Committee.

The Chair has advised the following:

Location/date: QUT Kelvin Grove O-A214 18/03/2019

Summary: Participant is 23 yo female, with no self-identified health risks, recreationally active through distance trail running. She passed the aerobic fitness assessment and Exercise Sports Science Australia Pre-Exercise Screening Tool. During the second of 4 walking events (walking on a treadmill wearing a helmet and weighted vest in a hot environment, each separated by 30 minutes of rest) the participant was noticeably fatigued. The participant's physiological measurements leading up to the event were not indicative of any major strain on her body. Her heart rate and core temperature were well within normal limits, and she was talkative and comfortable right up until the events the researcher asked if they were OK to continue the participant stumbled, but was able to control the stumble through holding on to the hand rails.

Action taken: The research team immediately followed the adverse event action plan:

1.Stopped the test. 2. Allowed the participant to recover in a supine position. 3. Elevated their legs and fan cooling. 4. Monitored physiological strain returning to baseline. 5. Verbally and physiologically confirmed that the participant was recovered before allowing them to leave.

Current situation: The research team contacted the participant that evening after the adverse event. The participant reported feeling a bit iffy and thought they might be coming down with a cold or something. The researcher recommended visiting their GP if symptoms progressed. The research team used this opportunity to revisit the action plan and remain happy that it is appropriate and well understood by the research team.

UHREC Chair's response: Thank you for notifying us of this adverse event.
The care for the participant in this instance was paramount, and I commend the researchers for implementing their adverse event action plan. The researchers have followed up with the participant who reported that they did have a cold, did not need any further medical treatment and has recovered.

Risk rating: Moderate

No further action is required.
The event will be reported to UHREC at its next meeting.
You only be contacted again if the UHREC raises any questions.

Should you have any further queries please do not hesitate to contact the Research Ethics Advisory Team if you have any queries.

Best regards

Research Ethics Advisory Team, Office of Research Ethics & Integrity
on behalf of Chair UHREC
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