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The effect of a liquid cooling suit on physiological and perceptual strain during uncompensable heat stress when wearing an explosives ordnance disposal suit in hot ambient conditions

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The effect of a liquid cooling suit on physiological and perceptual strain during uncompensable heat stress when wearing an explosives ordnance disposal suit in hot ambient conditions

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Abstract

Introduction Explosive ordnance disposal (EOD) operatives often wear protective clothing in the form of an EOD suit for protection when disarming and/or disposal of explosive devices. EOD suits are heavy, cumbersome and encapsulating, which increases the physical challenge of work and predisposes the wearer to uncompensable heat stress (UHS). If unchecked, UHS will affect physical and cognitive capabilities, limit the amount of work performed, as well as increasing the likelihood of heat strain and/or heat illness, putting the health and safety of the operator at risk.

Aims To characterise the physiological and perpetual benefits of wearing a liquid-cooled suit (LCS) under an EOD suit whist working in high ambient temperatures (40ºC; relative humidity 30%) and to estimate the cooling power provided by the suit.

Methods Seven healthy, non-heat acclimated males (age, 30±5 years old; height, 181±7 cm; body mass, 88.6±11.8 kg) undertook one familiarisation session followed by two experimental trials each separated by at least one week. Trials consisted of walking on a treadmill at 4 $km \cdot h^{-1}$ for 60 mins in 40°C ambient temperatures whilst wearing an EOD suit either with or without an activated water-based liquid cooling suit (active, AC vs. no cooling, NC respectively) in a balanced cross-over design. Trials were terminated if the participant's HR exceeds 95% of maximum (220-age) for 1 min or if core temperature reached 39.5ºC or 3ºC greater than initial baseline temperature, whichever was lowest.

Results No participant completed 60 mins of treadmill walking in either condition. However, exercise duration was significantly longer in AC compared to NC (37 mins vs. 32 mins, $p<0.05$, $\eta p^2 = 0.828$). Active cooling resulted in more favourable physiological variables (heart rate, mean skin temperature, core temperature; both gastrointestinal and rectal), and perceptual variables (thermal sensation and comfort). However only gastrointestinal ($F(1, 35) = 658{,}778$, $p = 0.025$, $\eta p^2 = 0.998$) and mean skin temperature ($F(1, 35) = 513{,}534$, $p = 0.028$, $\eta p^2 = 0.998$) were significantly different in the AC condition compared to NC. Oxygen consumption ($\dot{V}O_2$) and rating of perceived exertion (RPE) did not vary between trials. The cooling power of the LCS for the first 20 mins of the trials (n=7) was estimated as being 73 W from changes in body heat storage between conditions and 199 W from changes in LCS inlet and outlet water temperatures within AC trials.

Conclusion AC resulted in lower physiological and more favourable perceptual responses when compared with NC. This resulted in a small increase in performance time in AC compared to NC. The cooling power of the LCS system was higher when estimated from changes in water temperature compared to actual cooling transferred to the participants (that estimated from heat storage). Further work investigating the LCS capability at lower work rates, within different environmental conditions and during simulated EOD activities is warranted.

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Acronyms & Abbreviations

Explosive ordnance disposal	EOD
Uncompensable heat stress	UHS
Active Cooling	AC
Non-Cooling	NC
Liquid-cooled suit	LCS
Phase change material	PCM
Phase change vest	PCV
Ice-based cooling vest	IBCV
Ice slushy & ice vest	IS&IV
Tolerance time	TT
Personal protective equipment	PPE
Chemical protective clothing	CPC
Nuclear, chemical and biological	NCB
Chemical, biological, radiological and nuclear	CBRN
Oxygen uptake / Maximal oxygen uptake	$\dot{V}O_2$ / $\dot{V}O_{2max}$
Rectal temperature	T_{re}
Skin temperature	T_{sk}
Ambient temperature	T_{amb}
Gastrointestinal pill temperature	T_{GI}
Chest skin temperature	T_{Ch}
Mean skin temperature	T_{ms}
Heart Rate	HR
Beats per minute	$b \cdot min^{-1}$
Minute/minutes	Min/mins
PSI & PhSI	Physiological strain index
PeSI	Perceptual strain index

Heat Storage	HS
Sweat rate	SR
Degrees Celsius	°C
Relative humidity	RH
Gastrointestinal tract	GI
Thermal sensation	TS
Thermal comfort	TC
Rating of perceived exertion	RPE
General symptoms	GS
n	Number of sample
Physical Activity Readiness Questionnaire	PAR-Q
Heath Screen Questionnaire	HSQ

1 Introduction

Explosive ordnance disposal (EOD) operatives are often tasked with disarming and/or disposal of explosive devices including improvised explosive devices (IEDs) unexploded ammunition (grenades), bombs and landmines. Protective clothing, in the form of an EOD suit, is often worn to protect against potential impacts, heat and fragmentation (Stewart et al. 2014). EOD suits commonly weigh in excess of 35 kg and are cumbersome to move in, thus increasing the physical challenge of work and resulting in an elevated metabolic rate (Bach et al. 2016). Materials used to design EOD suits are impermeable, resulting in heat exchange between user and ambient environment becoming severely limited (Stewart et al. 2011). A key feature being the microclimate created between skin surface and suit, which limits the capacity for heat dissipation by reducing the capacity for conduction, convection and evaporative heat transfer (Stewart et al. 2011; Cheung et al. 2000). Despite compensatory physiological responses under such conditions heat storage (HS) continues to increase. If unchecked, this uncompensable heat stress (UHS) will rapidly progress increasing the risk of heat strain and/or heat illness (Stewart et al. 2011). UHS has been shown to reduce physical capabilities due to rapid increases in core temperature and heart rate occurring relatively quickly during simulated operational exercise tests (Stewart et al. 2011; Stewart et al. 2014). Working in high ambient temperatures decreases cognitive capabilities (Gaoua et al. 2010; Racinais et al. 2008; Schmit et al. 2016). As well as impairing memory (Stewart et al. 2011; Stewart et al. 2014), motor drive transmission is reduced, limiting the amount of work performed during exercise. With the magnitude of restriction being greater at higher internal temperatures. These reductions in physical and cognitive ability and associated increased risk of heat illness put the health and safety of operators at greater risk (Stewart et al. 2011).

Cooling practices and equipment have been developed to mitigate the dangerous rise in HS whilst wearing personal protective equipment (PPE). Examples of these include precooling (Bongers et al. 2014), manipulating work: rest ratios (Hostler et al. 2016), wearing air/ liquid-cooled garments (Bartkowiak et al. 2017) or phase change material (PCM) garments (Davey et al. 2020), which create microclimates between body and suit to cool individuals. A recent meta-analysis by Chan et al. (2015) investigated different cooling strategies in T_{amb} above 28°C in a range of settings, including sports,

military operations, chemical protection and firefighting. By identifying common physiological and perceptual variables such as core temperature (measured via rectal thermistors and ingestible pills) and rating of perceived exertion (RPE), they collectively ranked the cooling effectiveness of different garments worn under various PPE across a range of activities. Cold air circulated garments proved most effective at maintaining physiological and cognitive performance during occupational work, followed closely by liquid-cooled garments, hybrid cooling garments (combination of air and liquid cooling), ambient air-cooled garments and finally finding PCM cooling garments least effective. Specific factors, such as load, the flow of air/water, the temperature of air/water and how it's distributed will have contributed to how effective the cooling garment is and are therefore necessary considerations when testing cooling strategies.

In high T_{amb} (>21°C), core (measured via gastrointestinal temperature (T_{GI}); °C & rectal temperature, (T_{re}); °C), mean skin temperature (T_{ms}; °C), heart rate (HR; $b \cdot min^{-1}$), sweat rate (SR) and perceptual indices including RPE and thermal sensation (TS) increase whilst wearing EOD suits (Stewart et al. 2013; Costello et al. 2015; Stewart et al. 2014; Thake et al. 2009; Thake and Price 2007). Normative data for these variables in high T_{amb} during exercise have shown core temperature to be between 37-39°C, T_{ms} 35-39°C, HR 110-190 $b \cdot min^{-1}$, SR 1-2 $L \cdot kg^{1} \cdot hr^{-1}$, RPE of 14-17 and TS around 6-7 (Costello et al. 2015; Stewart et al. 2014; Thake et al. 2009; Thake and Price 2007). These studies have used ambient temperatures between 30-40°C, EOD operations have been deployed in temperatures above 40°C e.g. Afghanistan and Iraq, however, controlled laboratory-based investigations have not exceeded 40°C. Exercise tolerance time (TT) has been shown to decrease once physiological and perceptual variables increase (Stewart et al. 2013; Costello et al. 2015; Stewart et al. 2014; Thake et al. 2009; Thake and Price 2007). Improvements in TT have been associated with a greater delay in the rise of variables such as core temperature (Chan et al. 2015), demonstrating a positive relationship between cooling strategies and improvements in physiological and psychological performance.

In the current study, researchers were tasked with conducting human-based trials to investigate the cooling capacity of a liquid-cooled suit (LCS) to be worn under an EOD suit by United Shield

International. United shield international estimated the LCS provides 270 W worth of cooling, however, no parameters have been set in regards to this level of cooling e.g. the environment (T_{amb} and relative humidity (RH)) or how long this level of cooling is sustained. Previous occupational research has demonstrated significantly lower T_{ms} and delayed increases in core and skin temperature (T_{sk}) whilst wearing a LCS with active cooling compared to no cooling (Bartkowiak et al. 2017; Cadarette et al. 2006). In similar research assessing performance, lower mean skin temp and delays in increased core and T_{sk} resulted in significantly improved performance and exercise recovery time (Kim et al. 2011). However, EOD suits are more cumbersome than PPE used in these studies (no PPE; chemical protective clothing which consisted of a charcoal-impregnated over-garment (top and bottom), cotton glove liners, butyl gloves and M-40 chemical-biological field mask with hood; fully-equipped firefighter ensemble) so inferences are difficult. Furthermore, the conditions applied in these studies e.g. T_{amb} and mode of exercise/work (30°C, 40% RH) with a variety of standing and slow walking at 2.5 and 3.5 $km \cdot hr^{-1}$; 30°C, 30% RH while walking on a treadmill at 4.8 $km \cdot hr^{-1}$with 2% incline; 35°C, 50% RH while performing three stages of 15 minutes (mins) exercise at 75% maximum oxygen uptake ($\dot{V}O_{2max}$) with 10 mins of rest following each stage are non-comparable with experimental conditions used in the current study.

When comparing LCS studies, as well as differences in PPE worn and environmental conditions, variation between LCSs is also a challenge. LCS design often varies greatly between manufacturers, with material, inlet coolant temperature, coolant used, flow rate and distance of tubing throughout suits varying, all of which can have a significant effect on the cooling capabilities of each system (Nunneley 1970). Therefore, individual products and manufacturers' claims about such products need to be tested in specific environments, using specific PPEs and representative exercise/work scenarios to assess their effectiveness. Knowing and understanding the cooling capability of LCSs allow predictions to be made on how individuals may respond physiologically and perceptually in specific environments, ultimately providing a greater understanding of how an individual may perform. Knowledge of potential thermal strain whilst working in hot conditions could inform operation

management decision-making. Currently, no human-based studies have assessed the effectiveness of this specific LCS when worn under an EOD suit. Therefore this study aims to:

1.1 Aims

- To characterise the physiological and perpetual benefits of wearing a liquid-cooled suit under an EOD suit when working in high ambient temperatures (40°C).
- To quantify the cooling provided by the LCS suit to the EOD suit wearer under these specific ambient conditions/activity.

1.2 Hypothesis

- Active cooling (AC) will result in lower physiological strain when compared with non-cooling (NC)
- AC will result in lower perceptual strain when compared with NC.

2 Literature Review

This literature review begins by focusing on the principles of heat transfer. It moves on to discuss how these principles can affect human physiology and issues associated with wearing PPE, specifically EOD suits, in high T_{amb}. It finished by discussing cooling strategies aimed at mitigating issues surrounding individuals wearing PPE in high T_{amb} and their success and/or failure at improving physiological, perceptual and ultimately performance indices.

2.1 Principles of Heat Transfer

The ability to regulate body temperature is critical to maintaining thermal homeostasis. Accordingly, the thermoregulatory system's primary goal is to maintain core body temperature within set limits despite changes in T_{amb} and metabolic rate (Kanosue et al. 2009). Core body temperature in humans fluctuates around 0.5°C throughout the day due to circadian variation, averaging around 37°C. If core temperature deviates ±3.5°C from 37°C, health issues such as hyperthermia (too high) and hypothermia (too low) can develop, which can cause serious health problems and even death if not identified and treaded quickly enough (Lim et al. 2008; Walker et al. 1990). Thermoreceptors found in the skin feedforward information regarding changes in T_{amb} (Tan and Knight 2018), whilst thermoreceptors found in the bodies core (the viscera, brain, and spinal cord) (Jessen 1985) feedback changes in internal temperatures, such as exercise-induced increases in metabolic rate, to the hypothalamus, the bodies thermoregulatory centre. If the body senses it is getting too hot, heat loss mechanisms will be triggered, including vasodilation of blood vessels and water evaporation from the skin (sweating) (Charkoudian 2003; Tan and Knight 2018).

To optimise heat loss, the body relies on its interaction with the environment to dissipate heat. Avenues for heat exchange include dry (radiative, conductive, convective) and wet (evaporative) pathways (Cheung et al. 2000). When the body comes into contact with cooler/hotter objects or surfaces heat is transferred via conduction while similar occurs with ambient air temperature and whether it is cooler/hotter than T_{sk}, whereby heat is transferred via convection. Therefore, dry pathways rely on a core > periphery temperature gradient to dissipate heat into the environment (T_{sk}

must be lower than core; shown in Figure 2) (Potter et al. 2016), which is disrupted in a UHS environment. In order for wet heat loss to take place, the body relies on a body surface > environmental pressure gradient (Figure 2). Sweat evaporates off the skin due to the latent heat of vaporization. This is defined as the heat required to change one molecule of liquid under standard atmospheric pressure (Datt 2011). The heat of vaporization of water is around 2,260 $kJ \cdot kg^{-1}$ (Datt 2011). As water droplets on the skin evaporate into the environment, heat is taken with it and removed from the body, therefore cooling the individual down. As sweat evaporates into the surrounding environment, the capacity of the environment to take up water vapour increases as temperatures rise. Previous research has reported maximal human sweat rates range between 1.5 and 2.5 $L \cdot hr^{-1}$. Theoretically, if all sweat produced was evaporated this would result in 1000 to 1700 W of heat loss every hour (Gagnon and Crandall 2018). However, this would heavily depend on the temperature and humidity of the environment, the clothing worn and individual characteristics such as fitness levels and body composition. The efficiency of sweating, which is defined as the ratio between secreted and evaporated sweat (Alber-Wallerstrom and Holmer 1985) plays an important role in cooling down an individual. Encapsulating PPE prevents sweat from evaporating into the surrounding environment and heat is trapped within a microenvironment between skin and clothing, resulting in increased T_{sk} and a restricted ability for the body to remove heat from its core. To understand this relationship, individuals can be weighed before and after trials whilst nude and whilst in the suit to then identify how much body mass has been lost from the individual and how much sweat has been excreted and absorbed by the suit.

Equation 1. The balance of all sources of heat exchange by the body to keep thermal equilibrium:

$$\acute{E}req = \acute{M} - \acute{W} \pm \left(\acute{C} + \acute{R} + \acute{K}\right) \pm \left(\acute{C}resp - \acute{E}resp\right)$$

(Cheung et al. 2000)

Where $\acute{E}req$ describes the evaporative requirement for heat balance, $\acute{M}$ represents metabolic rate, $\acute{W}$ is the rate of mechanical energy from the generation of external power, $\acute{R}$, $\acute{C}$ and $\acute{K}$ are the rates of radiative, convective and conductive heat transfer, respectively, $\acute{C}resp$ defines convective heat

transfer through respiration and $\acute{E}resp$ represents evaporative heat loss with respiration (Cheung et al. 2000).

Metabolic rate is a substantial driver of temperature regulation. Physical exercise can increase metabolic heat production by 10-20 times resting values, with only 30% of this heat being converted into mechanical energy, whilst the rest is dissipated into the environment (Lim et al. 2008; Sawka and Wenger 1988). Issues occur when T_{amb} exceeds T_{sk} as this results in heat-dissipating mechanisms struggling against metabolic heat production (Lim et al. 2008) as the body gains more heat via dry pathways and leaves wet pathways as the only way of heat leaving the body. Unfortunately, in situations where the evaporative requirement exceeds the evaporative capacity of the environment, wet pathways can also find themselves to be restricted. This can be caused by specific environmental conditions e.g. a humid jungle or by specific clothing e.g. encapsulating clothing (EOD suits) which creates a skin > clothing microenvironment.

Clothing, specifically PPE, has been shown to disrupt the body's heat generation and removal in high T_{amb}. Significant increases in metabolic rate of 13 to 18% in chemical protective clothing (CPC) have been found when compared to standard army uniform during exercise including treadmill walks at various speeds and bench step tasks (Patton et al. 1995; Aoyagi et al. 1994; Duggan 1988). This is likely due to increased load and encapsulating nature of the PPE. Fully encapsulated PPE can cause significant issues for temperature regulation due to the creation of a microclimate between skin and clothing (Stewart et al. 2011). This prevents dry and wet heat exchange pathways from cooling the body down as temperature and pressure gradients between the skin and ambient environment become restricted (as shown in Figure 1). Rather than heat escaping into the environment, heat begins to build up in the microenvironment, thereby raising T_{sk} simultaneously. During conditions of high T_{amb} and/or encapsulating clothing which restricts evaporative heat loss, the maximal evaporative capacity of the environment may exceed the required evaporative heat loss of an individual to maintain a thermal steady state (Cheung et al. 2000). In these situations, stored heat and will eventually result in UHS, where the body can no longer maintain thermal homeostasis. The rate of heat production is a key factor in determining the rate of temperature increase as harder work will result in more rapid

elevation. If there are no improvements in internal environmental conditions, i.e. the microclimate, the ability of the individual to dissipate stored heat (removal of encapsulating PPE) or a reduction in metabolic heat production (work), core body temperature will continue to rise. This pattern is clear despite external environmental temperatures, which was demonstrated during a comparison between 20°C and 40°C in an EOD suit during exercise, whereby researchers found T_{re}, T_{ms} and HS all increasing during exercise in both temperatures, with a more rapid increase in 40°C. When core body temperature exceeds 40.5°C, individuals are at serious risk of heat illness and even death (Coris et al. 2004; Cheung et al. 2000). Therefore finding ways to slow/stop the rate of rise in core temperature is of the utmost importance.

Figure 1. Heat exchange in normal clothing (left) versus an EOD suit (right) (Potter et al. 2016).

2.2 Physiological Strain

EOD operatives wearing EOD suits undergo significantly higher physiological strain when compared without the EOD suit (Wu et al. 2021). Physiological strain can be determined by physiological variables such as HR, core temperature and $\dot{V}O_2$ and also indicated by perceptual measures such as RPE, TS and thermal comfort (TC) (Epstein and Moran 2006; Young et al. 1987). The physiological strain an individual may experience is influenced by many factors such as body mass and composition (Havenith et al. 1998; Pandolf 1997), gender (Moran et al. 1999), hydration and aerobic capacity

(Merry et al. 2010), heat acclimation (Aoyagi et al. 1997), exercise intensity (Borg et al. 2015), environmental conditions (Stewart et al. 2013), clothing (Dorman and Havenith 2008) and load (Thake and Price 2007). Calculations of physiological strain, calculated using HR and core temperature have been created to quantify strain and are discussed further in section 2.2.4. Table 1 includes physiological strain associated with wearing an EOD suit in conditions similar to those in the current study's methodology.

Table 1. Comparison of EOD results from studies conducted using similar environmental conditions. Specifically focusing on tolerance time, physiological and perceptual measurements whilst wearing an EOD suit (>30kg weight). Data was taken at the cessation of each trial. NR = Not reported

	Stewart et al. 2014	**Costello et al. 2015**	**Thake et al. 2011**	**Thake et al. 2009a**	**Thake et al. 2009b**
Ambient Temperature (°C) & RH (%)	30°C wet bulb globe temperature	30°C wet bulb globe temperature	40°C; 25%RH	40°C; 48%RH	40°C; 24-38%RH
Exercise protocol	60 min treadmill walk at 4 km·hr^{-1}	60 min treadmill walk at 4 km·hr^{-1}	109 min activity cycle	66 min activity cycle	66 min activity cycle
Cooling strategy	No Cooling	No Cooling	NC, a single phase change vest (PCM1) & phase change vest swapped out (PCM2)	Acclimation & ambient air fan system	Acclimation & ambient air fan system
Tolerance time (mins)	38.4 (24–55)	31.5±6.0	All completed	Pre acclimation 53:48±11:59; Post acclimation 60:10±09:34	All completed
Core Temp (°C)	38.3 (37.8–38.7)	38.3±0.4	NC 38.0±0.3; PCM1 37.9±0.3; PCM2 37.4±0.5	Pre acclimation 38.5±0.3; Post acclimation 38.2±0.3	In 37kg EOD suit: 38.3±0.14
Heart Rate (b·min^{-1})	169.6 (156–190)	170.6±8.3	NC 135±25; PCM1 129±34; PCM2 119±25	Pre acclimation 151±16; Post acclimation 141±15	In 37kg EOD suit: 170±12
Mean Skin Temp (°C)	37.4 (36.9–38.9)	38.3±0.4	NC 37.2±0.3 PCM1 37.4±0.3 PCM2 36.5±0.5	Pre acclimation 37.9±0.6; Post acclimation 38.1±0.5	In 37kg EOD suit: 37.67±0.28

Heat Storage ($J \cdot g^{-1}$)	NR	NR	NC 4.2±0.5; PCM1 3.8±0.5; PCM2 3.1±0.9	NR	In 37kg EOD suit: 5.3±0.29
PSI	6.6 (5.7–7.5)	7.1±1.2	NR	NR	NR
PhSI	NR	NR	NC 4.4±1.0; PCM1 3.4±1.7; PCM2 2.5±0.6	NR	In 37kg EOD suit: 5.6±0.5

2.2.1 Heart Rate

HR is commonly used in laboratory and field-based studies as a measure of physiological strain. HR is elevated when an EOD suit is worn and responses are augmented in high T_{amb} (Stewart et al. 2011; Stewart et al. 2014; Stewart et al. 2013; Thake et al. 2009a; Thake and Price 2007; Thake et al. 2009b). HR is affected by differences in suit weight as well as temperature, as Thake et al. (2009b) demonstrated when comparing physiological responses in four conditions whilst performing a 66 min EOD activity cycle: 20°C 3010 EOD suit (lighter suit), 20°C 4010 EOD suit (heavier suit), 40°C 3010 EOD suit and 40°C 4010 EOD suit. At 20°C, HR was lower in the 3010 suit (111±14 $b \cdot min^{-1}$) when compared with the 4010 suit (133±23 $b \cdot min^{-1}$). This trend continued at 40°C, with an average HR of 159±9 $b \cdot min^{-1}$ in the 3010 suit and 170±12 $b \cdot min^{-1}$ in the 4010 suit. HR was observed to be lowest in the 20°C 3010 suit trials, while it was highest in 40°C 4010 suit trials, demonstrating increased stress from higher environmental temperatures and an increased strain from the suit. Two other studies demonstrated elevated HR during 60 mins of treadmill walking in an EOD suit at 4 $km \cdot hr^{-1}$ in 30°C WBGT. They reported mean end point HRs of 169.6 $b \cdot min^{-1}$ (range of 156–190 $b \cdot min^{-1}$) (Stewart et al. 2014) and 170.6±8.3 $b \cdot min^{-1}$ (Costello et al. 2015). For the safety of participants, HR cut-off points are often implemented during heat trials, usually set at around 90% HR_{max} (Stewart et al. 2014) (Maley et al. 2020) (Costello et al. 2015).

2.2.2 Core body temperature

Measuring core temperature is a key outcome variable for any heat-related study and is often monitored in real-time during trials in the interest of safety. Core temperature is commonly measured via the rectum via a rectal thermistor inserted 10cm past the anal sphincter. T_{re} is considered the most

practical and accurate method of measuring body temperature (Moran and Mendal 2002) and is recommended by the National Athletic Trainers Association as the criterion standard for recognizing exertional heat stroke (Casa et al. 2007). However, T_{re} may have a delayed response time when compared with other techniques, such as oesophageal temperature, during quick changes in core temperature (Moran and Mendal 2002). This delay is important to acknowledge whilst measuring T_{re} during heat-related trials as core temperature can quickly rise, especially in UHS environments. For example, during Stewart et al. (2014)s treadmill walk trials whilst wearing an EOD suit, average T_{re} matched T_{ms} after just 32 mins, whilst another study showed average T_{ms} crossing over core at only 23 mins. Safety cut-off points for core temperature are often used in heat studies to protect participants from core temperature getting too high. These have been previously set at around 39.5°C (Tikuisis et al. 2002).

Another method of measuring core temperature is via a telemetric ingestible pill sensor. These pills have been greatly improved in recent years, making them easier to use, cheaper, easier to swallow (smaller) and lasting longer than in the past. Ingestible pills are ideally swallowed at least 2-3 hours before testing where temperature is then recorded from the gastrointestinal tract (GI) (Lim et al. 2008). Sparling et al. (1993) compared both T_{GI} and T_{rec}, concluding capsule sensors consistently reported lower core temperature during steady-state 30 to 90 mins of progressive cycling or treadmill exercise when compared with T_{re} (38.01±0.3°C vs. 38.94±0.2°C). However, this study was performed almost 30 years ago and technology and measurement accuracy have improved since. For example, in the current study, body cap e-Celsius capsules are being used, which claim to have an accuracy of ±0.2°C, with most data points under 0.1°C (BMedical 2021). Also, in the previous study, exercise was conducted 3-9 hours after ingestion of the pill, meaning there was little consistency between participants and the ingestible pill was likely to be in a variety of locations along the GI for each individual. More recent research demonstrated a mean difference of 0.06°C when comparing an ingestible pill against a rectal thermistor over 12 consecutive days, which included two exercise training days (Darwent et al. 2011). Also, Casa et al. (2007) used 15 men and 10 women to compare T_{re} with T_{GI} with a range of other common sites, including aural, forehead and temporal whilst

performing a variety of team sports including football and ultimate frisbee outdoors in 29.4±1.4°C wet bulb globe temperature (WBGT). They concluded that T_{GI} was the only measure of agreement when compared with T_{re} (Figure 2).

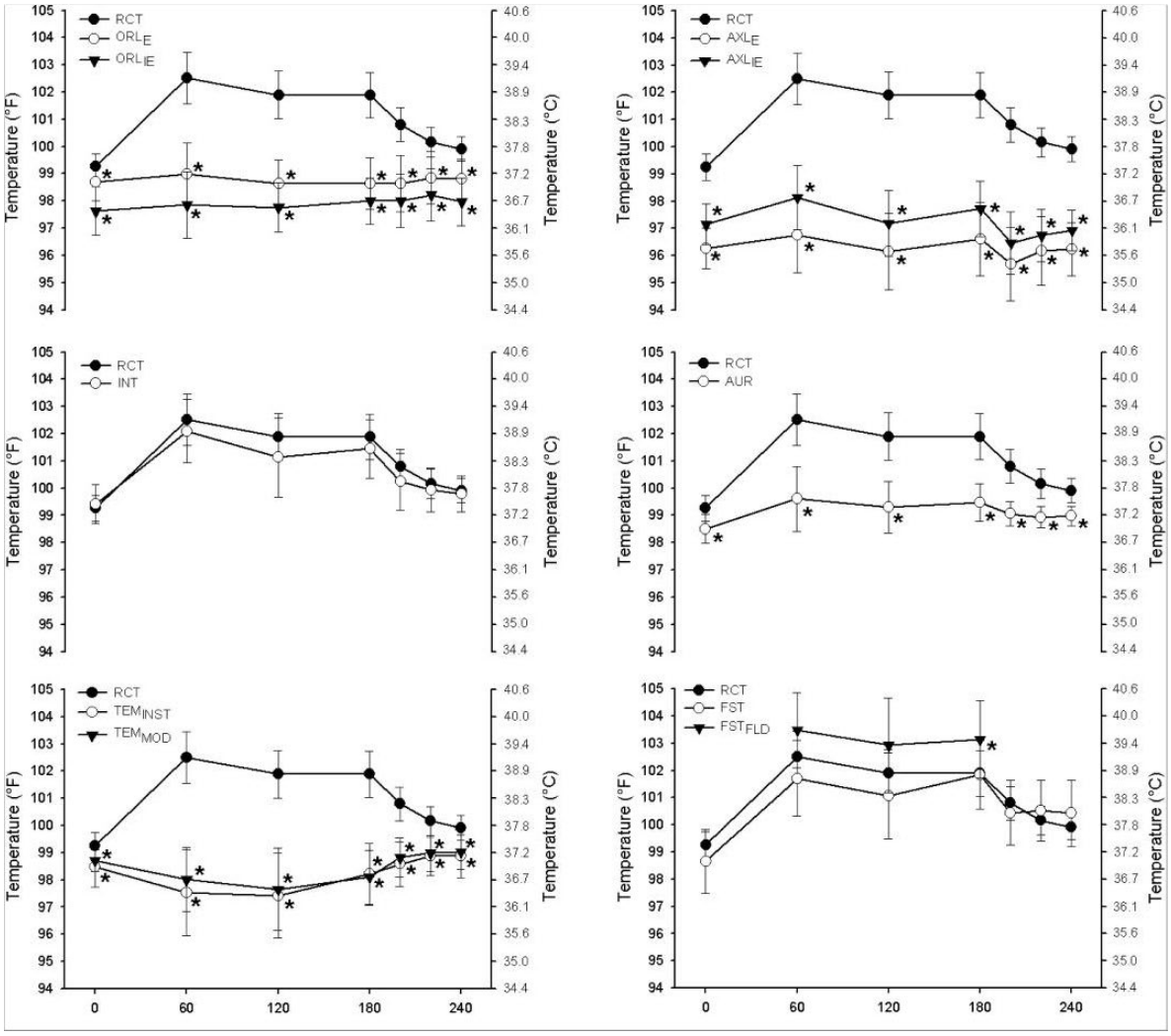

Figure 2. Core temperature measured at various body sites using various devices compared to rectal temperature (Mean ±SD; Taken from Casa et al. 2007). Whereby RCT = rectal temperature, ORL IE = oral temperature with an inexpensive thermometer, ORL E = oral temperature with an expensive thermometer, AXL IE = axillary temperature with an inexpensive thermometer, AXL E = axillary temperature with an expensive thermometer, INT = intestinal temperature, AUR = aural temperature, TEM INST = temporal temperature measured with the method described by the instructional manual, TEM MOD = temporal temperature measured in a modified method, FST = forehead sticker temperature, and FST FLD = forehead temperature measured on the field. *Indicates significant difference from RCT at the same time point ($p<0.05$).

2.2.3 Physiological Strain Index

Core temperature, HR and maximum $\dot{V}O_2$ are all used individually to assess physiological strain whilst exercising. However, to establish a combined strain of the body and stress of the ambient environment, Moran et al. (1998) created the physiological strain index (PSI) (see section 3.8.7,

Equation 5) This was calculated using HR and core temperature (via T_{re} or T_{GI}) responses, which were chosen due to their ability to reflect cardiovascular and thermoregulatory strain (Moran et al. 1998). PSI combines physiological variables to describe individual physiological strain more easily from no strain (0) to high strain (10). It has been successful over a range of challenging environments and exercise intensities (Moran et al. 1998), however, it is limited by its upper HR limit of 180 $b \cdot min^{-1}$ and core temperature of 39.5°C. Due to these limitations, an adapted version of the physiological strain index was created (PhSI) (see section 3.8.7, Equation 6) with a more individualised approach concerning HR (Tikuisis et al. 2002). Instead of setting a HR limit of 180 $b \cdot min^{-1}$, PhSI sets measured or predicted HR_{max}, although direct measures are preferable, as the upper limit. This allows for a more personalised approach, as HR_{max} varies between individuals due to age and fitness levels (Stein et al. 2008; Williams and Williams 1983). However, an issue with PSI is its relationship with tolerance time. In theory, a high PSI would be a strong indicator of an individual nearing maximum tolerance. However, some individuals are able to tolerate high PSI for extended periods, while others cannot (Tikuisis et al. 2002) e.g. those with military or athletic backgrounds. This makes it a poor indicator of tolerance time in certain circumstances, due to high levels of individualisation between individuals and potentially specific cohorts. It's important to note PSI has been established in continuous steady-state exercise and not stop-start/work-rest patterns as would be the case in occupational settings, therefore its real-world use is limited (Davey et al. 2021). However, in the current study, PSI is used under constant work and environmental conditions, which is how the equation was formulated and designed to function.

Previous studies, as shown in Table 1, have assessed physiological strain using either PSI or PhSI calculations. During a 60 min treadmill walk at 37°C whilst wearing an EOD suit with no cooling strategies, Stewart et al. (2014) and Costello et al. (2015) used the PSI calculation and found an average PSI of 6.7±1.7 and 6.8±1.1 respectively at the cessation of their trials. In other EOD studies, Thake et al. (2011) used the PhSI calculation and reported a PhSI of 4.4±1.0 in his non-cooling trial and 3.4±1.7 in his cooling trial when using PCM.

2.2.4 Skin Temperature

T_{sk} is commonly monitored using temperature sensors at multiple locations on the body. This allows a greater understanding of how specific regions are heating/cooling and also allows an overall T_{ms} to be calculated. T_{ms} allows greater insight into how an individual's skin surface is heating up, allowing further estimations to be conducted such as HS. Several calculations have been created to obtain overall T_{ms} (Burton 1948; Hardy et al. 1938; Ramanathan 1964; Nielsen and Nielsen 1984). A popular calculation, and the one being used in the current study (see section 3.8.4), is Ramanathan's (1964), which includes T_{sk} from the upper arm, chest, medial thigh and lateral calf in its equation, weighting each based on body surface area and/or thermal sensitivity. Ramanathan's (1964) calculation simplifies the process of obtaining T_{ms} as it requires fewer skin surface locations without compromising on accuracy.

In the current study, T_{sk} was measured using iButtons due to their ease of use, accuracy and wireless capabilities. iButtons were found to be within acceptable limits for T_{sk} measurement comparisons with typical errors of <0.3°C when compared with thermistors during exercise, (Smith et al. 2009). A previous validation study demonstrated a mean accuracy of 0.09°C when compared with a thermometer in a water bath and a variability of 0.05°C when comparing all 30 iButtons with one another (Lichtenbelt et al. 2006).

2.2.5 Heat Storage

Calculating T_{ms} also allows for HS to be calculated, using T_{ms} and core temperature (Havenith et al. 1995). Calculating HS allows for a greater understanding of how much heat is being stored in the body whilst performing work in high T_{amb}, which can theoretically increase without a defined upper bound (Tikuisis et al. 2002). Too much heat being stored in the body is dangerous, and can quickly result in heat illness. In an ideal scenario, heat from the body can be transferred from core to skin and then ambient environment, therefore facilitating heat loss. However, in UHS, T_{sk} can match and exceed core, disrupting core > skin thermal gradients and trapping heat inside the body. Once this occurs, heat loss is severely restricted while HS is increased, rapidly increasing core body temperature (as shown in Figure 3). During trials, it's important to monitor a potential skin-to-core crossover

point, as after this crossover there is a high risk of heat illness as individuals will begin to heat up more rapidly. Therefore, in the current study, T_{re}, measured via a rectal thermistor (see section 3.8.3), and chest skin temperature (T_{Ch}), was measured via an equivital vest (see section 3.6.1) which were monitored live throughout the trials for safety reasons.

Unfortunately, there are issues associated with calculating HS. The HS calculation works off a fixed ratio of core body temperature (see 3.8.4). At rest, core body temperature is deep inside the body, however as the core body temperature heats up during UHS, a larger volume of the body represents core temperature. Therefore, using fixed ratios from start to finish is fundamentally flawed as the partition of core and periphery is dynamic. The HS calculation assumes a 0.8 ratio for core and 0.2 for skin, however, this is more likely to be accurate in later stages of exercise, rather than the beginning. Therefore a dynamic equation would prove to be more representative. The HS calculation aims to quantify the effectiveness of the core > skin gradient at dissipating heat. However, the method of obtaining core temperature poses another issue. Core temperature differs based on where you take it from (see section 2.2.2), therefore HS data will differ depending on the method of obtaining core temperature. For example, aural temperature would be an inappropriate and likely inaccurate measure of HS due to the location of the temperature measurement.

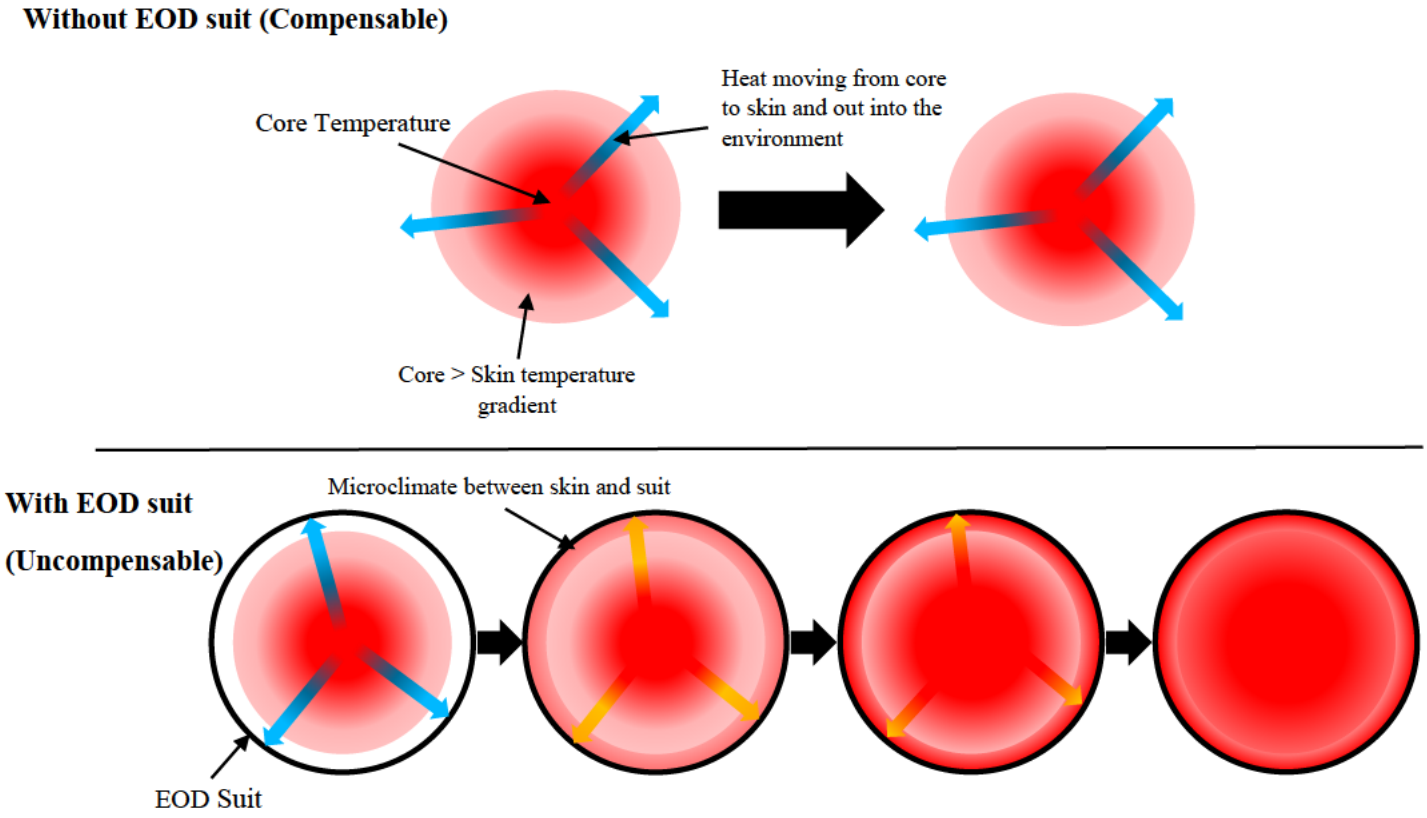

Figure 3. Evolution of the core body temperature to skin surface gradient in compensable compared to uncompensable heat stress.

Figure 3 shows the process of the core > skin > ambient environment gradient in compensable and uncompensable heat stress situations. In a compensable heat stress environment, heat builds up in the core and moves towards the skin as T_{sk} is lower than core. It is then dissipated into the surrounding environment (via sweat) and therefore removes the heat from the body. In a UHS environment, the encapsulating and impermeable PPE (in this case an EOD suit) blocks the heat from dissipating into the environment. This causes a build-up of heat between skin and suit (a microclimate) and as a result, T_{sk} begins to rise. Without anywhere for the heat to escape to, this process will continue until skin crosses core temperature, removing the skin > core temperature gradient and leaving nowhere for heat being produced in the core to escape to. This results in core temperature rising rapidly and causing potentially serious health issues previously discussed (section 2.1).

2.2.6 Respiratory analysis

Due to the mass of the clothing, restriction in movement and altered gait mechanics caused by many PPE (Duggan 1988; Qu and Yeo 2011), the metabolic cost of wearing and moving in PPE is greater. Previous research investigating metabolic cost associated with working in 12 different protective clothing designs (weighing up to 7 kg) found metabolic cost increased by 12-21% when compared to the control condition whilst walking at 5 $km \cdot hr^{-1}$, with the two heaviest garments, which were both standard firefighting ensembles, causing metabolic rate to rise 15.7% and 14.5% respectively (Dorman and Havenith 2008). In fire-fighting PPE, which weighed 19.9 kg, metabolic cost was 47% greater when compared with the controlled condition (no PPE) at a 4.8 $km \cdot hr^{-1}$ treadmill walk (Taylor et al. 2012). Interestingly, a comparison between army nuclear, chemical and biological (NCB) clothing and army upper body protective armour (UBPA), both of which were of similar weight (5.27 kg and 5.32 kg respectively), found a 7.3% rise in metabolic rate in the UBPA and a 12.4% rise in NCB when compared against no PPE (Dorman and Havenith 2008). These suits differed in their overall encapsulation, with NCB covering the whole body while the protective armour did not. The increased skin coverage in the NCB and decreased movement ability due to the full encapsulation is a likely reason for the greater metabolic cost, showing load is not the only variable contributing to increased work.

EOD suits can weigh up to 40 kg, making them highly cumbersome. This is reflected in the metabolic strain of walking in an EOD suit, as demonstrated by Bach et al. (2016) who found metabolic rate rose 49%, 65% and 78% when compared with control whilst walking at 2.5, 4.0 and 5.5 $km \cdot hr^{-1}$ respectively. These increases were demonstrated at 24°C 67% RH, whilst the current study is operating at a temperature of 40°C. This will likely result in a higher metabolic rate during exercise, as metabolism rises with increases in T_{amb} due to higher oxygen consumption, as shown in previous research, where an increased metabolic rate in high T_{amb} (>30°C), when compared with lower T_{amb} (<30°C), was found without any PPE (Sawka et al. 1993). Therefore, higher metabolic strain whilst wearing an EOD suit in high T_{amb} is likely due to added thermal strain (Costello et al. 2015), increased load and restricted movement (Duggan 1988; Qu and Yeo 2011). However, these studies have all used

indirect calorimetry to calculate metabolic rate. While this is a common practice and is being used in the current study, it is still an estimation via pulmonary gas exchange and is not the gold standard. In order to assess true metabolic rate, CO_2 output would be required to calculate an R-value, which would then reveal carbohydrate and fat uptake from the different amounts of Kcal per litre of oxygen.

2.2.7 Hydration

Hydration has been shown to play an important part in UHS and exercise tolerance time as dehydration has been shown to increase core temperature and HR during exercise (Casa et al. 2010). Whilst wearing nuclear, biological, and chemical (NBC) protective clothing in 40°C, 30% RH, a 2.5% decrease in body mass due to hypohydration resulted in significantly reduced TT on a treadmill during low (3.5 $km \cdot hr^{-1}$, 0% incline) and high exercise intensities (4.8 $km \cdot hr^{-1}$, 4% incline) by 14 mins and 7 mins respectively (Cheung and McLellan 1998a). Similar TT differences were found by Mclellan et al. (1999), who demonstrated an 11-min TT difference between dehydrated (47 mins) and euhydrated (59 mins) in hot ambient conditions (35°C 50 % RH) whilst wearing NBC protective clothing. This is likely due to 1) a reduction in plasma volume 2) a linear increase in core temperature and HR responses as dehydration increases 3) a decreased sweating rate with increased severity of hypohydration (Sawka et al. 1985). Due to the clear effect hydration status has on an individual's performance during heat trials, it is important to control for or at least be aware of hydration levels before each trial. In the current study, urine osmolality will be tested to assess any potential difference in trials based on hydration levels.

2.3 Perceptual Strain

Perceptual strain during heat studies is determined by the individual's perception of their thermoregulatory status and/or work output, e.g. how hot/cold they feel or how hard they feel they're working. The most widely used scales for assessing thermal strain during heat studies include TS, which relates to how hot or cold an individual is feeling, and TC, which relates to how comfortable an individual is (Young et al. 1987; Epstein and Moran 2006). TS is a 7-point scale that ranges from -3 (cold) to +3 (hot), while TC also ranges from -3 to +3, but is described as very comfortable (-3) to very uncomfortable (+3). RPE is also widely used in heat studies to obtain perceptual exertion in high

temperatures (Borg 1970). RPE is a 16-point scale starting at 6 (no exertion) and finishing at 20 (maximal exertion). These scales can be found in the appendix (section 7).

Previous research in EOD-related studies have found participants felt high levels of muscular activation in upper back muscles whilst performing object manipulation tasks, performed in the kneeling position (Wu et al. 2021). This perceptual feedback highlights thermal-related feedback is not the only consideration when assessing EOD-related studies in high ambient temperatures.

2.3.1 Perceptual Strain Index

As well as PhSI, Tikuisis et al. (2002) also developed a perceptual strain index (PeSI) (see section 3.8.9, Equation 7) which was designed to run alongside PhSI. This was developed to assess whether physiological and perceptual indices are interchangeable for predicting physiological strain, which would allow assessment of physiological strain without the use of expensive and intrusive equipment. PeSI is also categorised from no strain (0) to high strain (10) and utilized TS and RPE responses which were asked to individuals during trials. Previous research has identified a high correlation between TS and core temperature during outdoor exercise in the heat (Casa et al. 2007) and also RPE and HR whilst wearing an EOD suit and CPC (Borg et al. 2015). However, more recent research has challenged the correlation between TS and core temperature, demonstrating weak relationships between core temperature and TS r = 0.28 to 0.72 (Borg et al. 2015; Gallagher et al. 2011; Ganio et al. 2009) when compared with RPE and HR r = 0.81 to 0.92 (Borg et al. 2015; Gallagher et al. 2011; Alberton et al. 2011). This led Borg et al. (2017) to attempt to improve the accuracy of PeSI when compared with PhSI by adding TC into the PeSI calculation, to determine whether it improved the ability of PeSI to predict PSI. However, this had no significant effect on improving the accuracy of PeSI when compared to PhSI. However, it is important to note these responses are situation-specific and may not apply to all circumstances.

When comparing the two scales (PhSI and PeSI) to accurately predict physiological strain, Tikuisis et al. (2002)'s observed a disparity between untrained and trained groups, defined by whether subjects exercised at least 3 days a week aerobic activities e.g. running & cycling and had a $\dot{V}O_{2max}$ in excess of 60 and 55 $mL \cdot min^{-1} \cdot kg^{-1}$ for men and women respectively. Participants were required to walk on a

treadmill at 3.5 km·h^{-1} in 40°C. PeSI had a strong correlation with untrained individuals, however, it was a poor indicator in the trained group. It was found that PeSI was consistently reported lower in trained individuals than PhSI, due to them consistently underestimating their perceptual strain, whilst untrained individual's perception of strain was correlated with HR and core temperature (Tikuisis et al. 2002). Trained individuals, such as those in the army or athletes, are likely to be highly motivated individuals who are used to pushing themselves to their limits, which is likely why they underestimate their perceptual strain. This highlights the risk of solely using perceptual-based predictors of physiological strain in trained individuals as consistent underestimation could lead to a continuation of exercise in high T_{amb} despite meeting or exceeding upper limits of HR and core temperature, increasing the likelihood of heat-related illness.

2.3.2 Region-specific thermal perceptions

Previous research has shown all body regions are more sensitive to cold than too hot temperatures (Stevens and Choo 1998). Thermal sensitivity is not uniform across the body (Nakamura et al. 2008; Cotter and Taylor 2005), with the face being identified as the most sensitive to thermal changes (Stevens and Choo 1998; Nakamura et al. 2008), demonstrating up to 2-5 times more heat-sensitive than the torso, forearm, thigh, leg and foot when assessing sudomotor responses (Cotter and Taylor 2005). The LCS used in the current study covers the whole body (except the face) including a hood for head cooling. However, the suit does not provide face cooling, which is instead provided by the helmet in the form of air cooling. Air cooling is an effective cooling method for a variety of PPE (Chan et al. 2015). However, it is designed to use ambient air, which at high T_{amb} (such as 40°C) is unlikely to provide significant cooling due to conduction and convection warming of the body and restrictive evaporative cooling from high T_{amb}.

The torso has been identified as a key area of local cooling to improve TC (Yang et al. 2019). Torso cooling has been shown to significantly improve overall TS and comfort in hot environments, with the upper back proving to have the most benefit, followed by lower back, abdominal cooling and chest cooling providing the least benefit at 28°C, 30°C and 32°C (Yang et al. 2019). However, this was performed without exercise, so while it does provide information on thermal-sensitive areas, it is a

poor indicator of cooling ability during exercise. Previous research involving exercise compared localised upper vs lower body cooling (Young et al. 1987). Cooling arms during upper body exercise provided no thermoregulatory benefit, whilst cooling the thighs during lower body exercise did provide improved TC. Another study compared head and torso cooling vs neck and torso cooling, finding head and torso was more effective at improving overall TC (Cohen et al. 1989). This is likely due to increased thermosensitivity of the head when compared with the neck (Nunneley and Maldonado 1983). When comparing head with torso cooling, Brown (2012) found torso cooling was the most beneficial at improving physiological, perceptual and cognitive responses at 20°C, while both head and torso were effective at 40°C when compared to control. Due to the full-body nature of the LCS used in this study, water-based cooling will be applied to the majority of thermal-sensitive regions, except for the face which will be ambient air cooling.

2.4 Cooling Strategies in UHS Environments Whilst Wearing PPE

To reduce the likelihood and/or severity of thermal strain whilst working in heat with PPE, cooling strategies have been proposed and extensively tested. These include clothing modifications (Thake et al. 2009b; Dorman and Havenith 2008), cooling-specific equipment and clothing such as phase change vests, cooling suits worn underneath PPE (Davey et al. 2020; Kim et al. 2011a) and also non-cooling specific strategies such as heat acclimation (Thake et al. 2009a), which aims to acclimate individuals to higher temperatures, rather than applying any specific cooling. Each method aims to reduce thermal strain by either acclimatising individuals to heat prior to testing, reducing weight and/or encapsulation to decrease metabolic heat production and/or enable environmental heat transfer or providing cooling to individuals directly.

2.4.1 Phase change material

PCM is designed to absorb and store heat produced by the body and is commonly used in the field due to its easy-to-use and lightweight design (Chan et al. 2015). Findings from applying PCM garments are varied. Carter et al. (2007) used a PCM vest underneath fire-fighter clothing at 28°C T_{amb} and found no differences between core temperature, T_{sk}, HR or sweat rate when compared with no cooling, concluding they would not recommend its use. More recently, Bach et al. (2019) compared

four separate cooling methods with no cooling, which included 1) Ice vest 2) Phase-change vest (PCV) 3) Water-perfused suit 4) Combination ice slurry/ice vest. They found PCV resulted in lower HR, T_{ms}, core temperature and improved work times when compared to control whilst in 35°C wearing chemical/biological protective clothing. In another recent study (Maley et al. 2020), four cooling protocols: 1) an ice-based cooling vest stored in a -18°C freezer (IBCV) 2) a non-ice-based cooling vest (covering the torso) with a melting point of 14°C 3) ice slushy consumed before work, combined with ice vest (IS&IV) and 4) a portable battery-operated water-perfused suit (WPS) were tested during a 120 min treadmill walk at 4.5 $km \cdot hr^{-1}$ in 35°C whilst wearing a chemical, biological, radiological and nuclear (CBRN) suit weighing 15 kg. Exercise tolerance time was extended in all cooling strategies (IBCV 48 mins; PCV 46 mins; IS&IV 56 mins; WPS 62 mins) when compared to control (39 mins) however, the PCV was the only strategy which did not reduce cardiovascular strain and increased tolerance time by the least amount when compared with other cooling methods (Maley et al. 2020).

A major issue with PCM is when PCM temperature matches skin surface. This results in no extra cooling for the individual, but the individual continues to bear the extra weight and movement restriction which accompanies phase change equipment, effectively giving the individual more insulation (Ying et al. 2004; Davey et al. 2020). This limits PCM effectiveness in long durations or high T_{amb} and will assist the rise in physiological strain in high temperatures (Reinertsen et al. 2008; Maley et al. 2020). To tackle this issue, Davey et al. (2020) conducted 3 trials at 40°C whilst participants wore an EOD suit. Participants were required to complete a series of tasks with a 10-minute rest period on completion of 3 cycles. The conditions included no PCM, one PCM cooling vest or the PCM cooling vest being replaced in the 10 min rest period. Results indicated replacing the PCM better attenuates the rise in physiological strain when compared with one PCM. Researchers concluded that not replacing the PCM once it has exhausted its cooling ability can increase the level of heat strain experienced and T_{sk} could potentially equal or exceed levels of wearing no PCM (Davey et al. 2020), due to the increased insulation provided by the vest.

2.4.2 Liquid-cooled suit

LCS have been around since the 1950s and were initially designed to alleviate heat stress in aerospace environments (Nunneley 1970). A LCS consists of clothing lined with tubes that pump cool liquid throughout the suit using a pump. LCS are most commonly made from cotton, however, after testing for thermal resistance, evaporative resistance and water distribution, on 18 different fabrics, it was found a LGS made of 80% polyester and 20% spandex was the most advantageous fabric for the inner layer of an LCS, as it fits desired characteristics for the suit, such as good thermal conductivity, tactile properties and moisture management, which help improve cooling and improve comfort (Cao et al. 2006). The performance of a LCS is determined by six variables, including the ambient environment, individual subject, suit design, associated clothing and equipment, specific system characteristics and cooling control (Nunneley 1970). Due to different manufacturers and environment-specific designs, LCS often differ in their material, the temperature of coolant, locations of tubing and flow rate. As such, the testing of multiple LCS are necessary to validate the effectiveness of different/new LCSs.

Accordingly, benefits of wearing new designs of LCS should be validated under conditions which are at least representative of work-based scenarios. Bartkowiak et al. (2017) presented a new LCS design, consisting of a tube system distributing cooling liquid, a sensor measuring the microclimate between skin and suit and a battery-powered cooling unit designed to control the temperature of the cooling liquid based upon feedback from the microclimate sensor. At 30°C 40% RH with no PPE, participants performed a variety of walking and standing conditions with and without cooling turned on. Results demonstrated a decreased temperature of around 2°C in the skin to suit microclimate during cooling trials, with humidity decreasing by up to 7% (Bartkowiak et al. 2017). The decrease in microclimate temperature and humidity resulted in a lower T_{ms} and more favourable TC in cooling trials, demonstrating the physiological and perceptual effectiveness of the LCS.

LCS users benefit from their ease of use and compatibility with other protective clothing, however, they often come with downsides. For example, suits are often expensive and have to be specially designed for the job or task (Sarkar and Kotharia 2014). There are also some safety issues, such as water leaks, which have the potential to affect electrics, as well as causing discomfort to users due to

wet clothes (Sarkar and Kotharia 2014). Furthermore, the LCS adds another layer of clothing to the individual, which further limits heat transfer by evaporative sweating, especially if the LCS is full body. However, despite the negatives, LCSs have shown to be one of the most effective methods of cooling when tested in a variety of occupational settings (Chan et al. 2015), including firefighters (Kim et al. 2011) and those working in hazmat suits (Semeniuk et al. 2005).

Liquid coolant temperature within the suit plays an integral part in the cooling capabilities of an LCS. Currently, no optimum widely accepted temperature exists. Inlet liquid temperature is initially determined by reservoir temperature. The decay of warming of the system (the rate at which the cooling capacity of the system is depreciated) depends on suit design, researchers choice, T_{amb} and individual metabolic heat generation. Previous studies have controlled water temperature throughout trials using exerted water circulators, choosing 18°C (Kim et al. 2011a) and 21°C (Cadarette et al. 2006) during 35°C and 30°C respectively. In the current study, water temperature is not controlled and will be provided/determined by a cooling bottle filled with half-frozen water and half room temp water, which is attached to the EOD suit.

Previous research whilst wearing a LCS in occupational settings has demonstrated a reduced rate of rise in core temperature, decrease T_{ms} and HR and reduce perceptual measures such as TS and TC in high T_{amb} (>30°C) whilst exercising and wearing impermeable protective clothing (Tolizawa et al. 2020; Kim et al. 2011b; Kim et al. 2011a; Semeniuk et al. 2005). LCS has also been shown to significantly improve recovery during short rest periods and increases TT during exercise (Kim et al. 2011a). All these studies applied continuous cooling to the individual whilst exercising. Interestingly, researchers compared intermittent cooling (IC) and constant cooling (CC) against non-cooling and found IC provided a similar benefit to core and T_{sk} than CC whilst walking on a treadmill at 4.8 $km \cdot hr^{-1}$ in chemical protective clothing (Cadarette et al. 2006). Core temperature in the non-cooling trial rose by 1.6±0.2°C whilst it only rose 0.5±0.2°C with IC and 0.5±0.3°C with CC. Similar was found with T_{sk}, with a T_{ms} of 36.1 ± 0.4°C in the non-cooling trial, 33.7±0.6°C during IC and 32.6±0.6°C during CC. The researchers concluded IC provides favourable skin to LCG gradient for

heat dissipation comparable to CC (Cadarette et al. 2006) and therefore reduces heat strain to a similar extent to CC.

2.4.3 Summary/rationale for the current study

The use of LCS whilst wearing PPE in high T_{amb} has been demonstrated to be an effective cooling strategy in occupational settings. New LCSs need to be validated to establish their cooling capabilities in specific PPE, occupation and environment for which they have been designed. This thesis evaluates the physiological and perceptual benefits of wearing a specific LCS under an EOD suit (United shield international) during hot (40°C) conditions. Furthermore, the cooling capability of the LCS will be quantified. No other cooling methods or strategies were used in the current study to assess the cooling suit's ability independent of other variables.

3 Methodology

3.1 Participants

This study was approved by Coventry University Ethics Committee. Fourteen moderately trained (see inclusion criteria below), non-heat acclimated males volunteered to take part in this study (age, 31±5 years old; height, 180±7 cm; body mass, 88±11 kg). Participants were almost all Coventry University staff and students, with one recruit from outside the university. Volunteers were screened before acceptance to meet the following inclusion criteria 1) Have performed arduous physical activity at least twice a week for two or more years 2) Have no history of cardiovascular, respiratory, nervous, renal, liver, skeletal/muscular or metabolic disease; no immunosuppression with HIV or forms of medication; no recent allergic reactions or illness 3) Individual must be non-heat acclimated (have not visited a hot climate in at least two months prior to participation). Once accepted, participants were required to fill in a Physical Activity Readiness Questionnaire (PAR-Q) and a Health Screen Questionnaire (HSQ).

3.2 Study Design

Participants visited the laboratory for a familiarisation session followed by two experimental trials, applied using a balanced cross-over design. Trials were undertaken at least one week apart at the same time of day. During both laboratory visits, participants donned an EOD suit + LCS composed of both a body and head cooling circuit. An active cooling (AC) trial was conducted with the LCS actively cooling the participant whilst the no cooling (NC) trial was conducted with the LCS inactive. Both trials were conducted at a T_{amb} of 40°C and RH of 30% to replicate ambient conditions experienced in the middle east, where EOD operations have been conducted frequently over recent decades. The exercise duration was 60mins, which is representative of an average EOD wear time. A treadmill speed of 4 $km \cdot hr^{-1}$ was chosen based on an operative walking 200 metres in 3 mins to the site of an explosive threat and as used in previous studies (Stewart et al. 2014; Costello et al. 2015). The metabolic challenge at this intensity is representative of metabolic rate found in EOD operations.

However, the focus of the study was to have reproducible heat production to facilitate comparison between conditions.

3.3 Pilot Tests

In order to be confident that the metabolic cost of treadmill walking was consistent between conditions, it was desirable to indirectly measure metabolic rate via respiratory gas exchange. However, since accurate respiratory gas exchange measurements are difficult to achieve when a person is wearing a helmet due to the potential for back pressure affecting the volume sensor and the potential for rebreathing expired gas from the space within the helmet pilot work was conducted to accommodate a breath by breath gas turbine and the associated gas sampling-line (Cortex 3b; see section 3.8.5) within the helmet a mouthpiece was chosen instead of a face mask. Furthermore, disposable gas turbines were purchased, as these are smaller than standard equipment, in an attempt to optimise the clearance distance between the turbine and the inner surface of the visor. Initial pilot testing yielded variable data. Walking was conducted whilst wearing the helmet visor in a ‘down’ position (replicating a threatening situation) compared to when the visor was lifted ‘up’ exposing the face and removing any external barrier to respiratory flow (Figure 5&6). It was concluded the visor was indeed causing significant variation in data. Whereby a section of the visor was removed to enable free flow of inspired and expired gas between the participant and ambient environment (via the respiratory measurement apparatus and mouthpiece). Once received, visor up/down tests were repeated (Figures 7&8). From comparing data from two tests (Figure 5&6 vs 7&8), it was clear the variability was reduced and the issue had been resolved.

Figure 4. Original visor and the modified visor.

The first pilot test (Figures 5&6) was performed over 40 mins split into four 10 min stages comprising of visor down, visor up, visor down again and visor up again. Each stage had a 1minute interval in-between where the participant straddled the outside of the treadmill so the investigator could re-arrange the helmet set up. Shown below are three stages of the test, showing both visor down conditions and a single visor up condition.

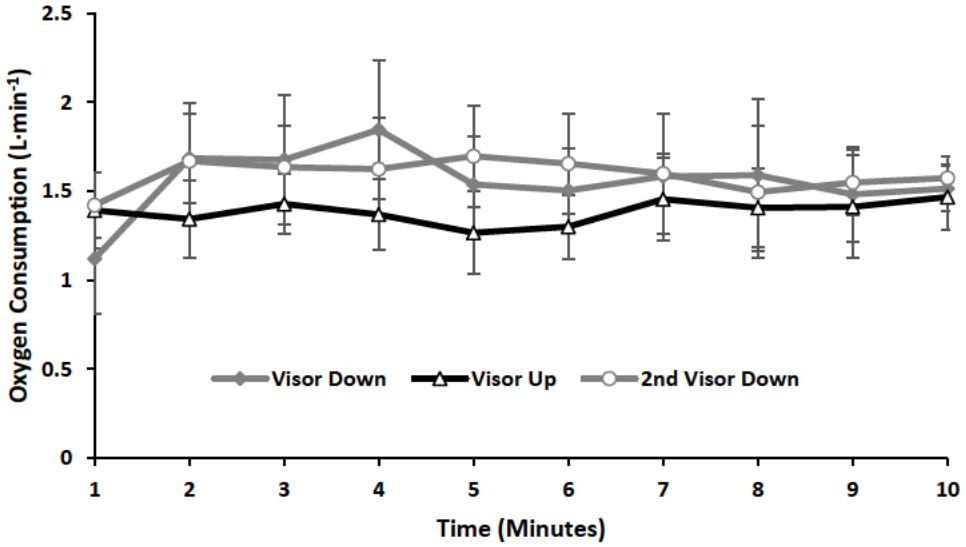

Figure 5. Oxygen Consumption during pilot testing with the original visor (n=1).

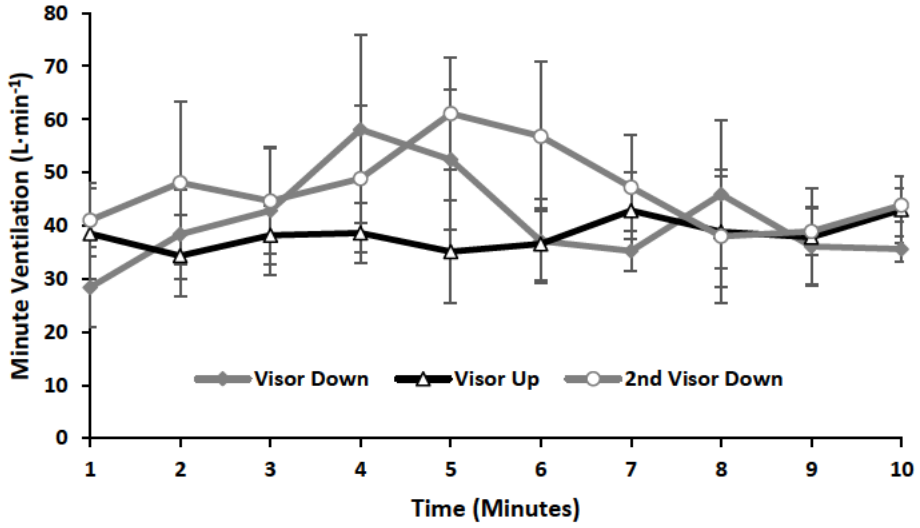

Figure 6. Minute Ventilation during pilot testing with the original visor (n=1).

The second pilot test (Figures 7&8) was performed over 20 mins split into four 5 min stages comprising of visor up, visor down, visor up again and visor down again. As with the previous test, each stage had a 1minute interval in-between where the participant straddled the outside of the treadmill for the investigator to re-arrange the helmet set up.

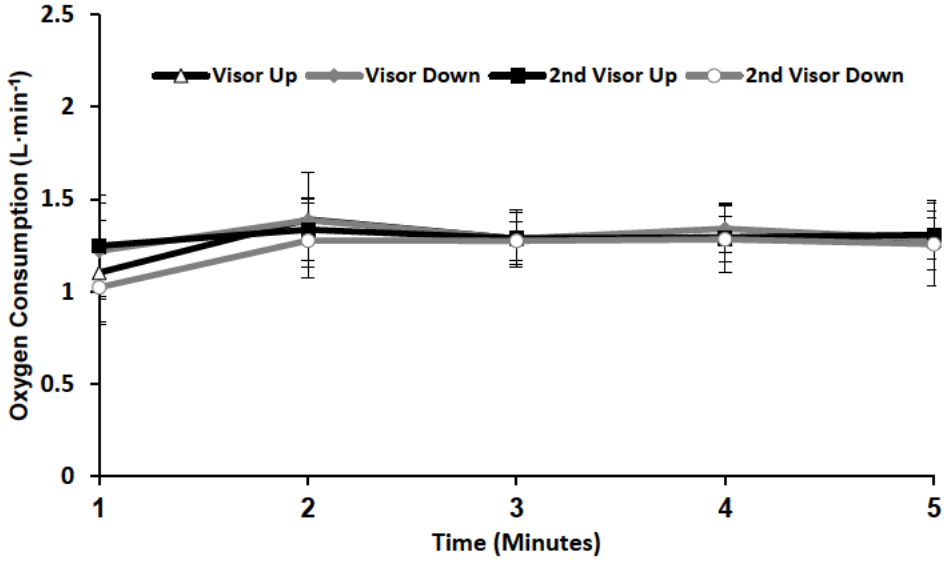

Figure 7. Oxygen consumption during pilot testing with the modified visor (n=1).

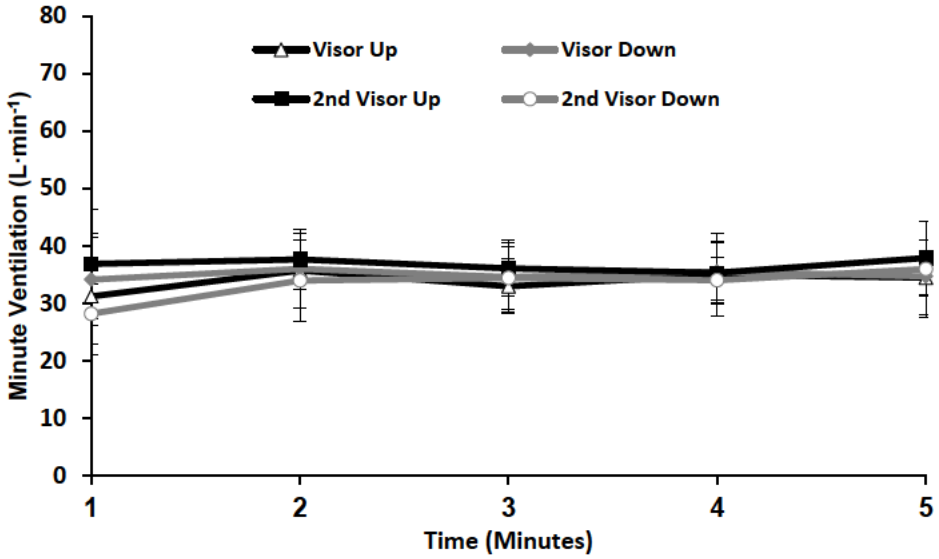

Figure 8. Minute Ventilation during pilot testing with the modified visor (n=1)

3.4 Familiarisation

A familiarisation session was performed prior to experimental trials taking place. Participants arrived at the laboratory and were informed of what the trial would involve. This included an introduction to the Tanita measurement system (Tanita BC-418 Segmental Body Composition Analyzer, Tanita, Tokyo, Japan), where participants would be weighing themselves before and after trials. Participants were then introduced to the perceptual scales used in the trials and were informed of their meaning. Fat mass was taken via Skinfold measurements (Harpend Skinfold Caliper, Baty International & Co., West Sussex, UK) (see 3.8.2) and height was obtained via a Stadiometer (SECA 217, SECA Instruments, Ltd, Hamburg, Germany). Once finished, participants were fitted with T_{sk} sensors (3.8.3), equivital vest (3.8.6) and then donned the required clothing, including the base clothing layer, LCS and the EOD suit. Once inside the chamber, a respiratory mouthpiece (3.8.5) was inserted and participants were then required to walk for 20 mins on a treadmill at 4 $km \cdot hr^{-1}$ in 40°C 30%RH. Participants were required to feedback TS, TC, SW, discomfort, RPE and general symptoms information every 10 mins whilst on the treadmill. Once completed, the suit was removed inside the

chamber and participants were taken back into the prep room and informed of the ingestible core pill procedure (3.7.1) and dates and times were arranged for pick up.

3.5 Experimental Trials

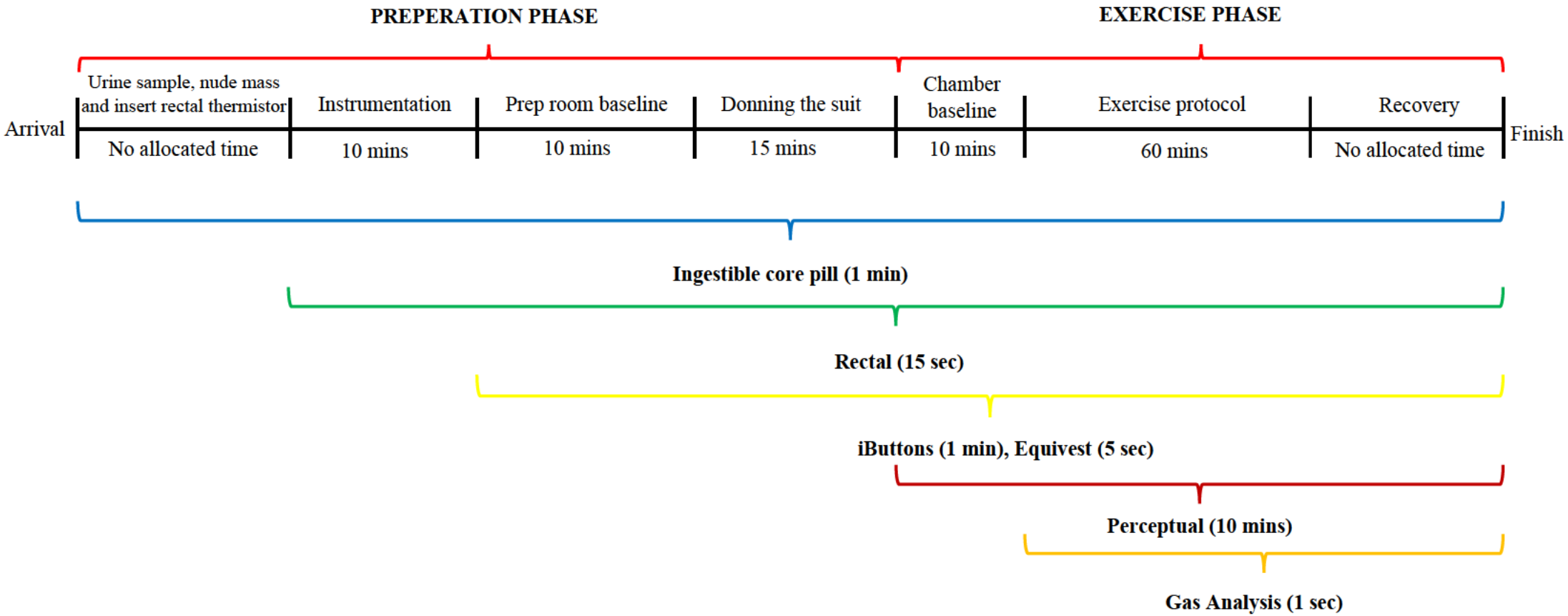

Figure 9. Schematic diagram of the experimental trial timeline.

Black lines represent the timeline and the cut-offs for specific sections of that timeline. Red lines represent the cut-off points for each phase of the trial. Below the timeline are 5 coloured lines. The length of the coloured lines represents the time at which the specific equipment or device was synchronised (ingestible core pill), inserted (rectal thermistor), attached (iButtons and Equivest), recorded manually (perceptual data) or began recording data (gas analysis). Coloured lines are labelled with the equipment/device with the recording frequency in brackets next to it.

3.6 Trial instrumentation

Figure 9 gives an overview of the trial. Trials were separated into two stages: a preparation phase and an exercise phase. The preparation phase included initial tasks given to the participant such as urine sample, body mass and inserting the rectal thermistor. This was followed by instrumentation of equipment, baseline data collection and donning of the suit. The exercise phase began on entry into the chamber and included chamber baseline data, the 60 min treadmill walk and the recovery time post-exercise. Each task in the trial has been labelled with the time it took to complete.

3.6.1 Preparation

At least 24 hours prior to the start of a trial, the cooling bottle was filled with exactly 1 L of tap water and a measuring jug was filled with 500 mL of tap water. Two iButtons (ibutton, type DS1921H; Maxim/Dallas Semiconductor Corp., California, USA) were activated and were placed (sensor up) in both the cooling bottle and measuring jug to track the temperature of the water within the cooling bottle and once the two are merged during the trial. The cooling bottle was placed into a -20°C freezer and left for at least 24 hours before trial. The measuring jug was left in the prep room for at least 24 hours before the trial began in order for it to reach room temperature (20-21°C).

Due to the coronavirus pandemic participants were required to complete a COVID-19 screening tool alongside a health screen questionnaire online prior to visiting campus. Once reviewed the participant was contacted to confirm their attendance and were sent a participant information sheet, as well as a COVID-19 mitigation document outlining COVID-19 related, policies which they needed to adhere to throughout their time at the university. Before each visit to the laboratory, each participant was contacted to enquire about any new onset of COVID-19 symptoms (dry cough, breathlessness, fever, migraine) to reduce the chances of turning away participants on arrival. Participants were also reminded to take the ingestible core pill 2-3 hours before arrival at the lab. On arrival at the university, participants were met outside the building and directed through to the lab, following all COVID-19-related policies.

On arrival at the laboratory, confirmation of swallowing the BodyCap e-Celsius Core Body Temperature Ingestible Capsule (Body Cap, Caen, France) at least three hours prior to the visit was

sought and core temperature was monitored via the e-Viewer Performance Monitor (Body Cap, Caen, France). Participants were then shown to the nearest toilet and instructed to collect a mid-stream urine sample using a collection pot, which was analysed using a Pocket Palosmo (Alago Vitech Scientific, West Sussex, UK) Once completed, participants returned from the bathroom and were given a list of tasks to do to perform in the prep room whilst the researchers left. This included recording their nude body mass, body composition and body water content on a Tanita measurement system and then body mass again on separate scales (SECA 875, SECA Instruments, Ltd, Hamburg, Germany). Participants were also instructed to insert a rectal thermistor (Soft Insertion Probe, Eltek Data Loggers, Cambridge, United Kingdom), 10cm past the anal sphincter which was then plugged into an Eltek GenII transmitter GD32 (Eltek Ltd, Cambridge UK), which was monitored on the computer via a Squirrel 1000 Series, RX250AL Reciever Logger (Eltek Ltd, Cambridge UK). Once completed the researcher entered the prep room and an Equivital vest (Equivital EQ-02EX, Hidalgo Ltd, Cambridge, UK) was placed on the participant. Six temperature sensors (iButtons) were taped to the participant (Figure 10) on the right mid-front thigh, right lower lateral calf, right pectoral, head, right upper arm and right upper back (Figure 18). The same iButtons were used on the same anatomical location throughout the trial for each participant, identified by small engravings on the iButton indicating an anatomical location (process shown in Figure 11). Once completed, participants were instructed to don the provided undergarments and were guided/supported in doing so where appropriate.

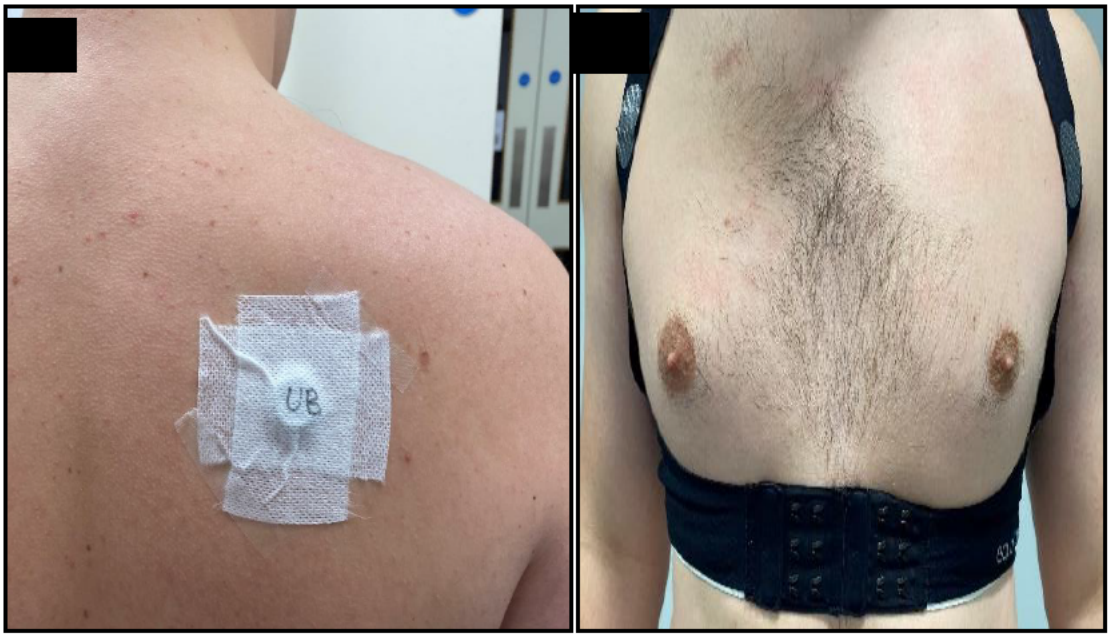

Figure 10. Sample images of positioning and fixing of iButtons (A) and Equivest (B).

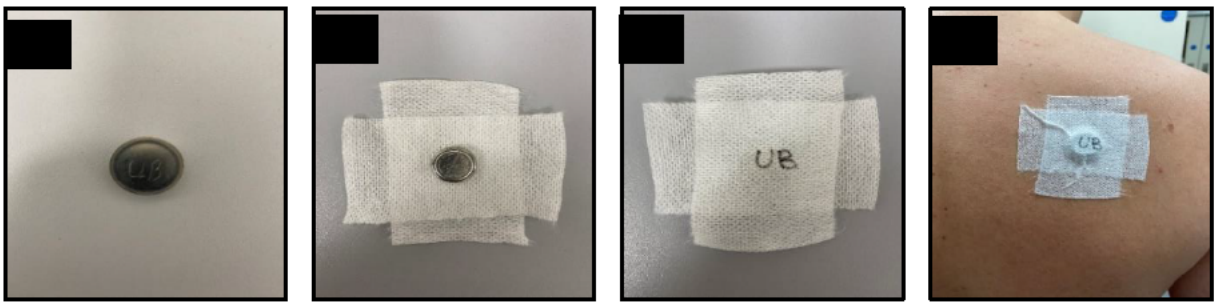

Figure 11. The 4 step process of preparing and citing iButtons to the desired location.

3.7 Clothing and PPE

Participants wore a base layer of clothing provided at the laboratory of a cotton t-shirt (100% cotton t-shirt, Fruit of the Loom) fatigue trousers (100% cotton fatigue bottoms, Feuchter Passau), socks (85.3% cotton, 13.2% polyamide and 1.5% spandex socks, Yuedge), and leather, steel toe safety boots, which were worn throughout each trial (Figure 13a). The LCS (Holdfast Systems, Germistons, South Africa) was then worn over the clothing base layer (Figure 13b). The LCS was fitted with temperature thermistors which were inserted into inlet and outlet tubes via a t-tube (Figure 12). This

allowed inlet and outlet temperatures to be measured throughout trials. Once the participant had donned the LCS, the EOD suit (Hawker Excel, United Shield International, Andover, UK) was then donned in the following order: groin protector, trousers, boots, jacket, gloves, chest plate, cooling pack, helmet and safety harness (Figure 13c to j). This was aided by the research team and performed within a fixed 15 min time frame. However, if it became clear from the familiarisation and first experimental trial that suit donning would take longer than 15 mins, an extended time was set with the duration specific to the individual participant and matched between trials.

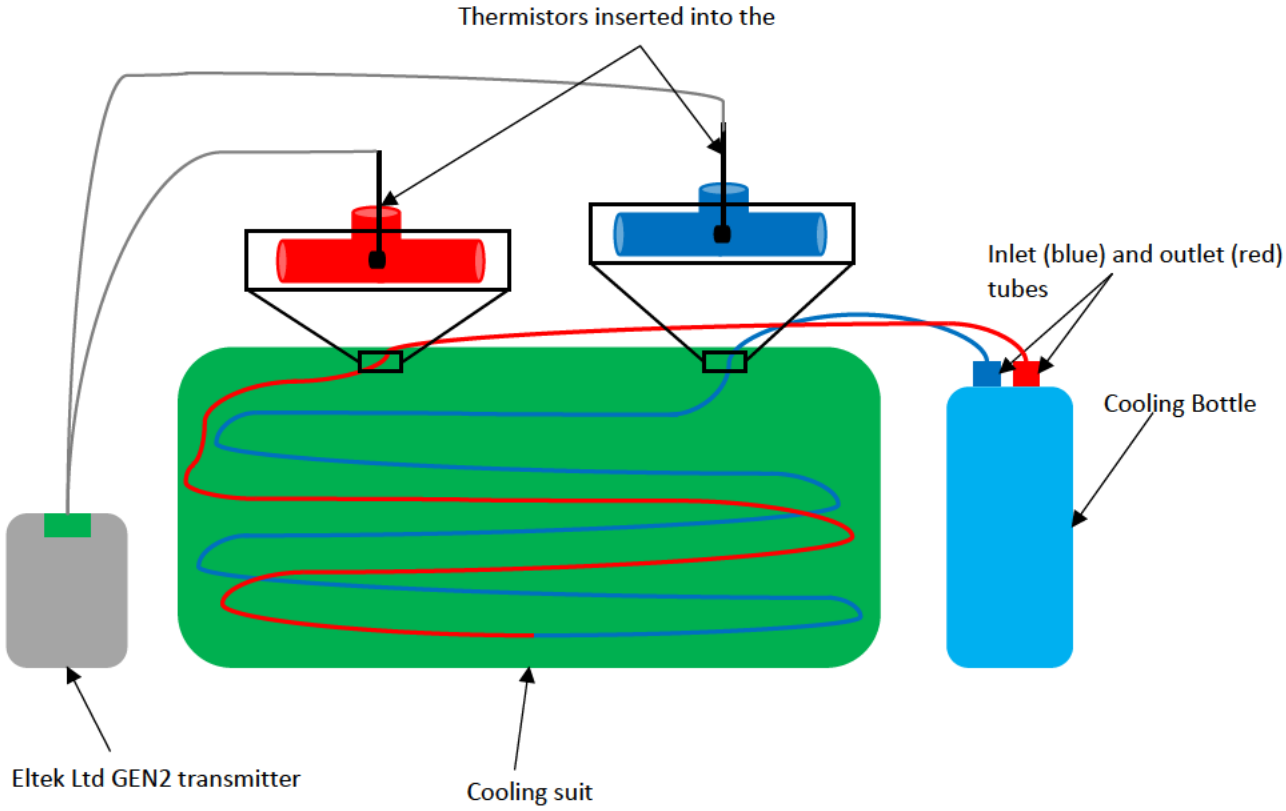

Figure 12. A diagram demonstrating how inlet (blue) and outlet (red) cooling temperatures were monitored throughout the trials.

Figure 13. Stages of the equipment donning process. Order of donning goes from undergarments (A), liquid-cooled suit (B) to full EOD suit (C to J).

3.7.1 Baseline measures

Participants were required to sit and rest for 10 mins in the provided undergarments at a T_{amb} of approximately 20.8±0.48°C in NC and 20.8±0.47°C during AC while baseline measures were taken. HR, T_{sk}, breathing rate (BR), T_{re} and T_{GI} measurements were recorded at 5 min intervals.

3.7.2 Environmental Chamber

Once the suit was donned participants entered the chamber observation room. On the next minute, a timer was started and participants were brought into the side chamber for 1 minute before entering the environmental chamber (Sporting Edge, Basingstoke, UK) which was set at 40°C 30% RH. A Kestrel 5400 (Nielsen-Kellerman, Boothwyn, USA) was in the chamber to measure chamber temperature throughout the trials. Once in the chamber, baseline perceptual measures were taken between mins 1-4. While the perceptual were being taken, the assistant researcher collected the frozen cooling bottle from the freezer and poured the 500mL of room temperature water into the bottle. At 5 mins, the cooling bottle was brought into the chamber and attached to the cooling system (Figure 16). At 6 mins, participants were helped onto the treadmill (Woodway ProXL, Woodway Inc, Birmingham, UK) and the metalyzer mouthpiece was inserted (Figure 14; section 3.8.5) and the participant's safety harness was hooked up to the treadmill. Once the metalyzer (Metalyzer 3B-R3, Cortex Biophysik, Leipzig, Germany, using Metasoft Studio version 5.14.00, Cortex Biophysik, Leipzig, Germany software) was started, participants were required to straddle the treadmill so it could be turned on to 4 $km \cdot hr^{-1}$. At exactly 9 mins (1 minute before the start of exercise), the helmet air cooling and LCS cooling pump control dials (cooling pump only in AC trials) were set at a level commonly recommended to be applied by the manufacturer (Figure 15). At exactly 10 mins after entering the chamber, participants were instructed to begin walking on the treadmill.

Figure 14. A participant with the mouthpiece inserted.

Figure 15. Dial markers for helmet fan (left) and cooling suit (right) turned to the cooling point used for each trial.

Figure 16. Cooling bottle and pump attachments within the circuit of the LCS.

Once either 60 mins of exercise has been completed or participants reach HR or core temperature safety cut-off points, trials were stopped. Once stopped, the respiratory mouthpiece was removed, the safety harness was unhooked and participants were required to step off the treadmill and onto weighing scales to record post-EOD suit body mass. As this was taking place, the temperature in the chamber was dropped to 30°C. Once participants had their weight recorded, the suit was removed from the participants whilst still in the chamber whilst core temperature was monitored to ensure it had dropped below 38.5°C before they were escorted from the chamber, which took around 10-30 mins. Once core temperature was at safe levels, participants were brought back into the prep room. Temperature sensors and physiological monitors were then removed. Participants were left to remove the rectal thermistor and repeat the nude bodyweight measurements. Once completed, a time was arranged to give the next ingestible core pill and participants were informed that the trial had ended.

3.8 Measurements and calculations

Data was collected at a variety of different time points due to differences in equipment settings. Once data was collected, it was time synced to appropriate time points of interest.

3.8.1 Mean sweat rate

Mean sweat rate was estimated using nude body mass pretrial, nude body mass post-trial and trial duration, shown in Equation 2.

Equation 2. Mean sweat rate calculation

$$Mean\ Sweat\ Rate\ (L \cdot hr - 1\ ) = (Change\ in\ mass \div Trial\ Duration)\ x\ 60$$

3.8.2 Body fat percentage

Body fat percentage was calculated from skinfold measurements taken from 4 sites: Biceps - vertical fold, Triceps - vertical fold, Subscapular - diagonal fold and the Suprailiac - diagonal fold. Each skinfold measurement was taken three times in a rotational order with a 1-2 seconds wait whilst maintaining a pinch before reading the calliper.

Body fat percentage was calculated by first calculating body density (Durnin and Womersley 1974), and then using the Siri (1961) equation to calculate body fat percentage (shown in Equation 3). The body density equation differs slightly based on an individual's age.

Equation 3. Body fat percentage calculation

$$\%\ Body\ Fat = (495 / Body\ Density) - 450$$

(Siri 1961)

3.8.3 Temperature measurements

Prep room and chamber temperature (ºC) and RH (%) were measured using a Kestrel 5400FW fire weather meter pro WBGT with Link compass and vane mount. These were monitored throughout trials and 5 min averages were calculated and time synced to match the trial timeframe.

T_{re} was measured using a rectal thermistor inserted 10cm past the anal sphincter (shown in Figure 17). Each thermistor was beaded to ensure it would not come out during trials (shown in Figure 17). The Eltek Ltd GEN2 transmitter was attached to the participant and temperature was transmitted to the 1000 Series Squirrel Meter. The Eltek was set up to log every 15 seconds during trials.

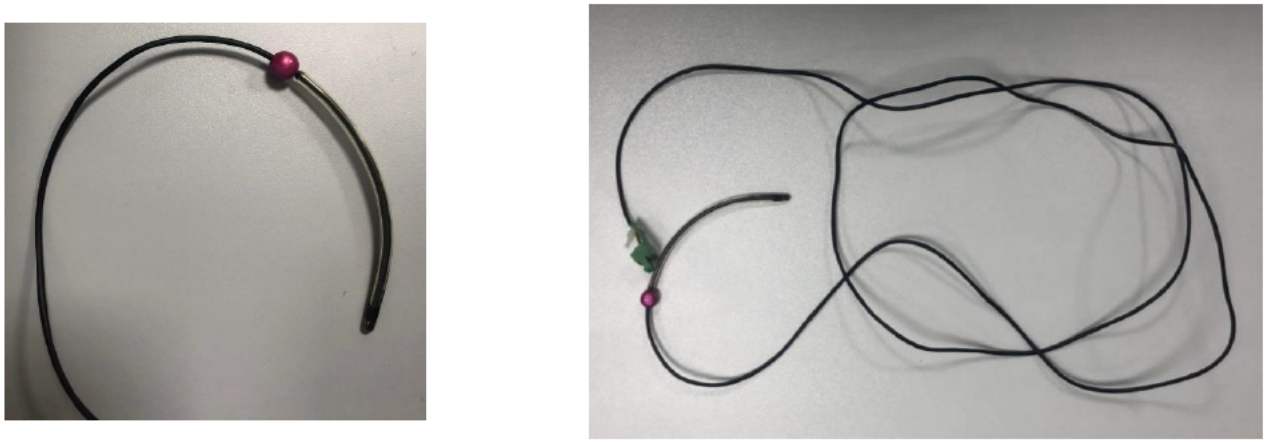

Figure 17. Beaded rectal thermistor.

T_{GI} was measured via a Bodycap core temperature ingestible pill.

T_{sk} was measured using iButtons in six locations. iButtons were set up to record temperature measurements every 60 seconds. T_{Ch} was also obtained and tracked throughout trials using the Equivital. Locations of iButtons and the Equivest are shown in Figure 18.

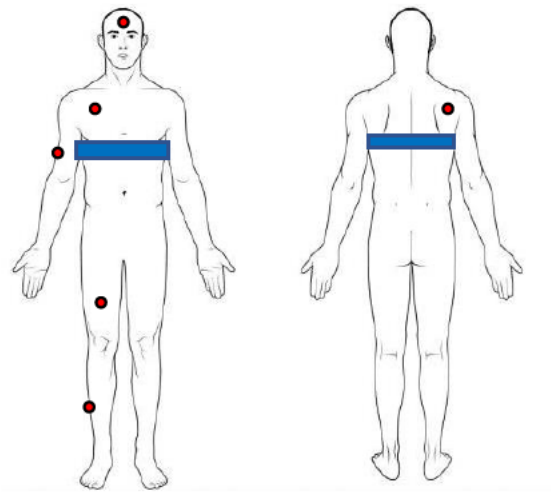

Figure 18. Front and back body map depicting sensor attachment locations. Red dots represents an iButton and long blue rectangles show placement of the Equivest (T_{Ch}).

3.8.4 Mean skin temp and heat storage calculations

T_{ms} was calculated via T_{sk}, obtain by iButtons in locations specified in 3.7.1, using Ramanathan (1964)'s equation, highlighted below:

Equation 4. Mean skin temperature calculation

$$Mean\ Skin\ Temperature\ (ºC)\ =\ 0.30\ (Chest\ +\ Arm)\ +\ 0.20\ (Thigh\ +\ Calf)$$

(Ramanathan 1964)

HS was calculated via mean skin temp and core temp, using the following equation by Havenith et al. (1995):

Equation 5. Heat storage calculation

$$Heat\ Storage\ (J \cdot g - 1)\ =\ [(0.8\ \times\ \Delta\ TcP)\ +\ (0.2\ \times\ \Delta\ Tsk,)]\ \times\ CB$$

(Havenith et al. 1995)

$\Delta\ TcP$ = Core temperature. $\Delta\ Tsk$ = Skin temperature. CB denotes specific heat capacity of the body

(3.49 J·g^{-1})

3.8.5 Respiratory measurements

Respiratory gas analysis was conducted via a Cortex Metalyzer 3B using Cortex disposable turbines. Outside ambient air was collected daily and used to calibrate the metalyzer alongside the gas canister according to manufacturer guidelines. Due to using disposable mouthpieces, the amount of dead space was set (in the software) at 20mL throughout trials. Data was reported breath by breath and second by second. Data was time synced to appropriate time markers and then last-minute averages were calculated every 5 mins based on second-by-second data. Measures included $\dot{V}O_2$ (L·min^{-1}), Carbon Dioxide Output (L·min^{-1}), Minute Ventilation (L·min^{-1}), Respiratory Exchange Ratio (RER), Tidal volume (L), Breathing frequency (Vf·min^{-1}), Energy expenditure (kcal·h), Fat Energy expenditure (kcal·h) and Carbohydrate Energy expenditure (kcal·h).

3.8.6 Cardiovascular measurements

HR and breathing frequency were obtained using an Equivital vest. HR was tracked throughout trials for data collection and also for participant safety. Last-minute averages were obtained every 5 mins.

3.8.7 Physiological strain index calculations

Physiological strain was calculated using HR and core temp in two different calculations, shown in equations 6&7. The difference between the two calculations is how HR is derived (PSI: 180 – HR0; PhSI: HR_{max} - 60). Both calculations are used to assess which is a more appropriate calculation to use to accurately assess physiological strain in hot environments.

Equation 6. PSI calculation

$$PSI = 5[(TCt* - TC0*) \div (39.5 - TC0*)] + 5[(HRt - HR0) \div (180 - HR0)]$$

(Moran et al. 1998)

Equation 7. PhSI calculation

$$PhSI = 5[(TCt* - TC0*) \div (39.5 - TC0*)] + 5[(HRt - 60) \div (HRmax - 60)]$$

(Tikuisis et al. 2002)

t denotes values at a given time point. 0 denotes baseline value. max denotes the maximum HR value seen from all trials. *substitute with T_{GI} or T_{re}

3.8.8 Perceptual measurements

Three thermal-related perceptual measurements were taken, along with discomfort, RPE and general symptoms (GS). All perceptual measurements were taken every 10 mins and took around 3 mins to complete. Because of this, measurements began 3 mins before the 10 min period ended. TS, comfort and skin wetness were sought for defined body areas, which included head, face, shoulders and chest, arms, back, groin legs and feet. Discomfort and RPE were asked in relation to the individual's whole body, upper body and lower body. Definitions for each perceptual chart were described to the participants (in the familiarisation and pre-trial if requested) in the following way 1) TS is how hot or cold the individual feels 2) TC is how comfortable the individual feels with the hot or cold sensation they previously indicated 3) Skin wetness is how wet the individual's skin feels with regard to

sweating 4) Discomfort is any discomfort or irritation the individual feels which is abnormal and likely caused by aspects specific to the trial e.g. the suit or exercise (not in relation to thermal load. 5) RPE is how physically hard the individual felt like they were working. 6) GS is a general health checklist that sort the individual to report any headaches, sickness, dizziness, confusion, tiredness and difficulty breathing.

3.8.9 Perceptual strain index calculation

Perceptual strain was calculated using TS and RPE in the following equation by Tikuisis et al. (2002):

Equation 8. PeSI calculation

$$PeSI = 5[(TSt - 7) \div 6] + 5[RPEt \div 10]$$

(Tikuisis et al. 2002)

TS and RPE denote thermal sensation and perceived exertion respectively.

t denotes values at a given time point.

3.9 Cooling capability of the suit

Cooling capacity was estimated at 5 min time intervals using two approaches; heat storage differences between AC and NC and via inlet and outlet temperatures taken from the LCS during the AC condition only. (HS and I&O in cooling only). See appendix (section 7) for a worked example.

HS was calculated using T_{GI} and body mass taken from pre-exercise in the AC trial. The calculation used to assess the cooling capability of the LCS based on HS data is shown below:

Equation 9. Cooling capability calculation based on HS data

$$Cooling\ cabability = (NCHS\ x\ 1000\ x\ BM - CHS\ x\ 1000\ x\ BM)/time(s)$$

Whereby NCHS is non-cooling heat storage and CHS is cooling heat storage. BM is the body mass of the participant.

The calculation used to assess the cooling capability of the LCS using inlet and outlet temperature data is shown below:

Equation 10. Cooling capability calculation based on inlet and outlet data.

$$Cooling\ cabability = (4.2\ x\ 335\ x\ (outlet - inlet))/37(s)$$

Whereby 4.2 represents the amount of KJ required to raise the temperature of 1 kg of water by 1°C. 335 represents the estimated circuit volume (mL) of the suit. 37 (s) refers to the time it takes for the water to go around the entire suit based on an estimated flow rate of 9 $mL \cdot s^{-1}$.

3.10 Discontinuation Criteria

Trials were terminated if a participant's HR exceeds 95% of maximum (220-age) for 1 min or if T_{GI} or T_{re} reach 39.5ºC or 3ºC greater than initial baseline temperature, whichever is lowest.

3.11 Data management

A visual process of how data was managed is shown in Figure 19. Once trials had finished, data was downloaded and saved into a secure OneDrive folder. Perceptual data was manually collected by the investigator on paper, which was digitised. Folders were appropriately named and data moved into specific folders e.g. 'EODP3' > 'Cooling' > 'Chamber data'. Once all raw data was downloaded, it was moved into a 'Time Sync' spreadsheet, where data was cut and analysed to show only 'Prep room baselines', 'Chamber baseline' and the exercise protocol. Once completed, data was moved into a 'Means & SDs' document, which calculated averages and SDs. Finally, data was moved onto a 'Master Sheet', which has all-time synced means and SDs for each time point for each participant all in one document. Once on the master sheet, overall means and SDs were calculated from all trials, which were used as the final data presented in this thesis.

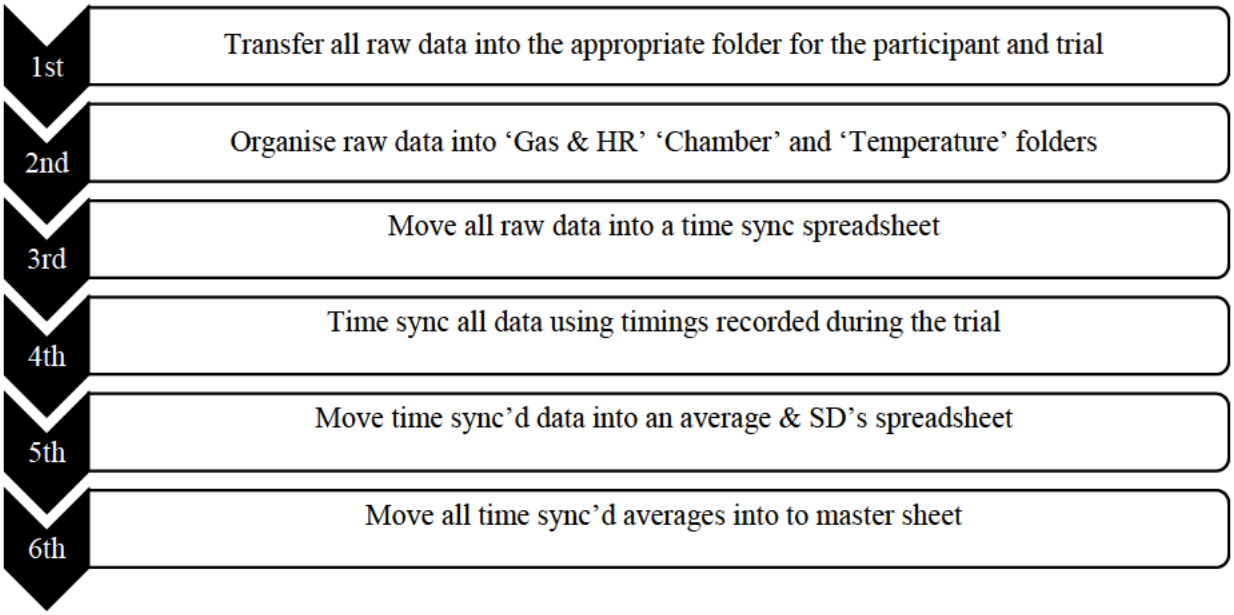

Figure 19. Step by step process of how trial data was processed.

3.12 Statistics

All variables were analysed for normal distribution using the Shapiro-Wilk test. Physiological and perceptual variables were analysed using a two-way (condition x time) repeated measures analyses of variance (ANOVA). Significance was adjusted using the Greenhouse-Geisser method if the assumption of sphericity was violated. Prep room and environmental chamber temperature and humidity and baseline measures such as urine osmolality, body mass, body fat, body water, heart rate and rectal temperature were compared between visits for each condition using a paired sample t-test. Tolerance time, end-point and change over time (Δ) data were also analysed using the paired t-test. A Pearson correlation and linear regression was also performed to assess the relationship between heat storage and body surface area. Effect size was reported with $\eta 2 = 0.01$ indicating a small effect, $\eta 2 = 0.06$ indicating a medium effect and $\eta 2 = 0.14$ indicating a large effect. Statistical analyses were performed using SPSS (Statistical Package for the Social Sciences) version 26 (SPSS Inc, Chicago, IL) with the level of significance set at $P<0.05$.

4 Results

Out of 14 participants, only 7 completed all trials (P1, P2, P4, P5, P7, P9, P13). P3 performed a familiarisation but dropped out during his first trial citing neck issues. P6 agreed on dates and then dropped out before performing any trials. P8 dropped out 3 mins into their familiarisation trial due to a substantial rise in HR and reported difficulty breathing. P10 dropped out during their familiarisation due to illness seemingly brought on by a combination of suit and chamber conditions. P11 completed their familiarisation however did not turn up for their next trials and did not reply to any further communication. P12 dropped out during his first trial as a result of reaching HR max within 10 mins. P12 performed their trials at a later date at a treadmill speed of 2.5 $km \cdot hr^{-1}$ instead of 4 $km \cdot hr^{-1}$. The results of which were not included in the main data set but are reported separately in section 4.7.

4.1 Ambient environment

Throughout experimental trials, T_{amb} and RH did not vary between conditions ($p>0.05$). Preparation room temperatures were similar between conditions with no significant difference between trials ($p>0.05$). Relative humidity was significantly different ($p<0.05$) between conditions in the preparation room, however, this is not of any biological significance. Wet bulb global temperature (WBGT) was not significantly different between trials ($p>0.05$).

Table 2. Ambient temperature (T_{amb}; ºC), relative humidity (RH; %) and wet bulb global temperature (WBGT; ºC) in the preparation room and environmental chamber in both active cooling (AC) and no cooling (NC) conditions. Reported values are mean±SD of values recorded every 5 minutes up to the end of each individual's trial (maximum 45mins) using a kestrel. * represents a significant difference between conditions.

	Condition	Temperature (ºC)	Relative humidity (%)	WBGT (ºC)
Preparation Room	**NC**	20.7±0.5	60.0±13.8*	15.8±3.3
	AC	20.8±0.5	53.5±9.2	16.1±1.7
Environmental Chamber	**NC**	40.1±0.4	22.5±1.7	28.0±0.3
	AC	40.1±0.4	21.9±0.2	27.9±0.3

*=(p=0.12)

4.2 Baseline

As expected, body mass (p=0.5), body fat percentage (p=0.1), body water percentage (p=0.8), urine osmolality (p=0.6), HR (p=0.1) and T_{re} (p=0.1) did not vary prior to exposure to each of the two conditions.

Table 3. Baseline characteristics before each condition under normothermic conditions (preparation room, n=7). Reported values are the mean±SDs of each individual taken at either the start of each trial (nude body mass, body fat percentage, body water percentage, urine osmolality) or the final minute average of 10 minutes of seated rest (Heart rate and rectal temperature). Body mass, body fat and body water values were all taken via the Tanita machine.

Condition	Body mass (kg)	Body fat (%)	Body water (%)	Urine Osmolality (mOsm·kg H^2O)	Heart Rate (b·min^{-1})	Rectal Temp (ºC)
NC	88.5±11.8	17.7±5.0	53.1±6.2	594±315	61.7±9.2	37.2±0.3
AC	88.8±11.7	18±6.2	53.2±7.0	513±279	66.9±8.0	37.1±0.4

4.3 Exercise duration

No participant completed 60 mins of exercise in either condition. 5 out of 7 participants lasted longer in their AC condition than their NC condition, one participant lasted the same amount of time in both conditions and one participant lasted longer in the NC trial. 5 out of 7 participants completed at least 30 mins in their NC trials. Only four individuals completed 40 mins, with two doing so in their AC trial only and two in both conditions. Nobody got further than 40 mins in the NC trial, with 45 mins being the longest time in the AC trial. Nobody reached 50 mins or further in either trial.

The average exercise duration in the NC trial was 32 mins (ranging from (22-40 mins), whilst the average duration in the AC trial was 37 mins (ranging from 30-45 mins). Exercise duration in the AC condition was significantly longer ($p<0.05$, $\eta p^2 = 0.828$) than in NC (Figure 20).

10 out of 14 trials were stopped by the participants (Table 4), while the remaining four were stopped by the investigator due to the individual HR safety cut-off point. No trials were ended due to T_{re} or T_{GI} temperature >39.5ºC.

Table 4. Exercise duration and termination criteria for each participant in both conditions (n=7).

Participant	Condition	Exercise duration (mins)	Termination
EODP1	**NC**	40:00	>95% HR
	AC	45:00	Participant stopped
EODP2	**NC**	40:00	Participant stopped
	AC	40:00	Participant stopped
EODP4	**NC**	26:00	Participant stopped
	AC	40:00	Participant stopped
EODP5	**NC**	32:00	Participant stopped
	AC	41:00	>95% HR
EODP7	**NC**	31:00	Participant stopped
	AC	30:00	Participant stopped
EODP9	**NC**	22:00	Participant stopped
	AC	30:00	Participant stopped
EODP13	**NC**	30:00	>95% HR
	AC	32:00	>95% HR

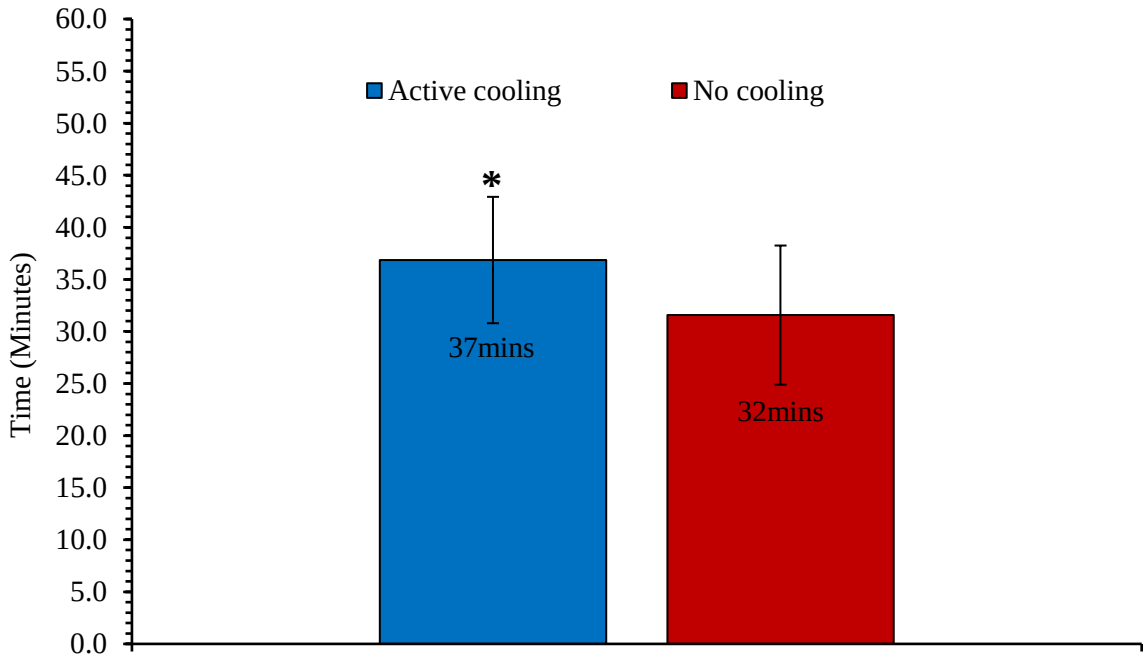

Figure 20. Treadmill walking time (4 km·hr^{-1}) with active cooling (AC) and no cooling (NC) (n=7). * represents a significant difference between conditions.

4.4 Physiological responses

4.4.1 Heart Rate

HR ($b \cdot min^{-1}$; Figure 21.) differed between trials by 5 mins of exercise. At 10 mins, HR began to rise quicker in the NC trial and continued throughout the rest of the trial. However, HR was not significantly different between trials ($F(1, 35) = 6.170$, $p = 0.861$, $\eta p^2 = 0.244$)

Four trials were stopped due to HR reaching 95% of estimated maximum (Table 4). These four trials were split between three participants, with one participant reaching HR_{max} in both his trials. Of those four trials, two were stopped during the NC trial and two during the AC trial.

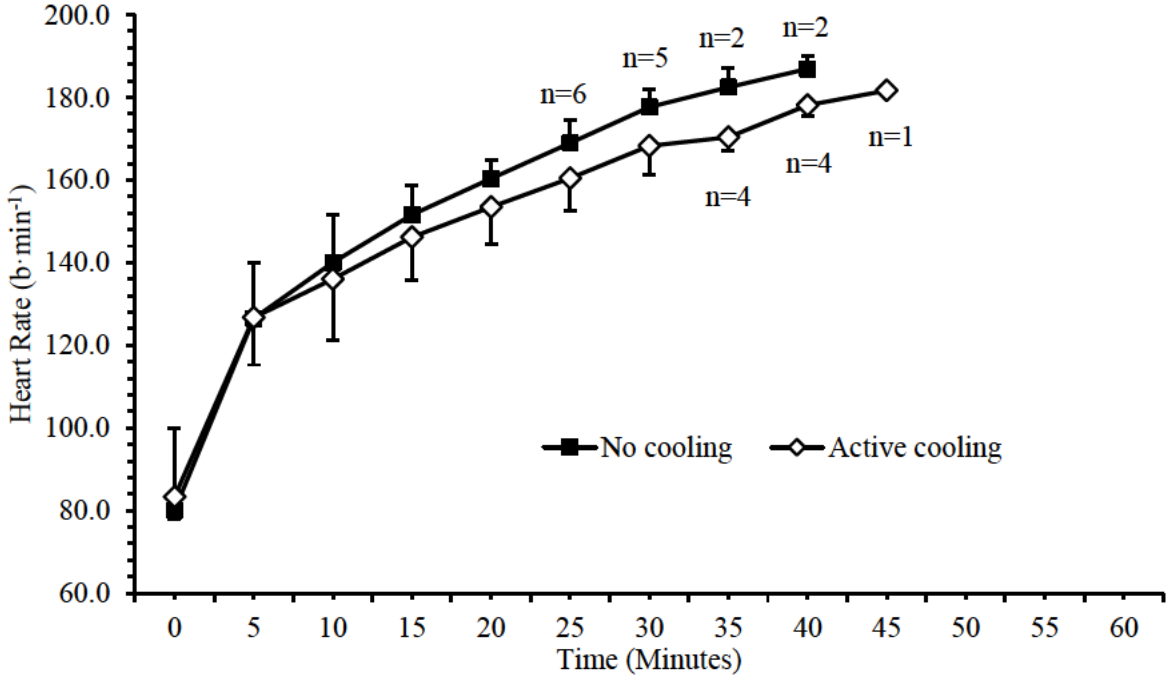

Figure 21. Heart rate (HR; $b \cdot min^{-1}$; mean±SD) responses during each condition. No significant difference between trials ($p>0.05$). n=7 unless specified in the legend. n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

4.4.2 Core and Skin Temperature

Core temperature stayed within safe limits during all trials, with the highest reported core temperature reading of 39.1ºC measured via an ingestible pill during a NC trial. Average pre-post changes in core temperature were 2.1ºC in the NC trial and 1.6ºC in the AC trial.

T_{GI} was similar between trials up to 20 mins (Figure 22). After 20 mins, T_{GI} during NC trials began to rise at a greater rate than in AC trials. Overall, T_{GI} was significantly higher in the NC conditions during exercise ($F(1, 35) = 658{,}778$, $p = 0.025$, $\eta p^2 = 0.998$).

T_{rec} followed a similar exponential increase after 20 mins, however, it was not significant between conditions ($F(1, 44) = 0.274$, $p=0.69$ $\eta p^2 = 0.215$).

T_{ms} was significantly higher throughout the NC condition when compared with the AC condition ($F(1, 35) = 513{,}534$, $p = 0.028$, $\eta p^2 = 0.998$) (Figure 22). At around 30 mins, T_{ms} (38.3±0.1 ºC) matched T_{rec} (38.3±0.3 ºC) and exceeded T_{GI} (38.1±0.2 ºC) in the NC trial (n=6), however in the AC trial, T_{ms} never matched or exceeded T_{GI} or T_{rec}. Two participants continued to 40 mins in the NC trial and saw their T_{GI} rise higher in the NC condition when compared with AC at 40 mins; (P1: NC 39.1ºC, AC 38.3ºC; P2: NC 39.0ºC, AC 38.3ºC).

In three participants, P1, P2 and P13, T_{ms} crossed over T_{GI} at 30 mins during the NC trial. No such crossover occurred in P1, P2 or P13's AC trial.

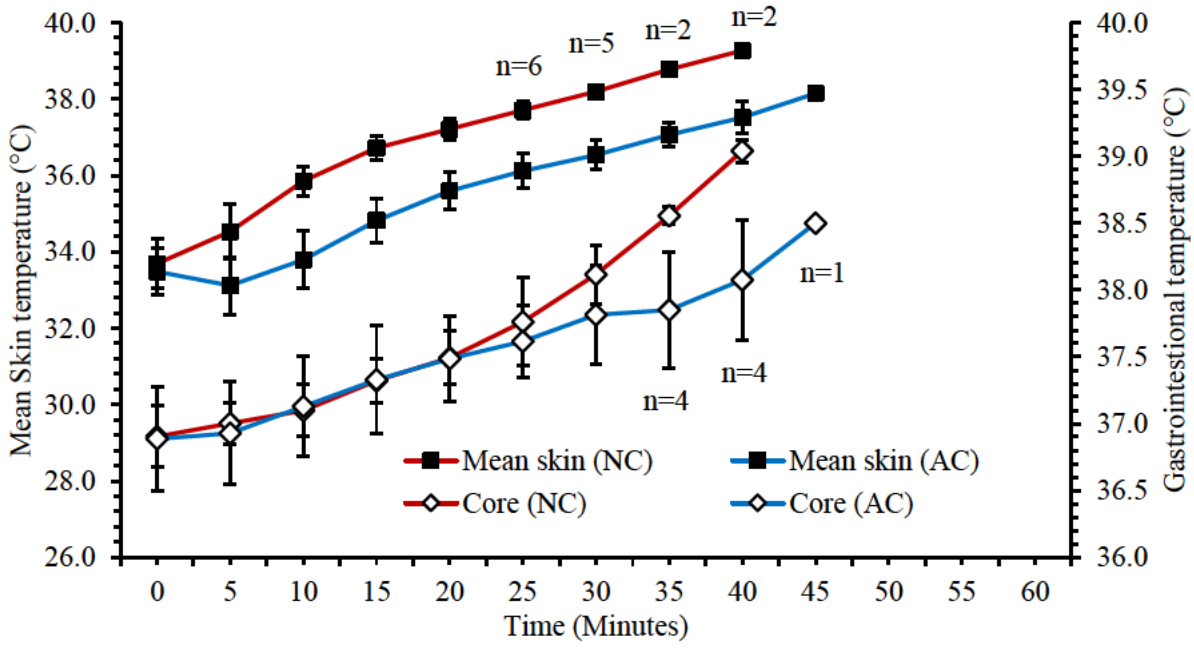

Figure 22. Gastrointestinal temperature (T_{GI}) and mean skin temperature (T_{ms}) during active cooling (AC) and no cooling (NC). Both gastrointestinal temperature ($p<0.05$) and mean skin temperature ($p<0.05$) were significantly different during exercise between conditions. n=7 unless specified in the legend whereby n values on top relate to the non-cooling (NC) trial whilst n values below relate to the active cooling (AC) trial.

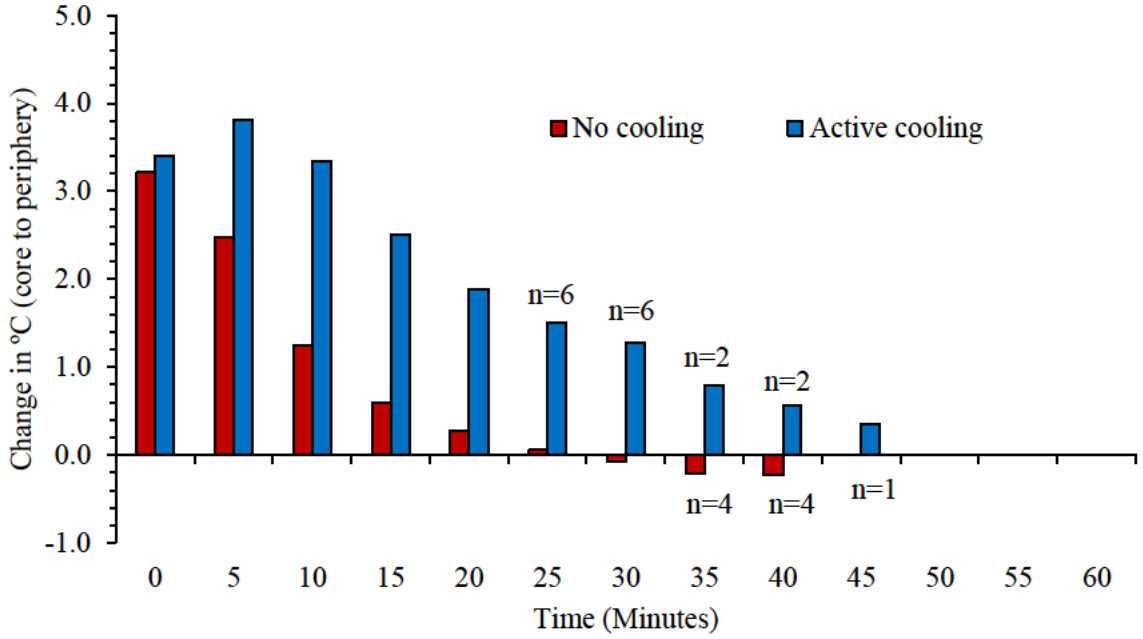

Figure 23. Core to skin gradient difference in active cooling (AC) and no cooling (NC). n values on top relate to the NC trial while the AC trial is below. n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

Average pre-post T_{GI} difference (Table 5) was 1.3±0.7 °C during the NC trial and 1.2±0.3 °C during the AC trial. Average change over time was 0.04±0.02 per minute during the NC trial and 0.03±0.01 per minute during AC.

Change in temperature (Figure 24) was inconsistent during the first 20 mins in both NC and AC. After 20 mins, an exponential rise in temperature is seen in the NC, while during AC temperature changes stay inconsistent.

Table 5. T_{GI} changes from baseline to the final minute of the individual's specific stop time and the average change over time calculated in minutes for each individual.

	Condition	Pre-post T_{GI} (°C) difference	T_{GI} (°C) change per min	Exercise duration (mins)
EODP1	**NC**	2.1	0.05	40:00
	C	1.6	0.04	45:00
EODP2	**NC**	1.9	0.05	40:00
	C	1.3	0.03	40:00
EODP4	**NC**	0.3	0.01	26:00
	C	1.2	0.03	40:00
EODP5	**NC**	MISSED	MISSED	32:00
	C	1.0	0.03	41:00
EODP7	**NC**	1.8	0.06	31:00
	C	1.5	0.05	30:00
EODP9	**NC**	0.8	0.04	22:00
	C	0.6	0.02	30:00
EODP13	**NC**	0.7	0.02	30:00
	C	1.0	0.03	32:00

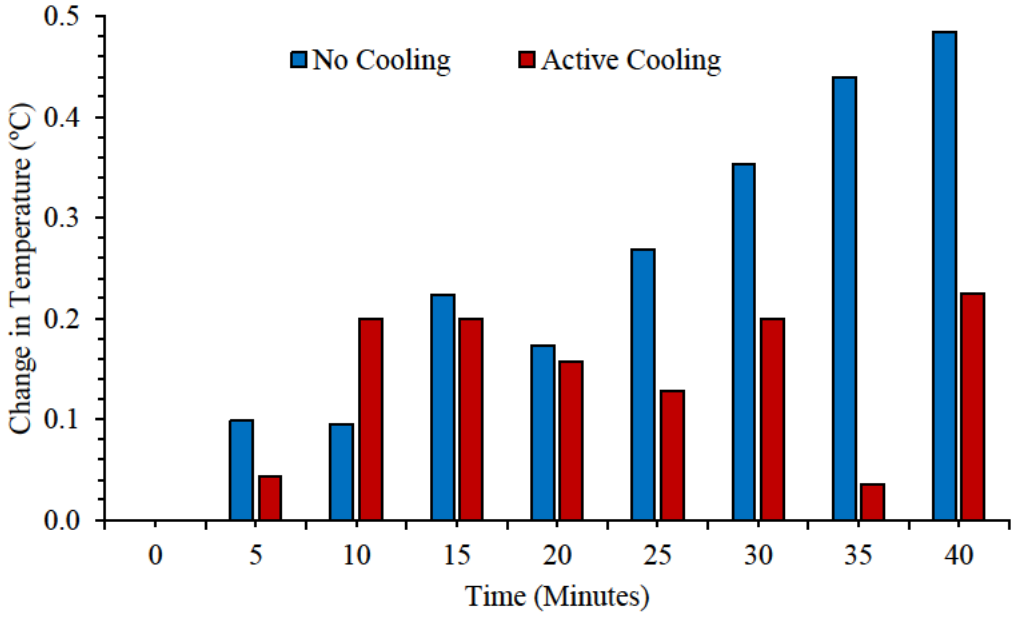

Figure 24. Change in T_{GI} (°C) (calculated by taking away the previous five mins) in no cooling (NC) and active cooling (AC) trials.

4.4.3 Heat storage

HS tended to be lower in AC when compared with NC (Figure 25), however, this was not significantly different ($F(1, 35) = 18{,}586$, $p = 0.145$, $\eta p^2 = 0.949$). At 40 mins HS during AC was 5.0±0.9 (n=4), higher than 5.7±0.4 (n=6) reported at 30 mins in the NC trial. Body surface area positively correlated with HS (R=0.76), the effect was significant (P=0.04) (Figure 26).

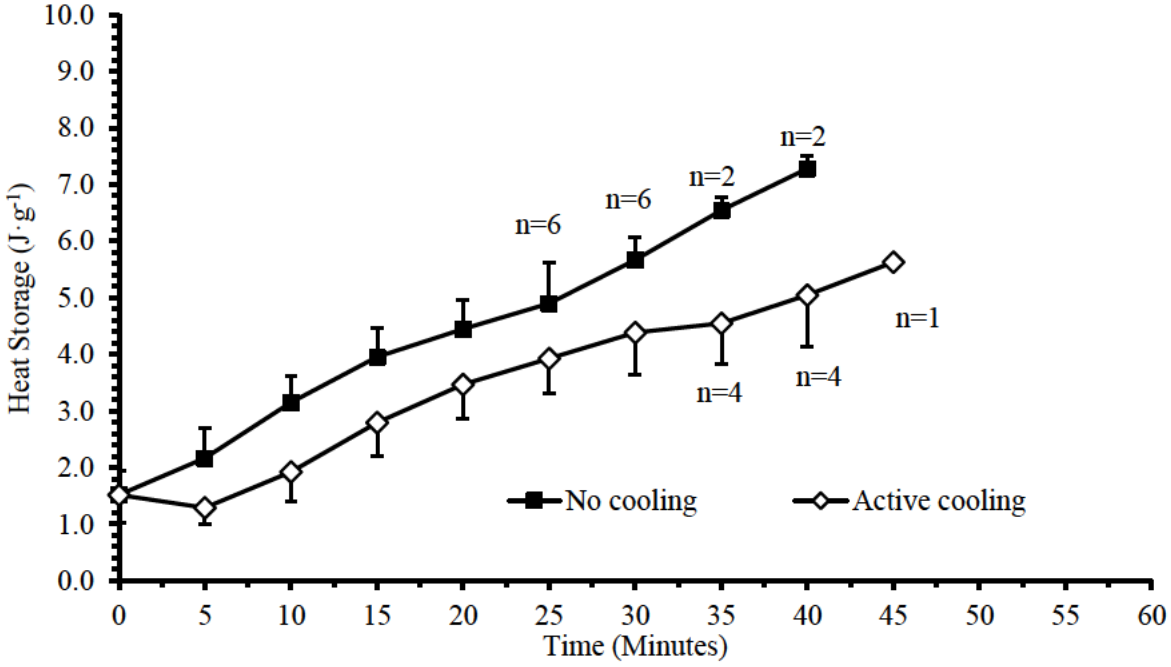

Figure 25. Heat storage (HS) with active cooling (AC) and no cooling (NC). HS was not significant between conditions ($p>0.05$). n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

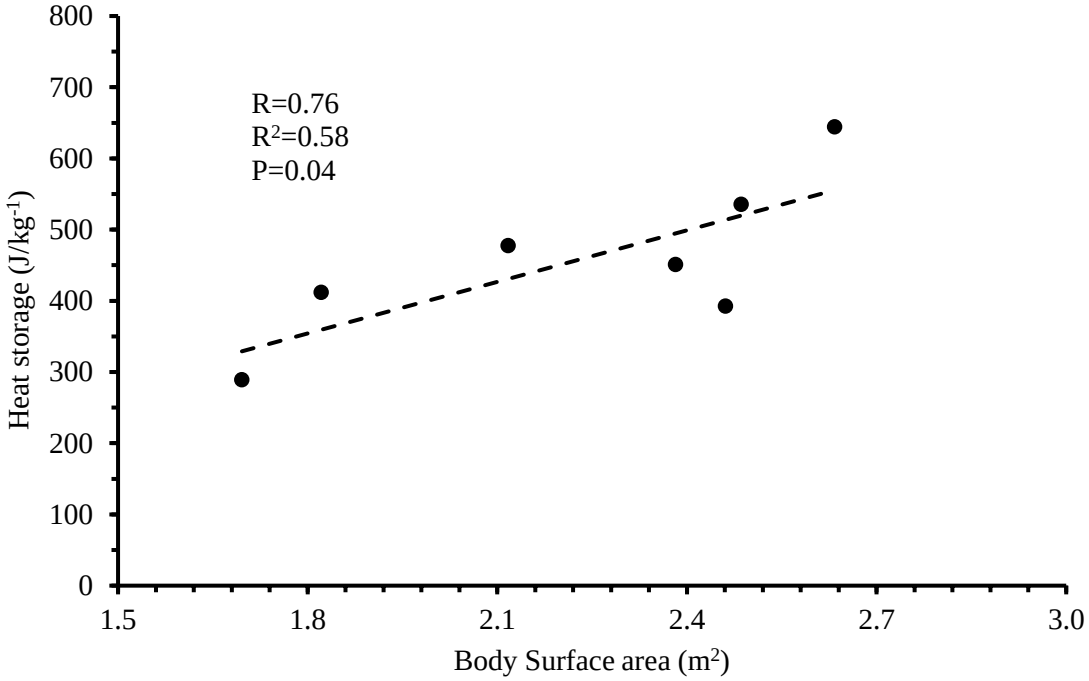

Figure 26. The relationship between body surface area (m^2) and heat storage (J/kg^{-1}).

4.4.4 Physiological strain index

PhSI during NC rose quicker than during AC, especially after 30 mins when T_{ms} crosses core. However, while there was a significant difference between conditions at 40 mins (p=0.05) (NC = 8.6±0.3; AC = 7.1±0.6), PhSI was not significantly different between conditions overall (F (1, 35) = 19.071, p = 0.143, $\eta p^2 = 0.950$)

PSI, measured in both GI and rectal locations, was consistently higher than PhSI in both conditions. Mean endpoint PSI was 7.3±1.5 via T_{re} and 7.3±2.0 via T_{GI}, whilst mean endpoint (final data collected from each participant before trials ended) PhSI T_{re} was 6.6±1.4 and 6.7±1.9 via T_{GI}.

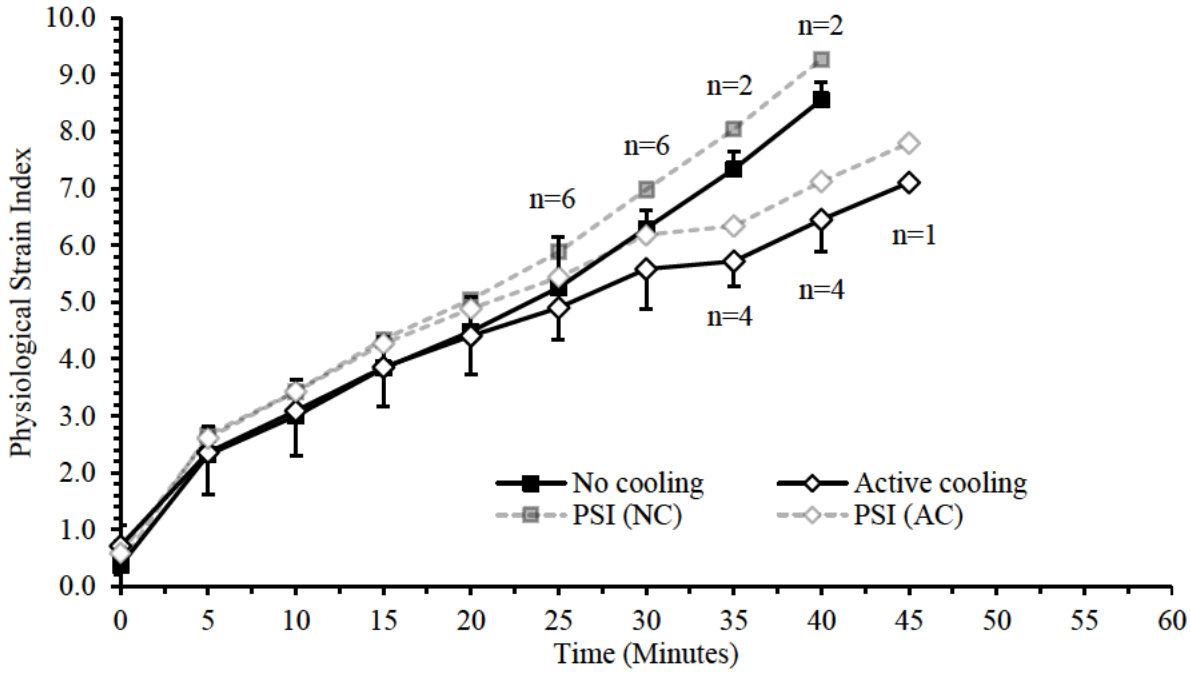

Figure 27. Physiological strain index (PhSI) with the PSI calculation in the background during active cooling (AC) and no cooling (NC). PhSI in both conditions. PhSI was not significantly different between trials ($p>0.05$). PSI is also presented in the background. n=7 unless specified in the legend. n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

4.4.5 Gas analysis

Oxygen consumption over time was not significantly different ($F(1, 20) = 0.010$, $p = 0.931$, $\eta p^2 = 0.005$). Endpoint oxygen consumption was not significantly different between trials ($p>0.05$) (NC 2.3±0.2 $L \cdot min^{-1}$); AC 2.4±0.2 $L \cdot min^{-1}$ (Table 6). However, delta values were calculated from start to finish of each trial and then compared between conditions. Oxygen consumption using delta values was significantly different between conditions ($p<0.05$), with a NC delta value of 1.7 $L \cdot min^{-1}$ and AC of 1.9 $L \cdot min^{-1}$. The highest and lowest delta value were both in the NC condition at 2.0 $L \cdot min^{-1}$, and 1.5 $L \cdot min^{-1}$, respectively.

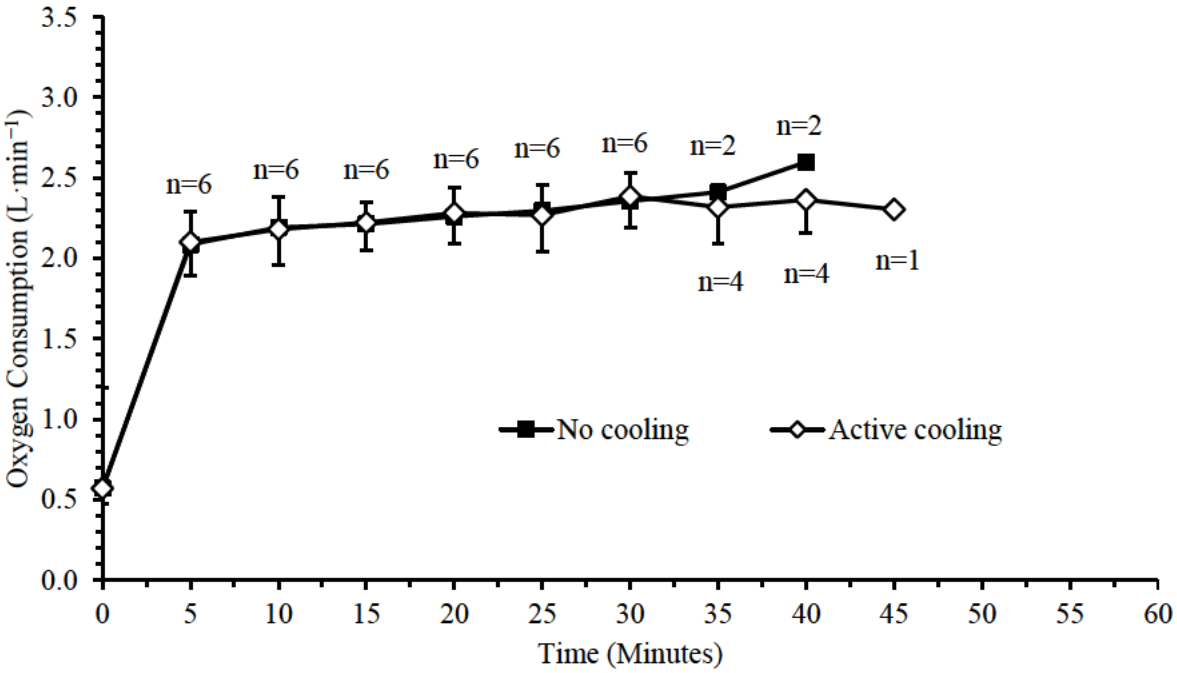

Figure 28. Oxygen consumption ($\dot{V}O_2$) in active cooling (AC) and no cooling (NC). Oxygen consumption was not significantly different between trials ($p>0.05$). n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

4.4.6 Physiological End-point Responses

Endpoint T_{re}, T_{GI}, T_{ms} and HR were similar in both conditions and not significantly different. Sweat rate was also not significantly different ($p<0.05$) between conditions (Table 6). Mean endpoint minute ventilation was higher in NC (77.2±12.7 L·min^{-1}) than AC conditions (74.4±9.9 L·min^{-1}), as was tidal volume (NC 1.5±0.4 L; AC 1.4±0.3 L) and carbohydrate energy expenditure (NC 570±83kcal·h; AC 545±123.9kcal·h). Mean endpoint relative oxygen uptake (NC 28.9±2.4 L·min^{-1}; AC 31.2±5.2 L·min^{-1}), RER (NC 0.97±0.03; AC 0.94±0.04), breathing frequency (NC 52.9±10.7·min; AC 53.8±8.8·min), energy expenditure (NC 684±73.3kcal·h; AC 715±57.3kcal·h) and fat energy expenditure (NC 51.6±24.0kcal·h; AC 104.7±76.1kcal·h) were all higher in the AC condition (Table 6), however, they were not significantly different between trials.

Changes in T_{re}, T_{GI}, HR, minute ventilation, tidal volume, breathing frequency and RER were not significantly different from baseline. However, change from baseline in T_{ms}, (NC 4.6±1.2 ºC; AC 3.8±0.8 ºC) oxygen consumption (NC 1.7±0.2 L·min^{-1}; AC 1.8±0.1 L·min^{-1}) and energy expenditure (NC 518.7±59.7kcal·h; AC 546.7±37.6kcal·h) were significantly different.

Table 6. Delta values and endpoint data of key physiological. Reported values are mean±SD's of rectal temperature (T_{re}), gastrointestinal temperature (T_{GI}), mean skin temperature (T_{ms}), heart rate (HR), sweat rate, suit sweat rate, oxygen consumption ($\dot{V}O_2$), minute ventilation ($L \cdot min^{-1}$), tidal volume (L), energy expenditure (kcal·h), breathing frequency ($Vf \cdot min^{-1}$) and respiratory exchange ratio (RER). * Represents a statistically significant difference between conditions.

Physiological variable	**No cooling (NC)**		**Active cooling (AC)**	
	Change from baseline (Δ)	**Cessation of trial**	**Change from baseline (Δ)**	**Cessation of trial**
Rectal temperature (ºC)	1.2±0.5	38.3±0.6	1.3±0.4	38.3±0.5
Gastrointestinal temperature (ºC)	1.3±0.8	38.2±0.8	1.2±0.3	38.1±0.4
Mean Skin temperature (ºC)	*****4.6±1.2	37.9±0.9	*****3.8±0.8	37.2±0.8
Heart Rate ($b \cdot min^{-1}$)	98±7.4	178±11	92±7.3	175±7
Sweat Rate ($L \cdot hr^{-1}$)	N/A	2.1±0.6	N/A	2.0±0.6
Sweat Rate Suit ($L \cdot hr^{-1}$)	N/A	0.1±0.9	N/A	0.3±0.3
Oxygen consumption ($L \cdot min^{-1}$)	*****1.7±0.2	2.3±0.2	*****1.8±0.1	2.4±0.2
Minute ventilation ($L \cdot min^{-1}$)	60.0±12.0	77.2±12.7	57.8±7.2	74.4±9.9
Tidal volume (L)	0.8±0.2	1.5±0.4	0.7±0.2	1.4±0.3
Energy expenditure (kcal·h)	*****518.7±59.7	684±73.3	*****546.7±37.6	715±57.3
Breathing frequency ($Vf \cdot min^{-1}$)	28.5±9.4	52.9±10.7	29.9±8.6	53.8±8.8
Respiratory exchange ratio (RER)	0.1±0.1	0.97±0.0	0.2±0.1	0.94±0.0

4.5 Perceptual Responses

Overall TS (Table 7a) during the trial ($F(1, 9) = 4.000$, $p = 0.295$, $\eta p^2 = 0.800$) and at the cessation of each trial ($p=0.4$) was not significantly different between conditions. On average, TS was higher at the final recorded data point in the NC trial when compared to the AC trial in the following locations:

Head, face, arms, back, legs and feet. No difference was found between conditions in the shoulders, chest, and groin at the final data log. TS was not higher in any location in the AC trial at the last recorded data points.

Overall TC (Table 7b) at the cessation of each trial was not significantly different between conditions ($p=0.17$), nor was TC during the trial ($F(1, 9) = 9.000$, $p = 0.205$, $\eta p^2 = 0.900$). During the first 20 mins of the trial, TC was significantly lower in the AC trial ($p<0.01$), however, past 30 mins there was no significant difference between conditions ($p<0.05$) (Figure 29). At the final data point collected, higher TC was reported on average in the head, shoulders, arms, legs and feet, while TC in the face was higher in the AC condition. Chest, back and groin were all similar between trials.

Skin wetness (Table 7c) was highest overall and in almost all locations in the NC condition with the exception of the groin.

Table 7. Thermal sensation (A), thermal comfort (B) and skin wetness (C) (mean±SD) at the final recorded points before the individual's trials ended in active cooling (AC) and no cooling (NC). Perceptual feedback was collected in regards to how the participant felt overall and also specific body regions, including the head, face, shoulders, chest, arms, back, groin, legs and feet.

A. Thermal sensation

	Overall	**Head**	**Face**	**Shoulders**	**Chest**	**Arms**	**Back**	**Groin**	**Legs**	**Feet**
NC	2.9±0.4	2.9±0.4	2.7±0.5	2.7±0.5	2.7±0.5	2.6±0.5	2.9±0.4	2.7±0.5	2.7±0.5	2.4±0.5
AC	2.7±0.5	2.7±0.5	2.6±0.5	2.7±0.5	2.7±0.5	2.4±0.3	2.4±0.8	2.7±0.5	2.6±0.5	2.3±0.8

B. Thermal Comfort

	Overall	**Head**	**Face**	**Shoulders**	**Chest**	**Arms**	**Back**	**Groin**	**Legs**	**Feet**
NC	2.9±0.4	2.7±0.8	2.4±0.8	2.9±0.4	2.7±0.5	2.4±0.8	2.6±0.5	2.6±0.8	2.7±0.5	2.4±0.5
AC	2.6±0.5	2.4±0.8	2.6±0.8	2.6±0.5	2.7±0.5	2.3±0.8	2.6±0.8	2.6±0.5	2.3±0.8	2.1±0.7

C. Skin Wetness

	Overall	**Head**	**Face**	**Shoulders**	**Chest**	**Arms**	**Back**	**Groin**	**Legs**	**Feet**
NC	5.1±1.2	5.0±1.3	4.9±1.2	5.0±1.3	5.1±0.9	5.0±1.3	5.0±1.0	4.9±1.5	4.9±1.1	4.1±1.6
AC	4.9±1.2	4.7±1.4	4.7±1.3	4.7±1.4	4.7±1.4	4.7±1.4	4.9±1.5	5.0±1.0	4.6±1.4	3.7±1.7

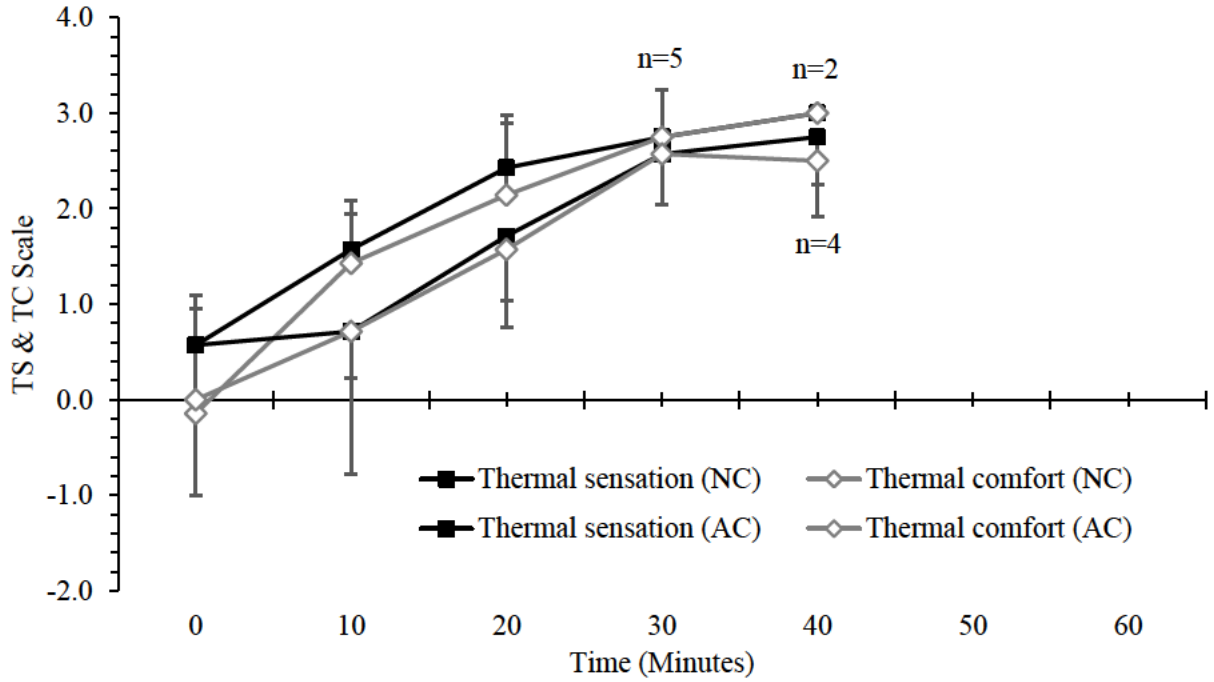

Figure 29. Thermal sensation (TS) and thermal comfort (TC) with active cooling (AC) and no cooling (NC). TS and TC were not significantly different over time ($p>0.05$). n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

Table 8. Rating of perceived exertion (RPE) (A) and discomfort scale (B) mean±SD's recorded at the final time points before individuals trials ended in active cooling (AC) and no cooling (NC). Perceptual feedback was collected from individuals regarding how their whole body and also upper and lower body specific.

A. Rating of perceived exertion

	Whole Body	**Upper Body**	**Lower Body**
NC	17.4±2.2	17.7±2.1	16.6±2.6
AC	18.1±2.1	18.6±1.4	17±2.7

B. Discomfort Scale

	Whole Body	**Upper Body**	**Lower Body**
NC	8.3±1.6	8.9±1.1	8.0±1.5
AC	8.7±1.1	9±1.0	7.9±1.6

Whole-body discomfort was higher during AC. When split by upper and lower body, upper body was found to be higher in AC, while the lower body was higher during NC. Highest levels of discomfort were reported in the upper body, regardless of condition. This was significantly different when compared with lower body ($p<0.01$).

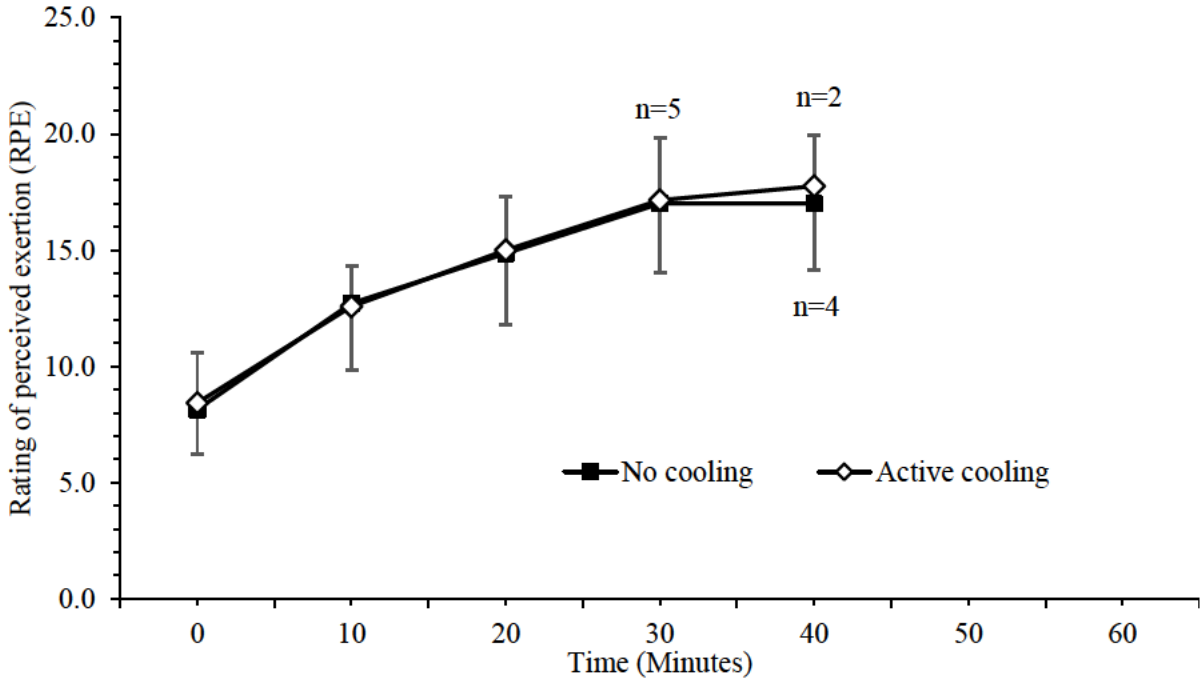

Figure 30. Rating of perceived exertion (RPE) in active cooling (AC) and no cooling (NC). RPE was not significant over time ($p>0.05$). n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

RPE was highest during AC in whole, upper and lower body (Table 8a). Whole-body RPE was not significantly different between conditions ($F(1, 9) = 0.000$, $p = 1.000$, $\eta p^2 = 0.000$). Highest perceived exertion was reported in the upper body, this was significantly higher than lower body ($p=0.01$).

GS (Table 9) were low throughout trials, with headaches, sickness and confusion all reporting less than 1 in both trials. Dizziness was reported higher during AC at 1.0±0.8 compared with 0.6±0.8 in NC, whilst tiredness was lower during the AC trial at 0.9±1.2 compared with 1.1±1.2 in NC. The highest reported symptom in both trials was difficulty breathing at 1.6±1.0 during NC and 1.7±1.3 during AC.

	Headache	**Sickness**	**Dizziness**	**Confusion**	**Tiredness**	**Difficulty breathing**
NC	0.7±0.8	0.6±0.8	0.6±0.8	0.3±0.5	1.1±1.2	1.6±1.0
AC	0.7±1.0	0.9±1.1	1.0±0.8	0.7±0.8	0.9±1.2	1.7±1.3

Table 9. General symptoms questionnaire with active cooling (AC) and no cooling (NC). Reported values are mean±SD of potential heat-related symptoms including headaches, sickness, dizziness, confusion, tiredness and difficulty breathing.

4.5.1 PeSI

PeSI did not vary between conditions over time ($F(1, 9) = 0.725$, $p = 0.551$, $\eta p^2 = 0.420$). PeSI was lower during AC up to 30 mins. However, endpoint PeSI was not significantly different between conditions ($p<0.05$). PeSI delta values were also not significantly different ($p<0.05$).

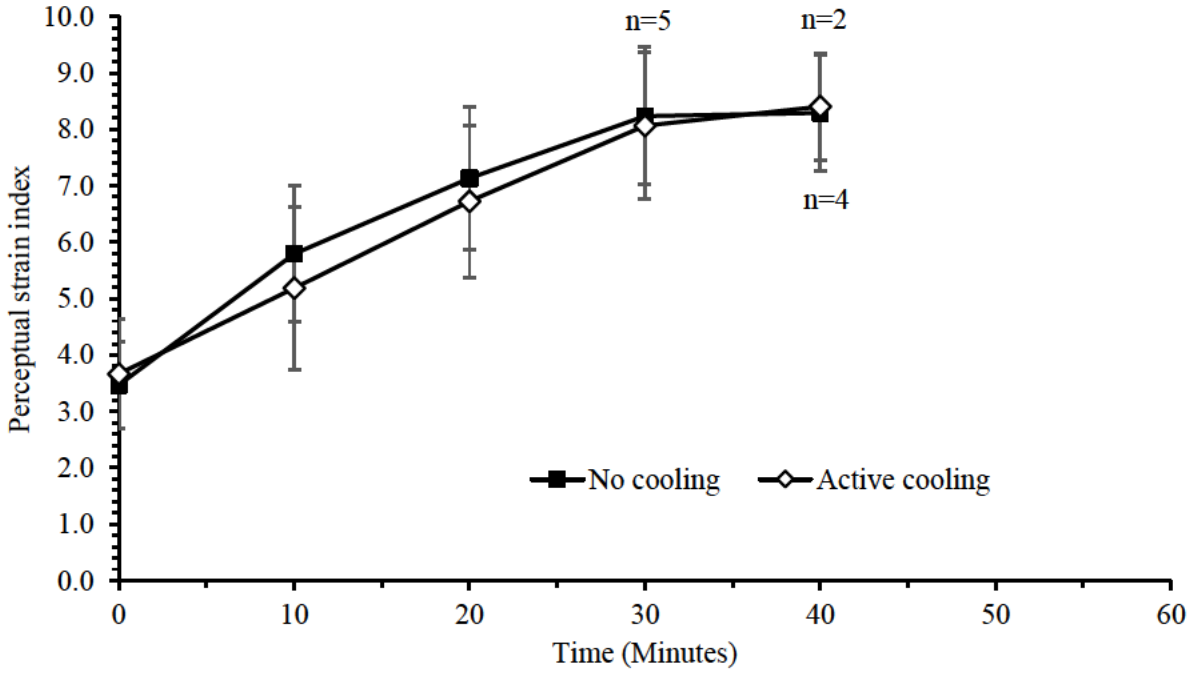

Figure 31. Perceptual strain index (PeSI) with active cooling (AC) and no cooling (NC). PeSI was not significantly different between trials ($p>0.05$). n=7 unless specified in the legend whereby n values on top relate to the NC trial whilst n values below relate to the AC trial.

4.6 Liquid cooling suit

Inlet water temperature (Figure 32) began on average at around 17.3±6.3ºC, whilst outlet began at around 27.4±2.2ºC. During the first 5 mins, inlet temperature dropped around 5 ºC and outlet temp around 10ºC. After 5 mins, water temperature began to rise steadily over the rest of the trial, with mean inlet temperature reaching 30.3±2.8 ºC and output 32.5±2.0 ºC at 40 mins. As trials continued, differences between temperatures (inlet and outlet) reduced. At 20 mins, inlet and outlet water temperature had a difference of around 5 ºC, at 30 mins it was 4 ºC, whilst at 40 mins the temperature

difference was only 2 ºC. Mean endpoint inlet and outlet water temperature was 35.3±1.4 and 36.2±1.7 respectively during NC (when it was turned off), whilst it was 27.3±4.6 and 30.7±2.9 in the AC condition when the LCS was turned on.

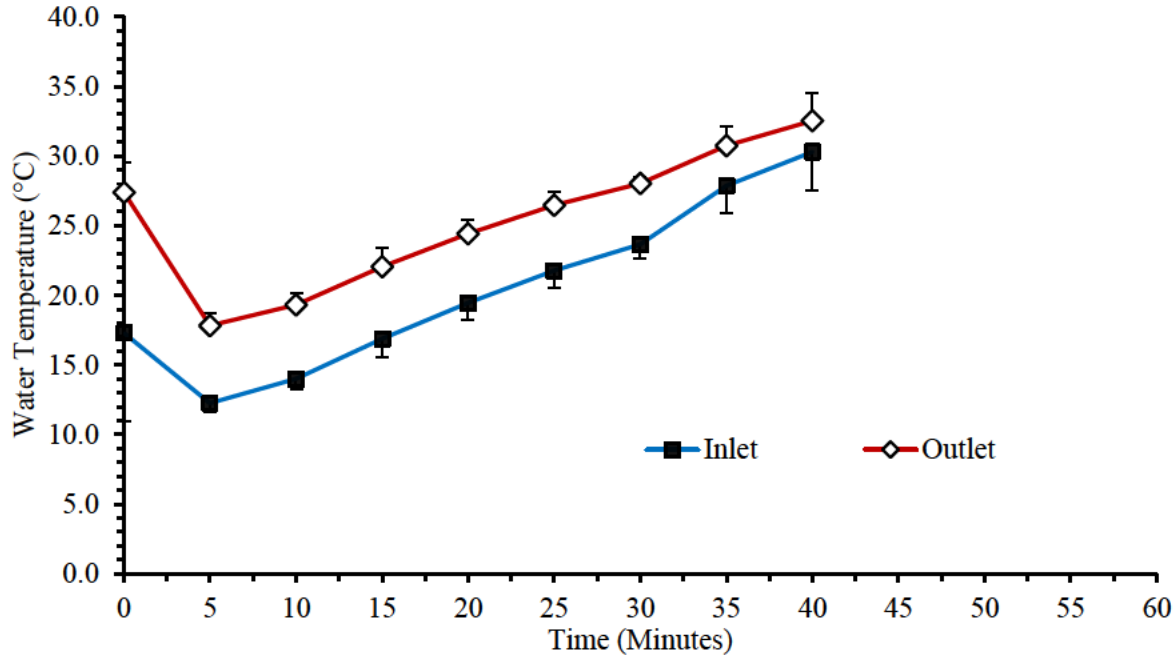

Figure 32. Liquid cooling suit (LCS) inlet and outlet water temperatures during active cooling (AC).

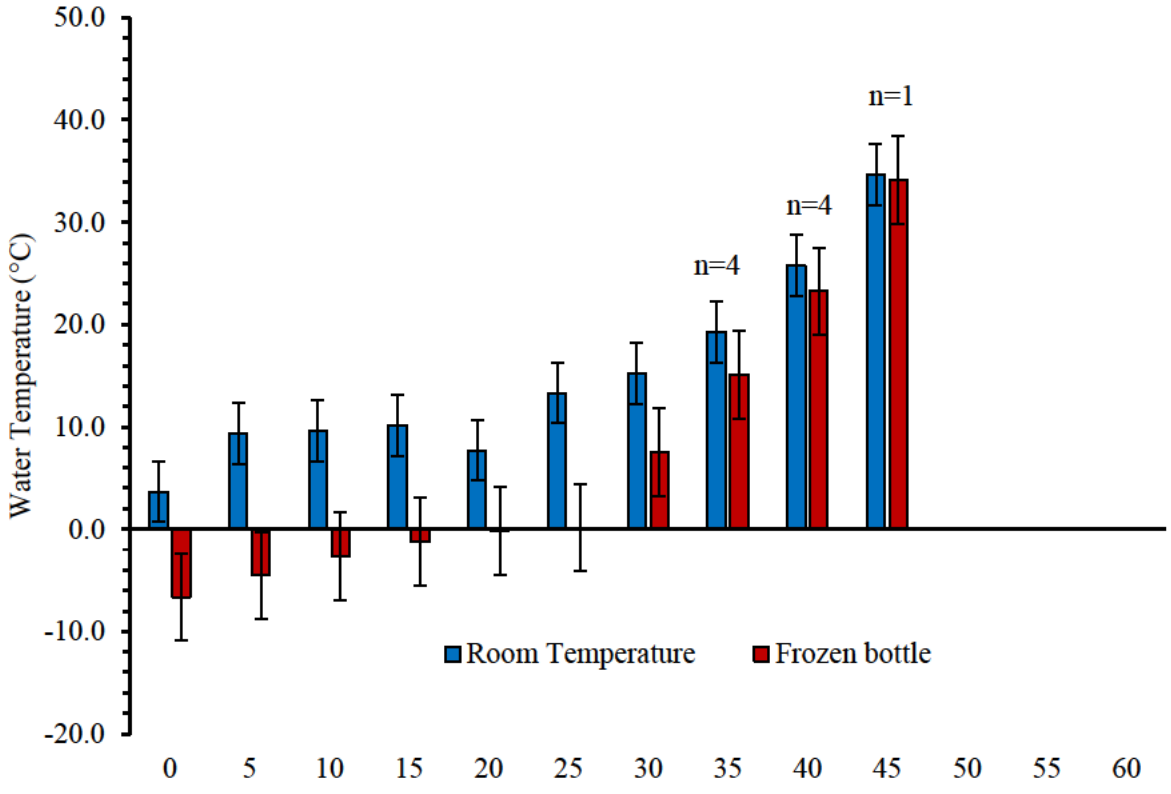

Figure 33. iButton room temperature and frozen bottle temperature during active cooling (AC). n=7 unless specified in the legend whereby n values on top relate to the no cooling (NC) trial whilst n values below relate to the AC trial.

iButton temperature from the frozen bottle and room temperature (Figure 33) during AC averaged 3.7±2.7ºC and -6.6±2.4 ºC respectively at 0mins (5 mins post-mix). At 25 mins, the iButton which had been placed in the frozen cooling bottle showed a positive temperature for the first time (0.1±0.2ºC) while the room temperature iButton was 13.3±4.1ºC at the same time. At 40 mins frozen bottle iButton temperature was 23.3±15.7ºC whilst room temperature iButton was 25.8±10.7ºC, however, this was n=4 rather than n=7. Only one participant lasted 45 mins where frozen and room temperature iButton temperatures reached 34.1ºC and 34.6ºC respectively.

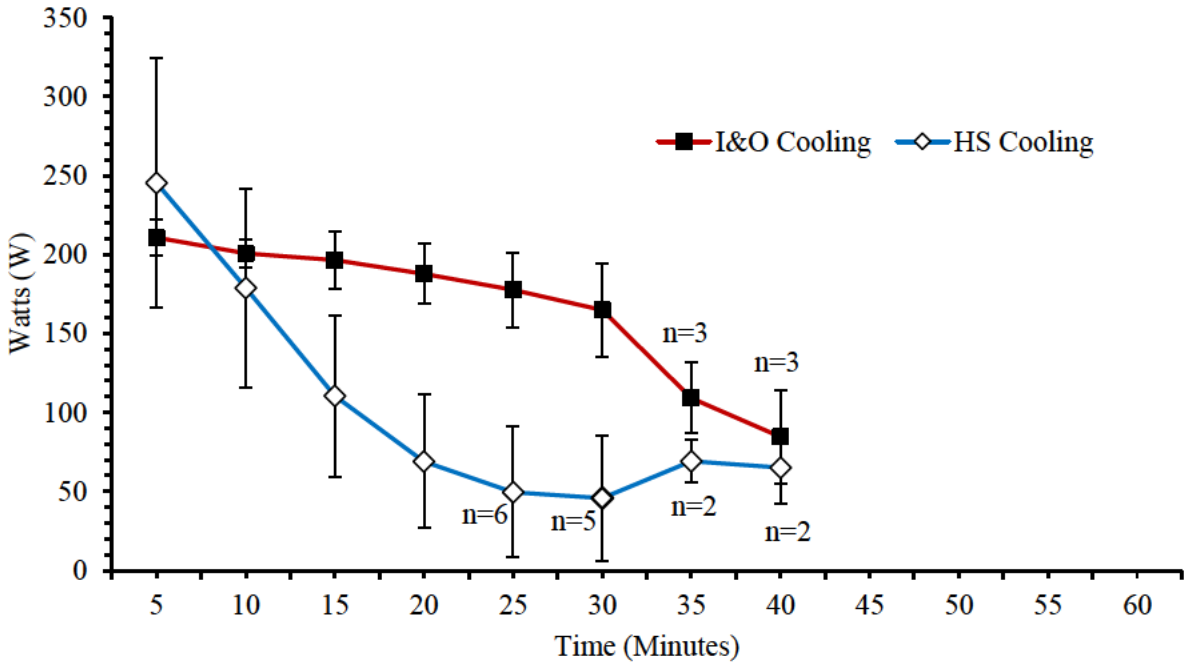

Figure 34. Estimates of inlet and outlet cooling capability and heat storage cooling capability. n=7 unless specified in the legend whereby n values on top relate to the inlet and outlet calculation, whilst n values below relate to the HS calculation.

The cooling capability of the LCS based on HS data (Figure 34) began at 245±79 W but dropped after 20 mins to 69±42 W. After 20 mins, the cooling capability plateaued between 50-70 W with 65±23 W of cooling at 40 mins. The cooling capability based on inlet & outlet data began on average at 211±12 W and slowly declined over 30 mins (165±30 W). The overall cooling capability of the first 20 mins

(n=7) was estimated at 73 W using HS calculation, while it was estimated at 199 W using the inlet and outlet calculation (n=7). There was not a significant difference over time between the two ($p>0.05$).

4.7 Reduced speed trial (n=1; 2.5 km·hr^{-1})

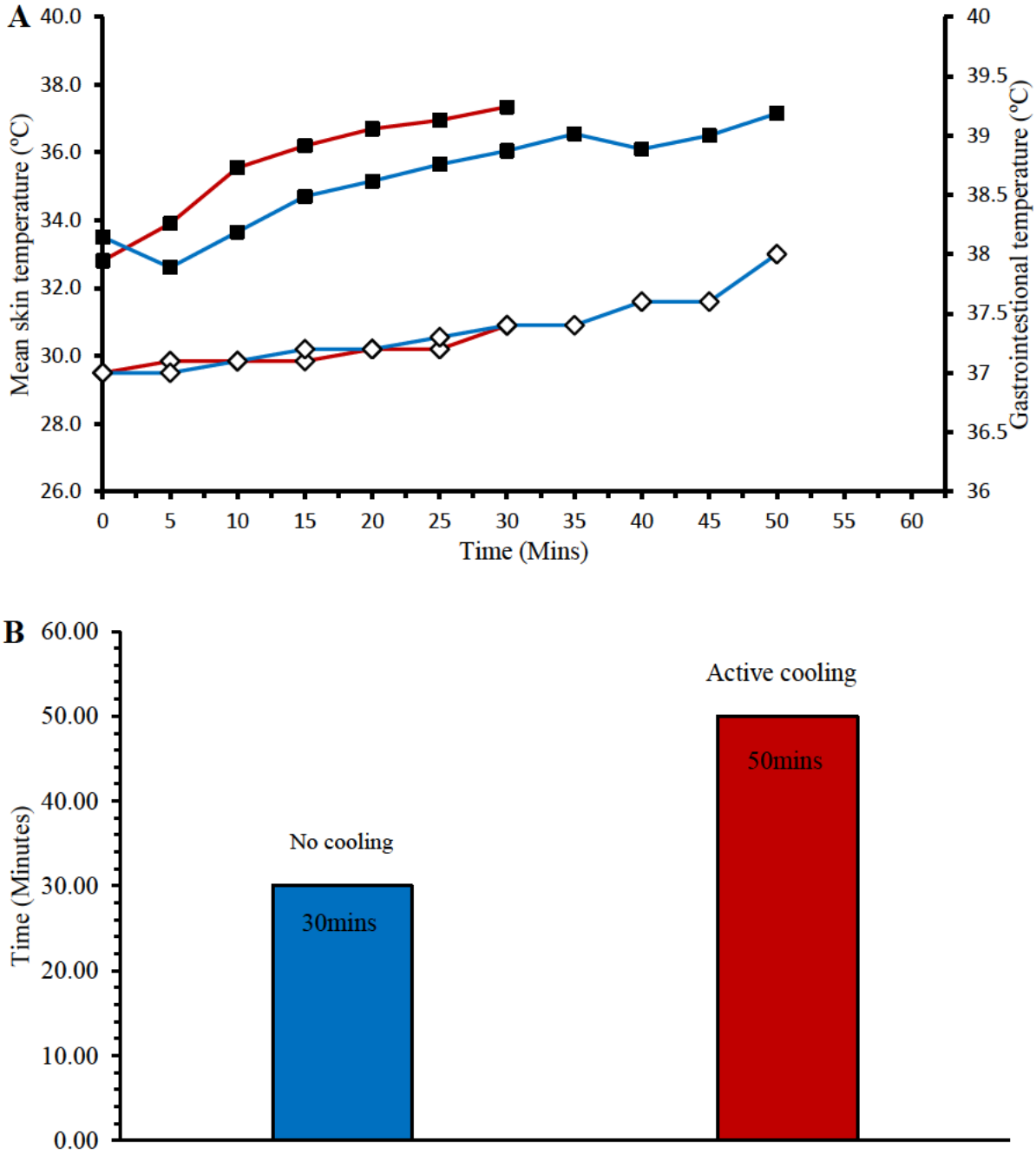

Figure 35. Mean skin temperature (T_{ms}) and gastrointestinal temperature (T_{GI}) (A). Exercise duration (B). n=1 2.5 km·hr^{-1} treadmill walk.

Figure 35 shows exercise duration and skin & core temperatures during the n=1 2.5 $km \cdot hr^{-1}$ trials. During the NC trial, the participant lasted 30 mins, while they lasted 50 mins during AC. During the NC trial, T_{ms} matched T_{GI} at 30 mins. T_{ms} did not match or cross T_{GI} throughout the AC trial.

4.8 Results summary

Physiological and perceptual temperature variables show improvements in core, skin, TS and TC in during AC for the first 30 mins. However, after 30 mins the cooling system's ability to cool down the individual becomes less effective as core, skin, TS and TC rates all begin to rise similar to that seen during NC. No individuals finished the exercise protocol, with the majority opting to stop themselves. Endpoint RPE and discomfort measures were high in both conditions and both finished higher in the upper body when compared with whole body and lower body. Estimations of the cooling capability of the suit were higher in the inlet and outlet calculation than the HS calculation, however, both reported a decrease over time during the trials.

5 Discussion

Firstly, this study sought to assess the thermal physiological and perceptual benefits of an LCS; and secondly to quantify the cooling capability of the LCS. The LCS extend TT and improved physiological and perceptual responses. The cooling capability of the LCS was estimated at 73 W over the first 20 mins from changes in body HS between conditions. Calculations from changes in LCS inlet and outlet water temperatures within AC trials estimate the cooling capability of the suit at 199 W. These estimates are both far lower than reported by the manufacturer (270 W).

5.1 Rationale for Methodology

Participant responses were compared between AC and NC with all other aspects of the protocol and environmental conditions identical between exposures. To avoid potential variability in movement/ activity between conditions and any subsequent interaction between the individual and the EOD suit e.g. varied bellows effect whilst crawling and undertaking various activities a simulation activity protocol was not adopted (e.g. Thake and Price 2007). Instead, treadmill walking at a speed of 4 $km \cdot hr^{-1}$ was used. Treadmill speed was equivalent to that used by Thake and Price (2007) as a component of their protocol that was based on an operative walking 200 metres in 3 mins to the site of an explosive threat. This exercise mode has been applied in other EOD studies under similar conditions e.g. Stewart et al. (2014); Costello et al. (2015) whereby participants were required to walk on a treadmill at multiple set speeds, including 4 $km \cdot hr^{-1}$, in an EOD suit at 30°C WBGT. Multiple studies have also been performed by Thake et al. using EOD suits in 40°C however participants undertook tasks representative of EOD activity as opposed to treadmill walking. Thake et al. (2011), Thake et al. (2009a) and Thake et al. (2009b) all performed activity cycles lasting over an hour (109 mins; 66 mins; 66 mins respectively) in 40°C T_{amb}. All participants finished all trials in Thake et al. (2011) and Thake et al. (2009b)'s studies, which included NC (Thake et al. 2011) and relatively little cooling in the form of an ambient air fan system. During Thake et al. (2009a), participants lasted 53:48±11:59 (min: sec) on average in the pre-acclimation trial which also had an ambient air fan system, which has shown to be one of the least effective methods for cooling individuals in high T_{amb} (Chan et al. 2015). Due to the ability of these participants to either complete or get very close to

completing at least 60 mins of these activity trials, 60 mins of steady-state treadmill walking was proposed to be an appropriate duration within which to compare and contrast the active (AC) compared to inactive (no cooling; NC) LCS under UHS conditions.

Unfortunately, out of the 7 participants who attempted all trials, nobody completed the full 60 min treadmill walk. Due to COVID-related time constraints, pilot work was not conducted to check whether the duration was achievable by the participant group. Once trials had begun, it became clear that 60 mins was not achievable for the participant group and the study became a comparative fixed load time trial, rather than a steady-state 60 min AC vs NC comparison. This is an issue as there is now limited information regarding how the suit operates over a 60 min period, a typical operational duration. Also, due to the majority of trials ending before 35 mins (Table 4), there is limited data on how the participant's physiological and perceptual status from 40 mins onwards. However, data from the first 30 mins provides important information regarding how the LCS is affecting participants albeit with participants undertaking relatively arduous work.

5.2 Exercise duration

Participants in the current study were staff and students at Coventry University and were likely not as physically fit or mentally strong as military EOD operatives. No $\dot{V}O_{2max}$ data was collected in the current study, so comparisons between military personnel are difficult. However, $\dot{V}O_2$ and HR data from each participant in both conditions showed an average $\dot{V}O_2$ of 27±3 $mL \cdot min^{-1} \cdot kg^{-1}$ at the final minute of each trial and an average HR of 176 $b \cdot min^{-1}$, which is well below the minimum requirement of aerobic capacity for a US air force male between the ages of 25-29 years (34 $mL \cdot min^{-1} \cdot kg^{-1}$) and 30-34 years (32 $mL \cdot min^{-1} \cdot kg^{-1}$) (Sporiš 2013). Despite no participants completing the full 60 mins in either condition, exercise duration was significantly longer (5 mins) in the AC trial, which supports previous research stating a LCS underneath firefighter PPE significantly prolongs performance time during strenuous exercise which included three 15 min stages of 75% $\dot{V}O_{2max}$ (Kim et al. 2011a). TT in the NC condition was lower than found in previous studies with similar methodologies (38 mins vs. 32 mins) (Stewart et al. 2014). Although another study with similar methodologies found an average TT of 32 mins (Costello et al. 2015) which is the same as found in the current study. Longer TT time

could be due to the weight of the EOD suit, which was 33.4 kg in Stewart et al. (2014) study while it was 38.7 kg in the current study. However, Costello et al. (2015) also used a 33.4 kg EOD suit and TT were similar. Therefore weight cannot be the only reason for differences in TT between these two studies.

Previous research has reported a PSI (core measured via ingestible pill) of 7.1±1.2 (Costello et al. 2015) and 6.6 (range of 5.7–7.5) (Stewart et al. 2014) at the cessation of their 30°C WBGT, 4 $km \cdot hr^{-1}$, NC treadmill walk. These are similar to the 7.3±2.0 PSI reported via ingestible pill during the current studies NC trial. Interestingly, cessation PSI in the current studies AC trial was the same and even higher (7.1±2.00) than found in previous research which used no cooling methods. This may be due to T_{amb} differences (30°C vs 28°C WBGT), or due to increased TT resulting in higher HR and core temperature responses. PhSI in previous EOD-related studies has reported absolute PhSI's of 4.4±1.0 during NC trials and 3.4±1.7 in their cooling trial whilst wearing a 38 kg EOD suit (using PCM) at the end of their activity cycles at 40°C (Thake et al. 2011). A higher PhSI of 5.6±0.5 was reported in Thake et al. (2009b)'s EOD study performing a similar activity cycle at 40°C in a 37 kg EOD suit. These reported PhSI's are both lower than found in the current study, despite nobody completing trials. This is likely due to continuous increasing % of $\dot{V}O_2$ required for exercise when compared with intermittent exercise mode used in the studies, which is also shown in Thake et al. (2009a) who performed the same activity cycle.

5.2.1 Trial ending

In the current study, 10/14 trials were stopped by the participant. This is very different to previous studies with similar methodologies, which saw the majority of trials stop due to the designated HR % cut-off limit (Stewart et al. 2014; Costello et al. 2015). Previous research has shown evidence of high T_{sk} and a smaller gradient between skin and core temperature being associated with the thermal tolerance limit (Davey et al. 2021). This could explain why participants stopped in the NC condition despite not reaching high core temperatures, however, it does not explain why 5/7 participants stopped during the AC trial, as no skin > core crossover occurred. However, when discussing with participants post-trial, many mentioned pain and discomfort in their shoulders and neck due to the

weight of the suit and associated equipment (38.7 kg). Perceptual measures of discomfort and RPE showed high levels of discomfort (NC 8.9/10; AC 9/10) and perceived exertion (NC 17.7/20; AC 18.6/20) in the upper body during final recorded perceptual measures before the finish time. Discomfort and perceived exertion were significantly higher in the upper body when compared with lower body, despite the exercise protocol being lower body specific. Thake et al. (2011) performed an EOD trial (suit weight 38 kg) at 40°C with a 109 min activity cycle, which included walking, crawling and cognitive tasks as the exercise protocol. Even in the NC trial, all participants completed activity cycles. This was also repeated a few years later, with non-acclimated individuals fully completing a similar 66 min exercise protocol at 40°C whilst wearing an EOD suit (weighing 37 kg) (Thake et al. 2009a). Due to the suit weights in these studies being similar, it's possible due to the upright posture maintained throughout treadmill walking, the weight of the suit was heavy enough on the shoulders and neck to cause significant, trial-stopping discomfort. While in previous research, the change in posture and physical rest during cognitive tasks throughout activity cycles resulted in the weight of the suit shifting off the upper body, allowing small periods of discomfort relief and allowing participants to complete the exercise protocols.

There are many potential reasons why participants stopped the trials and these reasons could differ between conditions. It's possible NC trials were primarily stopped due to high T_{sk}, whilst participants stopped AC trials due to high levels of discomfort due to increased time wearing the suit. This suggests that within the current cohort exercise tolerance time in an EOD suit in high T_{amb} is determined by musculoskeletal discomfort and potentially high T_{sk}, rather than high core temperatures. However, it could also be due to the speed at which core temperature rose, as a rapid increase in core temperature due to elevated metabolic rate could cause an individual to drop out quicker (González-Alonso et al. 1999). This suggests a 4 $km \cdot hr^{-1}$ treadmill walk is too high for the recruited cohort when trying to investigate UHS. This is supported by previous research which showed increased TT with decreased treadmill speeds (Stewart et al. 2014; Costello et al. 2015). It's also supported by EODP12 (n=1) in the current study, whose NC trial data were not included in the final data set reported as they only lasted 10 mins before hitting 95% HR_{max}. However, data of them

undertaking slower treadmill walking (2.5 km·hr^{-1}) is reported separately (section 4.7) where they were able to last for 30 mins in the NC trial and 50 mins in the AC trial. In the NC condition, core temperature data (T_{GI} and T_{rec}) showed T_{ms} cross over T_{rec} and match T_{GI} at 30 mins, whilst in the AC trial even at 50 mins no T_{ms} > core temperature crossover occurred. This hints toward 2.5 km·hr^{-1} providing more information in this particular cohort as the rate of rise in core temperature would be decreased, potentially resulting in participants lasting longer and maybe even finish the treadmill walk.

5.3 Cooling vs Non-cooling

5.3.1 Physiological Strain

Physiological strain, measured via T_{GI} in both PhSI and PSI calculations, were similar between conditions up until around 30 mins. Between 30 and 40 mins, physiological strain rose considerably faster in the NC condition when compared with the AC condition (36% vs 14% respectively). This was due to increases in core temperature from 30-40 mins during the NC trials, likely due to T_{ms} crossing over core temperature at around 30 mins during the NC trial in three of the participants, while no such crossover occurred in their AC trial. Once T_{sk} crossed core (30 mins), core temperature (measured via T_{GI}) rose by 0.9°C in 10 mins, whilst it had taken 25 mins to rise by the same amount earlier in the trial (0-25mins). HR was also higher in the NC condition which will have contributed to increased physiological strain. However, HR rose linearly throughout each condition, rising 9 b·min^{-1} during the NC condition and 10 b·min^{-1} in AC in the same period, so the increased rate of rise of physiological strain after 30 mins in the NC condition is attributed to core temperature rather than HR.

As previously discussed in section 2.2.4, PSI is not tailored to the individual and is therefore not a reliable indicator of physiological tolerance (Davey et al. 2021). This was demonstrated in the current study as n=2 exceeded 180 b·min^{-1} HR during trials. Both PSI and PhSI calculations were performed in the current study and it was found the more individual-specific PhSI calculation was repeatedly lower than PSI in both T_{re} (PhSI: NC 6.6±1.42; AC 6.6±0.87 PSI: NC 7.3±1.54; AC 7.3±0.88) and T_{GI} (PhSI: NC 6.7±1.94; AC 6.4±0.87 PSI: NC 7.3±2.00; AC 7.1±0.66) temperatures. This is due to the

180 b·min^{-1} heart rate ceiling set for the PSI calculation assuming the same maximum HR for all participants.

Participants reached steady-state $\dot{V}O_2$ by the first 5 min time point in both conditions and continued to range between a rate of approximately 2.1 to 2.4 L·min^{-1} up to 30 mins. Previous research in an EOD suit has shown a 65% increase in metabolic rate when compared to no suit at 4 km·hr^{-1} walk on a treadmill in 24°C (Bach et al. 2016). While this study had no control condition, previous EOD research by Thake et al. (2009a) examining pre and post-heat acclimation showed a $\dot{V}O_2$ fluctuating between 0.4 and 1.2 L·min^{-1} throughout a 66 min activity cycle in 40°C with no EOD suit. This increased to between 0.5 and 1.4 L·min^{-1} whilst wearing an EOD suit when examining both pre and post-acclimation conditions. Comparing the two studies, peak $\dot{V}O_2$ is 52% higher in the first 30 mins in the current study when compared with Thake et al. (2009a). This will in part be due to increases in core temperature in the current study, as Thake et al. (2009a) reported a pre-acclimated T_{rec} of 37.7°C at 33 mins, whilst in the current study, T_{GI} was 38.1±0.22°C at 30 mins. Another contributing factor is likely the continuous vs intermittent exercise modes previously discussed in section 5.2.

5.3.2 Perceptual strain

During the first 20 mins, TS and TC were significantly different between NC and AC trials. However, at 30 mins the gap closed as TS and TC in the AC condition increased to similar levels seen in the NC trials. Therefore, from around 30 mins and onwards participants felt little difference in heat and comfort between the two conditions. At around this point, the room temperature and frozen iButtons in the cooling bottle had risen from 3.7°C at baseline to 15.2°C at 30 mins and -6.6°C at baseline to 7.5°C at 30 mins respectively, while inlet and outlet temperatures within the suit were 23.7°C and 28°C respectively at 30 mins. It is possible that the water in the suit heating up so quickly played a significant part in an individual's thermal perception and could have even played a role in participants stopping their trial due to decreased TC (see section 5.6). Despite little difference in TS and TC in the AC condition when compared with NC, the participant's average exercise duration was over 5 mins longer in the AC condition, likely due to physical challenges previously discussed. Other factors contributing to participants terminating exercise are outlined in section 5.2.1.

PeSI was not significantly different at any timepoints throughout each trial. PeSI was lower in AC up to 30mins, however, after 30 mins there was no difference between AC and NC. While TS was significantly lower in the AC condition up to 30 mins, RPE was almost identical throughout both conditions. These results are different to previous studies done, where RPE was found to be higher in the NC condition when compared to phase change material (Thake et al. 2011), although maximum HR reached was lower in the current study. In the current study, HR responses were lower throughout the AC condition. However, $\dot{V}O_2$ and RPE were very similar between trials up to 30 mins as cooling seemed to have very little effect on either variable. This is unsurprising as there were only marginal differences in core temperatures, however, the similar $\dot{V}O_2$ is likely the reason why RPE was also similar between trials, as high $\dot{V}O_2$'s may have resulted in participants still feeling like they're giving the same amount of effort in both trials, regardless of thermal perception.

5.4 Cooling Capability of the Liquid Cooled Suit

5.4.1 Heat storage

HS (measured via T_{GI}) found in the current study was higher than in previous comparable research. During Thake et al. (2011)'s 40°C EOD activity cycles, HS in their NC condition was 4.2±0.5 $J \cdot g^{-1}$ and 3.8±0.5 $J \cdot g^{-1}$ in their cooling condition at the end of the 109 min activity cycle (all participants completed). In comparison, HS reached 4.4±0.5 $J \cdot g^{-1}$ in the NC trial after just 20 mins and 4.4±0.8 $J \cdot g^{-1}$ in the AC trial after 30 mins. In another study, HS finished at 5.3±0.3 $J \cdot g^{-1}$ after a 66 min activity cycle whilst wearing a 37 kg EOD suit in 40°C (Thake et al. 2009b), which is closer to what was found at the cessation of the current study (NC: 5.7±1.5 $J \cdot g^{-1}$; AC: 5.1±0.8 $J \cdot g^{-1}$) but with a significantly lower average TT (NC: 37mins; AC 32mins). This is likely due to the relatively higher work rate in the current study, which is clear due to the higher $\dot{V}O_2$ when comparing the two studies (discussed in 5.3.1).

Change of T_{GI} over time (Table 6) shows an average increase in temperature (every minute) of 0.04 during NC and 0.03 during AC. However, this is a poor representation of what is happening. As shown in Figure 24, the change in T_{GI} every 5 mins clearly shows in the NC trial after 20 mins, there is an exponential rise in T_{GI}. While there is no such rise in the AC trial. This shows that while core

temperature begins to rise exponentially during NC, the LCS (during AC) prevents this rise from occurring.

5.4.2 Inlet & Outlet Temperatures

In the current study, a cooling bottle filled with a mixture of frozen (1 L) and room temperature (20±0.8°C) water (500 mL) was used as the cooling liquid pumped around the suit. Because of this, a change of cooling ability (water temperature) was seen throughout the trial (Figure 27), which is similar to that observed when PCMs are used in torso garments for example. This resulted in an inlet and outlet water temperature of 12.2±0.7°C and 17.8±0.8 respectively at 5 mins, which rose to 23.7±1.0°C and 28±0.5 at 30 mins. 21°C is the most popular self-selected inlet water temperature for thermal comfort (Shitzer et al. 1973). Based on this reporting, inlet temperatures in the current study exceeded a point of optimum thermal comfort at around 25 mins into exercise. While inlet and outlet temperatures reached high temperatures relatively quickly in the current study, the use of a cooling bottle allows for greater freedom of movement in the field. Previous research (Cadarette et al. 2006) has controlled water temperature in a LCS to 21°C due to Shitzer et al. (1973)'s previous findings to optimise thermal comfort throughout their trials. However, this requires a temperature-controlled water bath to be connected to the individual, making it severely limited in the field and not a practical solution for real-world use. A potential solution to this issue would be to swap out the cooling bottle with a new frozen bottle after a certain period, therefore decreasing the temperature circulating the suit (discussed in section 5.7).

5.4.3 Quantifying cooling

Previous studies have attempted to calculate the cooling efficiency of LCS (Cadarette et al. 2006) by using calculations derived by Cheuvront et al. (2003), who estimated cooling efficiency based on the ratio of cooling provided per unit of surface area perfused. Cadarette et al. (2006) also estimated the cooling capability of a LCS in high ambient temperatures (35°C) whilst walking on a treadmill at 4.8 $km \cdot h^{-1}$ and provided a theoretical heat removal of 305 W during constant flow (which was calculated at 1.2 $L \cdot min^{-1}$ or 20 $mL \cdot s^{-1}$). This is considerably more cooling than found in the current study. However, it's difficult to compare the two, as the LCS used in the current study is different to the LCS

used in Cadarette et al. (2006) having over twice the flow rate (20 $mL \cdot s^{-1}$) than the current study (9 $mL \cdot s^{-1}$). This has the potential to significantly increase the cooling capabilities of the suit, as a more than double flow rate at the same coolant temperature will increase cooling by more than double, although this will depend on tubing, dimensions and material used. T_{amb} (35°C vs 40°C) and PPE were also different between the two studies, with US army chemical protective clothing being used rather than an EOD suit, which is considerably lighter.

In the current study, two calculations were used to estimate the cooling capacity of the LCS (Figure 33). However, the two calculations employed estimated values with slightly different parameters. The inlet & outlet calculation aimed to quantify the system-specific cooling capability of the suit, while the HS calculation attempts to calculate how much cooling from the system is getting to and affecting the individual. In the first 5 mins, there is seemingly more cooling given to the individual than the cooling suit system provides, as the HS calculation estimates 245±79 W of cooling, while the LCS is only providing 211±12 W of cooling. This suggests the individual in the suit is potentially being cooled down by factors other than just the cooling system. This could be the inside of the suit, as it would have not yet heated up to the 40°C T_{amb} of the chamber and elements could still be closer to 20°C from it being stored in the preparation room and therefore cooler than average chamber baseline T_{ms} (33.3±0.7°C). Throughout the trial, both the cooling capability of the suit and the amount of cooling the individual received both decreased. However, this decline did not follow a linear form. While the cooling suit cooling capability decreased steadily from 211±12 W at 5 mins to 188±39 W at 20 mins, the amount of cooling the individual received dropped off considerably after 10 mins (245±79 at 5 mins to 69±42 at 20 mins). During the first 20 mins of exercise, the LCS was estimated to provide 199 W worth of cooling to the individual, however, based on HS estimates, the participant only received 73 W worth of cooling. Therefore for the first 20 mins of exercise, there is a deficit of approximately 126 W worth of cooling between the LCS and the participant. This cooling deficit could be a consequence of the microclimate between skin and suit or the inside of the suit itself absorbing this energy. Interestingly, sweat rate data shows a slightly higher sweat rate in the NC trial in the nude, however, when comparing sweat rates when wearing the suit, the AC condition had a

slightly higher sweat rate. It is possible more sweat is being held by the suit in the AC trials due to the inside of the suit being cooled down by the LCS system and subsequently limiting its potential for evaporation of sweat. While this cannot be confirmed by the current study, if this were the case, it would suggest the inside of the suit was being cooled more than the individual at certain points during the trial. Although it is noted that cooling the suit itself is also of potential benefit to the individual as this remains part of the participant/ microclimate between the suit and participant/ suit thermal system. It's important to note that there are limitations to the calculations applied, such as the HS calculation itself (discussed in 2.2.5) and the fact that neither calculation considers evaporative sweat from the individual.

In the current study, one-size LCS was provided for all participants regardless of body size. This changed the fit of the LCS on each individual and potentially increased or decreased the ability to directly cool the individual based on their body size. This is due to how much of the tubing was in contact/close contact with the skin which would have had a profound effect on the LCS's ability to cool down the individual. This could also be related to the undergarments worn by the individuals, which create a barrier between suit and skin for all body regions except arms and head. Therefore, cooling may be improved without the use of undergarments or the LCS worn below the cotton t-shirt and trousers underlayer.

5.5 Recommendations for operational use

The LCS increased exercise duration whilst reducing the physiological and perceptual strain of participants at matched time points prior to reaching volitional exhaustion. This suggests it is beneficial to wear a LCS underneath an EOD suit in high ambient temperatures. However with the current methodology, the following points must be considered when used in commercial use.

1) Wearing the LCS (with AC) does improve work duration. However this was only by 5 mins on average. Military operations lasting an hour or longer will be required to develop strategies to further enhance cooling mechanisms (e.g. swap out the cooling bottle for a new one (as discussed in section 5.7)) or decrease the workload in which the user is subject to.

2) Reduced perceptual strain was only observed for the first 30 mins of exposure. When operators are required to wear the suit for longer than 30 mins, further cooling strategies may be required to enhance the individuals thermal comfort.

5.6 Limitations

Data collection for the current study was conducted between June – August 2021 as COVID-19 lockdowns delayed the start date until face-to-face research was allowed to continue. Conducting the study during the summer resulted in many difficulties, especially surrounding participant recruitment as staff and students were away from the university. This resulted in very few individuals (n=14) volunteering for the study. Unfortunately, the study also had a 50% dropout rate (section 4), leaving only n=7 by the end of the data collection period.

While the study was going on there was a heatwave which saw high ambient outdoor temperature >25°C for around a week. In one participant, EODP7, there was anecdotal evidence to suggest they had been mildly heat acclimatised between his first and second trial. EODP7 performed their cooling trial first and lasted 30 mins. A week later he performed his NC trial and lasted 32 mins. Due to the hot weather and the unexpected result, questions were asked regarding if he had been outdoors often this week. They mentioned they had been out walking for at least an hour most days this week due to the hot weather. This has led to investigators suspecting the participant had undergone mild heat acclimatisation in between their AC and NC conditions and this had contributed to their increased TT in the NC trial. However, the study was designed to mitigate this by having the familiarisation session and trials at least one week apart to avoid a cumulative effect.

5.7 Future Research

To assess the full capabilities of this LCS, further research should aim to investigate the effectiveness of the LCS in different temperatures and environments (such as temperatures less than 40°C e.g. an ambient temperature of 33°C, representation of skin temperature at rest), modes of exercise e.g. specific EOD related activity cycles and also exercise intensities which reflect real-world use cases. Investigating strategies to extend the time inlet/outlet water temperature stays cool would also be of

use. This could be done by testing intermittent cooling strategies to potentially extend the time water stays cool or by swapping out the cooling bottle for a new bottle halfway through trials. Future research could also incorporate radiant heat load / solar lamps into the protocol as lab studies do not consider the impact of solar radiation.

This study is the first in a series of studies to assess the cooling capability of the LCS whilst wearing an EOD ensemble and has contributed to informing a bigger investigation. The information gained from this study has provided valuable information concerning methodology design (specifically related to treadmill speed and the duration of the trials). Future research will likely reduce treadmill speed to 2.5 $km \cdot hr^{-1}$ to extend the trial duration and increase the likelihood of participants completing the full duration of the trial to acquire more physiological and perceptual data on wearing EOD suits in UHS environments whilst tracking the cooling power of the LCS system.

5.8 Conclusion

This is the first in vivo investigation into the cooling capability of United Shield International's LCS whilst wearing an EOD suit in high T_{amb} (40°C). No participant completed the 60 min treadmill walk at 4 $km \cdot hr^{-1}$. However, AC resulted in a significantly longer TT when compared with NC.

AC did result in lower physiological temperature and perceptual variables including T_{ms}, core temperature (both T_{GI} and T_{rec}) TS and TC, with T_{GI} and T_{ms} being significantly different. However, $\dot{V}O_2$ and RPE were not significantly different between trials.

The cooling power of the LCS system was higher when estimated from changes in water temperature (199 W) compared to the actual cooling transferred to the participants (73 W).

Based on the data collected during this study, it's clear that wearing the LCS whilst the cooling was active was beneficial to the wearer yielding both physiological and perceptual benefits, resulting in a greater exercise tolerance time overall.

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7 Appendix

A) Perceptual scales

Thermal Sensation	
+ 3	Hot
+ 2	Warm
+ 1	Slightly Warm
0	Neutral
- 1	Slightly Cool
- 2	Cool
- 3	Cold

Thermal Comfort

+ 3	Very Uncomfortable
+ 2	Uncomfortable
+ 1	Slightly Uncomfortable
0	
- 1	Slightly Comfortable
- 2	Comfortable
- 3	Very Comfortable

Skin Wetness

0	**Dry**
1	
2	**Moist**
3	
4	**Wet**
5	
6	**Extremely Wet**

Discomfort Scale

0	**No Discomfort**
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	**Worst possible discomfort**

RPE

6	**No Exertion At All**
7	**Extremely Light**
8	
9	**Very Light**
10	
11	**Light**
12	
13	**Somewhat Hard**
14	
15	**Hard**
16	
17	**Very Hard**
18	
19	**Extremely Hard**
20	**Maximal Exertion**

General Symptoms

Headache

0	None at all
1	Mild
2	Moderate
3	Severe

Dizziness/ Light-headedness

0	None at all
1	Mild
2	Moderate
3	Severe

Mentally Confused

0	None at all
1	Mild
2	Moderate
3	Severe

Sickness

0	None at all
1	Mild
2	Moderate
3	Severe

Difficulty Breathing

0	None at all
1	Mild
2	Moderate
3	Severe

Tiredness

0	None at all
1	Mild
2	Moderate
3	Severe

Ethical documents

SECTION 1 SUMMARY OF KEY INFORMATION AND CHECKLIST OF POSSIBLE HAZARDS

Person(s) undertaking project:	David Walkland
Project supervisor:	Doug Thake

Brief outline of project:	The effect of wearing a liquid-cooled suit (LCS) under an explosives ordnance disposal (EOD) suit on the thermal strain experienced when walking (4 km·hr-1) on a treadmill for 60 min at 40°C will be investigated. Participants (n=12) will visit the laboratory for a familiarisation session followed by two experimental trials, applied using a cross-over design, each undertaken at least one week apart. The trials will be composed of wearing the same equipment configuration, an EOD suit + body and head LCS. One trial will be conducted with the body and head LCS actively cooling the participant. The other trail will be conducted with the LCS inactive. Thermal physiological strain will be measured throughout using a combination of skin surface temperature and heat flux sensors alongside indices of deep core body temperature (rectal and gastrointestinal) and perceptual information sought from participants. Metabolic rate will be calculated via respiratory gas analysis.

Dates of study (from – to)	1/03/2021 – 01/03/2022
Location(s) of activity: *Country and specific area.*	England – Coventry University

Will the project involve laboratory work? *If yes, you will be required to complete separate risk assessment(s) prior to carrying out any laboratory work.- this is section 2 of this form*	Yes / No
~~Will the project involve workshop work? (only relevant to engineering workshops)~~ ~~*If yes, you will be required to complete an induction and may carry out a separate risk assessment(s) prior to carrying out any workshop work.*~~	~~Yes / No~~

Will the project involve travel? *(If yes, complete this section as fully as possible. The form may require review prior to travel to add missing details)*		Yes / No
Contact details at destination(s): Contact details of next of kin in case of emergency:		
Approximate dates of travel:		
Arrangements to maintain contact with the University:		
Emergency contact information:	School/Faculty contact (Daytime): 02476 ..... 24hr University contact (Protection Service): 02476 888 555 Local healthcare/emergency services:	
Has suitable travel insurance been obtained? (*Please attach a copy of certificate*)		Yes / No
If EU travel, has EH1C card been obtained?		Yes / No
Has advice/vaccinations from GP been sought (*where appropriate*)?		Yes / No
Are medical kits required (*i.e. in countries with poor healthcare facilities*)?		Yes / No
Are there any warnings issued by the FCO* against travel to the area?		Yes / No
Have you registered with the FCO* service LOCATE? *(British nationals only)*		Yes / No

*FCO = http://www.fco.gov.uk/en/travel-and-living-abroad/travel-advice-by-country/

INDICATE ANY HAZARDS RELATING TO THE BOXES BELOW

IF ANY ARE NOT APPLICABLE CLEARLY INDICATE THIS- DO NOT JUST LEAVE BOXES BLANK

Hazard	Precautions to be used
Work factors: *E.g.: dealing with the public, interviewing on sensitive issues, lone working, driving, working on boats, laboratory work; biological, chemical hazards etc*	Laboratory work

Site specific factors (in the field): *E.g.: remote area, construction site, local endemic diseases, political unrest, terrorism risk etc* *If travel abroad see FCO* website – list any risks greater than there would be for the UK*	N/A

Environmental factors (in the field): *E.g.: extremes of temperature, altitude, weather conditions, tidal conditions, cliffs, bogs, caves, mountains etc*	High Ambient Temperatures

Equipment: *E.g.: operation of machinery, use of specialist equipment, manual handling/transportation, compressed gases, etc*	Operation of treadmill

Other: *Detail any special arrangements required, i.e. permissions required, accommodation, travel, catering etc*	

SECTION 2 DETAILS OF RISK ASSESSMENT

Detailed Description of Operation	Highlight hazard (e.g. grinding blade)	Actions needed to reduce risk
Treadmill	Risk of injury	Participants will be familiarised with the equipment prior to testing. This will include an introduction and 20 minute walk on the treadmill. Risk of accidents will be low as the intensities used will low and participants physiological and perceptual measurements will be tracked throughout. Participants will also be in a harness when walking on the treadmill which will automatically stop if there is a trip etc.
High ambient temperatures	Heat illness	Participants physiological and perceptual measurements will be tracked throughout.
EOD suit & exercise	Risk of syncope	Participants physiological and perceptual measurements will be tracked throughout.

High ambient temperatures with EOD suit and exercise	Heat illness	Participants physiological and perceptual measurements will be tracked throughout. An experimental trial will be terminated if; heart rate exceeds 95% of maximum (220-age) for 3 minutes, gastrointestinal or rectal temperature reach 39.5ºC or 3ºC greater than initial baseline temperature, whichever is the lowest.

(Add more rows to the table if needed)

1. Manufactures control or safety measures	
2. Training	
Date training received:	Date of laboratory / undertaking
Name of Trainer (Trained operator)	Doug Thake

3. Personal Protective equipment	
PPE required: COVID related PPE (see COVD-19 risk assessment)	
Are access restrictions necessary during operations for the safety of others	Yes No

4. Other equipment required	
Please give details and sources:	

5. Supervision or assistance required during operation?
Please give details of supervisor or assistant. Doug Thake

RISK ASSESSMENT: This part must be completed by named operator and supervisor	
Assessment of risk to named operator when carrying out operation WITHOUT implementation of risk reduction measures	Assessment of risk to named operator when carrying out operation WITH implementation of risk reduction measures
Low	Low
Medium	Medium
High	High

Assessment review period as agreed between supervisor and operator.	This assessment is valid for the period of the student project only i.e. from 01/03/2021 until 01/03/2022

Student	Supervisor
I have carried out a thorough risk assessment and will implement the risk reduction methods so that I and others in vicinity may be safe. I understand that I should not continue to use the equipment after the end date above unless the risk assessment form has been reviewed and updated.	I agree that this is a thorough risk assessment and that the risk reduction methods are appropriate so that the operator and others in vicinity may be safe.
Signed [redacted] Date: 12/03/2021	Signed: [redacted] Date: 17/03/2021

Risk Category:		High		Medium	√	Low			Ref No.				
Department/School: CSELS							Section: DASH						
Task/Operation Being Assessed:				Guidance for the COVID secure management of human participants visiting CU research facilities.									

Purpose/Method of Work

This is a generic risk assessment document highlights the need for investigators to consider the management of participants recruited to studies that require them to visit research facilities and related premises on Coventry University campus during the COVID19 era. Notwithstanding ethical decisions around known COVID19 high-risk groups whom would usually be targeted for participation in certain investigations, researchers are also encouraged to consider designing projects that require minimal participant visits to campus. This may take the form of a potentially larger study being broken down and relative bite size investigations prioritised that address principle aspects of the research question(s).

The document outlines a generic risk assessment for managing COVID19 risk around people visiting Coventry University campus as research participants. This approach assumes that participant attendance on campus is solely due to their involvement in a specific research study and accordingly responsibility for informing them of local COVID19 mitigation requirements is that of the persons involved in the study. It is highlighted that this includes a participant's presence on campus prior to and after leaving the specific research venue.

Although the screening procedure noted within reduces the risk of a person infected with *SARS-CoV-2 entering a University building the assumption remains that all persons may potentially transmit or become infected by the virus.*

This document should be considered as an adjunct to risk assessments for specific investigations.

Persons affected	Level of Skill/Training Required
Principal Investigators. All those working with human participants on Coventry University campus	High. Overseen by principal investigators, all research team members usually (staff, postgraduate) will be familiar with the risk and mitigation outlined within.
Internal Procedures	

Main Hazards Involved/Encountered	Control Method in Use/Required

Participant recruitment, screening and consent	Participants will be recruited using the methods approved by CU ethics committee. Prior to visiting the campus participants will be required to complete the COVID19 screening tool alongside a health screen questionnaire and study consent form on-line / return electronic file(s) to the corresponding investigator. Once reviewed the investigator will reply to the individual and confirm their attendance or withdraw them from the study. Prior to consent investigators will provide participants with a participant information sheet that outlines their potential involvement in the study as well as the COVID19 mitigation to be followed throughout. Investigators are then encouraged to have an on-line discussion or telephone conversation with the perspective participant to enable them to field questions and queries around the investigation and/or COVID19 risk. Under no circumstances should any potential participant be invited to visit the campus without having returned a completed COVID19 screening tool. If the study requires participants to visit the campus more than once it is noted that the COVID19 screening tool should be completed as close to each visit as possible alongside the health screen questionnaire and preferably on the day or the day before the visit. Participants will be informed that they must let the principal investigator know of any change in circumstances as soon as possible.
Prior to arrival on test day	Prior to participant arrival, participants scheduled for testing should be contacted to enquire about new onset of COVID-19 symptoms (dry cough, breathlessness, fever, migraine) prior to attending the site. This should be done to reduce the chances of turning away participants on arrival thus pro-actively reducing potential transmission and the participant traveling unnecessarily. Immediately on arrival at CU the participant will be met outside the building at a defined location by an investigator whom will also act as their chaperone throughout the visit. Prior to entry to any building the participant will be asked if their responses to the COVID19 screening tool (and health screen questionnaire) have changed since they completed it (ideally within the preceding 24 hrs). If they report any

	change that alters the risk associated with their involvement they will not be admitted to the building and directed to follow current public health advice.
Arrival at host building	On entry to the building participants will be directed to review the local COVID19 information stands/posters available at each entry point alongside applying alcohol gel/rub to their hands. They will also be required to sign in. Throughout the visit both the participant and investigators are encouraged wear face masks, if they are able to do so, and maintain 2 metre social distancing. Wearing a face mask is essential in 'pinch point' areas such as toilets, corridors, lifts and any enclosed space were social distancing could be breached. The investigator will lead the participant to the research venue limiting their contact with fomites (e.g. doors and other surfaces) throughout.
Navigation through host building to research venue	Researcher and participant will use alcohol gel/ hand rub on arrival. The participant's arrival at the research venue will be recorded and their contact details checked. They will also be encouraged to contact the research team should they experience any COVID19 symptoms over the coming one to two weeks after their participation. In such an instance the research team will report this to the University using the following link: Coronavirus reporting https://livecoventryac.sharepoint.com/sites/coronavirus-reporting In addition, the team will review the signing in log book and inform individuals whom were known to be in the vicinity of the participant. Under such circumstances the investigators will be required to leave the campus and be tested for the virus before continuing to work with any participants. In advance of any participant visiting the university the research team will have identified toilets in the vicinity of

Arrival at venue (potential for track and trace).	the research venue that participants will be directed to (ideally those with the lowest usage, single occupancy with no or nominal queuing). In addition to alcohol gel / rub used by visiting participants they will be asked to use more (where the researcher has sight of them) on returning to the research venue. Toilet facilities are currently being deep cleansed by facilities staff at least twice daily. Although many investigations require participants to undertake activities that will result in them sweating and getting wet (e.g. exercise at high intensities and/or be exposed to extreme heat, hot/cold water immersion) no shower facilities will be available. Accordingly, participants should be advised to bring a change of clothing for their own comfort after participation. The requirement and facilities available for changing clothes must be considered. Participants changing in toilets is deemed an unacceptable viral transmission risk. Participants that are required to undertake exercise will be encouraged to arrive in their exercise kit. A private space within the research area will be made available for changing. This may take the form of a separate room / cupboard space / screened area or simply be researchers stepping out of the venue.
Use of amenities during visit (toilets and showers)	The requirement for refreshments will depend on the nature of investigation being conducted e.g. *ad libitum* fluid consumption during exercise may or may not be allowed. Participants should be encouraged to bring their own refreshments. Ideally a water bottle of adequate volume, to avoid the need for refilling, for the entire visit. If refilling is required the participant should be asked to do this themselves, if possible, avoiding contact with fomites e.g. turn taps with tissue / gloved hand. Alternatively the investigators may provide bottled water or other prepacked appropriate beverages. These should be stored and accessible rather than hand held and passed between people. Often the majority of fluid is consumed during recovery from an exercise bout / activity, possibly when a person is fatigued and less likely to readily adhere to COVID mitigation procedures. Accordingly, researchers should be particularly vigilant in pre-empting this and guide / remind participants around their actions when fatigued.

Changing facilities	Foodstuffs should not be consumed in a research venue unless part of the specific protocol. Investigators should continue to use PPE as and when appropriate to protect against non-COVID risks. Investigators in the vicinity (same room, closer than 2 metres) of participants are obliged to be fully aware and versed in COVID transmission mitigation procedures. Although prior screening will have been undertaken to insure that participants are unlikely to be SARS-COV-2 positive, and that the researcher(s) are also SARS-COV-2 negative, the potential for transmission should be assumed and in accordance strict guidance adhered to.
Refreshments	*Social distancing and hygiene are key to a COVID19 secure environment with the addition of PPE generally only providing minimal additional protection, unless the risk of viral transmission is deemed very high. Due to the greater potential risk of viral transmission when needing to work closely with human participants* additional / varied PPE is deemed appropriate for various procedures. A common risk being when human participant respiratory patterns that potentially result in droplet and /or possible aerosol generation (e.g. intense exercise, coughing and shouting). Furthermore, when face to face contact cannot be avoided due to requirements of measurement / sample techniques appropriate face coverings should be worn e.g. FFP3. **General regulations for laboratory practice where physical contact is required.** The mitigating steps discussed below are in line with or exceed the current expert advice from the Physiological Society outlined in the following web page: https://www.physoc.org/covid19/returning-to-the-lab/resuming-laboratory-testing-with-human-participants/ **General regulations for PPE:**

Personal Protective Equipment (PPE)	For researchers appropriate PPE will include eye and face protection and a disposable gown. Face protection could include either an appropriately fitted facemask or face protector/visor which covers the entire face to below the chin. Face protectors can be re-used but requires appropriate disinfection as detailed below. This information is based on the latest government advice on effective PPE use in health and social care sector. https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control/covid-19-personal-protective-equipment-ppe The full COVID-19 guidance collection is available at https://www.gov.uk/government/collections/coronavirus-covid-19-list-of-guidance Is it noted that if Aerosol Generating Procedures (AGPs) are not being undertaken then the advice in all healthcare settings is to wear the standard droplet protective equipment. As such Fluid Resistant Surgical Mask (FRSM), with a visor (or goggles), disposable gloves, disposable plastic apron. Where a higher level of personal protective equipment is required because of the potential for generating an aerosol. (In healthcare referred to as - Aerosol Generating Procedures; AGP's). The following is recommended: FFP3 mask, with a visor (or goggles), disposable gloves, long sleeved fluid repellent disposable gown. Note: any facemasks and respirators worn must be fit checked. Researchers using PPE are required to apply correct donning (putting on) and doffing (taking off) procedures. For example see' PPE a guide for hospital clinical staff'. https://youtu.be/kKz_vNGsNhc When 2 researchers are present, they should be encouraged to check over their colleagues PPE to ensure it is correctly worn. They can also assist with the donning

	and doffing of PPE as demonstrated in the afore noted guide. As the requirement to wear PPE is based on protecting the wearer from the potential transmission of the virus it must be assumed that all PPE is potentially contaminated. Accordingly, all **PPE will be disposed of in laboratory clinical waste.** For example see 'Correct order for the removal and disposal of PPE' https://youtu.be/oUo5O1JmLH0 **NOTE:** Expert guidance on PPE recommends that gloves are not a necessity when conducting 'hands on' procedures and may in fact increase the spread of the virus. As such, regular and thorough hand washing before during and immediately after any 'hands-on' contact with a participant is essential. Gloves should be worn as they would be for any non-COVID procedure (e.g. collecting bodily fluids or are handling equipment contaminated with bodily fluids) whilst following standard infection control procedures. This includes single use and immediate disposal without touching and potentially contaminating any other equipment. Any adverse events will be reported, as usual, via the 'accident reporting' link on the staff portal homepage. If anyone develops COVID19 symptoms whilst on campus the COVID19 symptoms action link will be accessed and advice followed via: https://share.coventry.ac.uk/staff/ps/estates/Pages/COVID-Return-to-Campus-Staff.aspx Staff and students experiencing symptoms should report this and follow guidance via the following link: https://livecoventryac.sharepoint.com/sites/coronavirus-reporting The research team will stagger the arrival of participants to minimise the number of individuals in the research venue

	at one time. They will also need to allow time for the area to be fully cleansed between each participant. Where the venue is occupied by multiple people (researchers and/or participants) spaces will be rearranged to enable 2 metre social distancing to be upheld. This may take the form of demarcated areas/ zones allocated to individuals (temporary floor markings/tape). Face to face working will be avoided where possible. Where this is not possible masks will be worn. Once a trial has been completed and the participant adequately recovered to leave the research venue. The participant will be signed out (lab and building) and escorted outside. As should be the case with non-COVID risk researchers will be aware of fire evacuation and first aid points. Note that in the event of a fire evacuation social distancing should be maintained where possible. **General regulations of disinfection:** Surfaces that may have been contaminated by respiratory droplets e.g. during exercise tests should also be cleaned with detergent and water/disinfectant wipes. Surfaces should be kept free of 'clutter' to facilitate ease of disinfection. Wipe down all surfaces with virucidal solutions/alcohol wipes when used (e.g. handles on kit, keyboards) and fully clean all surfaces at the end of each testing session and day. All equipment which has come into contact with the participant should be sterilised, this will include masks, turbines, sample lines, heart rate monitors etc.). Milton disinfecting fluid is an appropriate solution for respiratory equipment. Decontamination: chlorine-based cleaning solutions have demonstrable ability to clear the virus from surfaces. Soap and water is also effective due to its action disrupting the lipid layer that encases the virus. Current WHO disinfection

	recommendations include the use of: 70 % Ethyl alcohol to disinfect reusable dedicated equipment (e.g. thermometers) between uses. Sodium hypochlorite at 0.5 % (equivalent 5000 ppm) for disinfection of frequently touched surfaces Treat anything worn in the laboratory (by participant and researchers as “infected” and dispose of it carefully before washing hands. Clothes can be disinfected by heating to approx. 56 °C for 45 mins. · Protective face screens should be cleaned (alcohol wipes or soap and water) on removal.
Report pathway for an adverse event	

Management of participants **General health and safety points** **(Fire evacuation and first aid)** **Cleaning laboratory space**	

Chemicals/Materials Involved	Assessment Date
Disinfectants	

Specific Work Equipment Provided

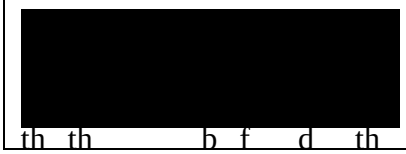
Manual Handling Risk	
None	
Is a detailed assessment required?	

Personal Protective Equipment Used		
Is training and instruction required?	YES	
Is there need for special storage?		NO
Is there need for test/examination?		NO
Is all P.P.E compatible?	YES	
Is there a need for further assessment?		NO

Monitoring: How will the effectiveness of controls be monitored and by whom?
Principal investigator (and research team) takes overall responsibility
Incident reporting
All incidents must be reported. This should be done as soon as practicable after the incident has been identified to ensure that the most accurate and complete information is recorded. Incidents are logged via the following link, available on the staff intranet homepage:https://federatedauth.coventry.ac.uk/adfs/ls/

Assessment Review Period				
1 year √	2 years	3 years	4 years	5 years

This general risk assessment will be updated should the circumstances surrounding COVID-19 change.

This assessment has been undertaken in pursuance of the legal duties imposed by the Management of the Health & Safety at Work Regulations 1999		
Signed  th th b f d th	Position/Title Associate Professor	Date 17/09/20

B) Informed consent & participant information sheet

INFORMED CONSENT FORM:

'Characterising the cooling capability of a liquid cooled suit for use in EOD operations in hot ambient conditions.'

You are invited to take part in this research study for the purpose of collecting data on characterising the cooling capacity of a liquid-cooled suit worn under an explosives ordnance disposal suit.

Before you decide to take part, you must **read the accompanying Participant Information Sheet.**

Please do not hesitate to ask questions if anything is unclear or if you would like more information about any aspect of this research. It is important that you feel able to take the necessary time to decide whether or not you wish to take part.

If you are happy to participate, please confirm your consent by circling YES against each of the below statements and then signing and dating the form as participant.

1	**I confirm that I have read and understood the Participant Information Sheet for the above study and have had the opportunity to ask questions**	**YES**	**NO**
2	**I understand my participation is voluntary and that I am free to withdraw my data, without giving a reason, by contacting the lead researcher and the Research Support Office at any time until the date specified in the Participant Information Sheet**	**YES**	**NO**
3	**I have noted down my participant number (top left of this Consent Form) which may be required by the lead researcher if I wish to withdraw from the study**	**YES**	**NO**
4	**I understand that all the information I provide will be held securely and treated confidentially**	**YES**	**NO**
5	**I am happy for the information I provide to be used (anonymously) in academic papers and other formal research outputs**	**YES**	**NO**
7	**I agree to take part in the above study**	**YES**	**NO**

Thank you for your participation in this study. Your help is very much appreciated.

Participant's Name	**Date**	**Signature**
Researcher	**Date**	**Signature**
David Walkland		[redacted]

Characterising the cooling capability of a liquid cooled suit for use in explosives ordnance disposal operations in hot ambient conditions

PARTICIPANT INFORMATION SHEET

You are being invited to take part in research to quantify the cooling capacity of a liquid cooled suit (LCS) worn under an explosives ordnance disposal (EOD) suit. Dr Doug Thake, Associate Professor at Coventry University is leading this research. Before you decide to take part it is important you understand why the research is being conducted and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

The purpose of the study is to investigate and quantify the benefit of wearing a liquid cooling suit (LCS) worn under an explosives ordnance disposal (EOD). The study aims to investigate the effect off cooling provided to the body and head when the ambient temperature (40°C) is above resting core body temperature (37 +/- 0.5 °C). This study will potentially contribute to informing the management of thermal stress experienced by EOD operatives.

Why have I been chosen to take part?

You are invited to participate in this study because you are physically representative of and within the age range of the population whom wear EOD suits in operational situations.

What are the benefits of taking part?

By sharing your experiences with us, you will be helping Dr Doug Thake and Coventry University to better understand the cooling capacity of a specific liquid cooled suit and the effect of this has on the thermal strain experienced by individual wearing an EOD suit in warm and hot conditions.

Are there any risks associated with taking part?

This study has been reviewed and approved through Coventry University's formal research ethics procedure. There is a nominal risk of fainting (syncope), due to wearing a heavy load and exercising in the heat. There is also a risk of heat illness, however, your physiology (including heart rate and core body temperature) will be continuously monitored and appropriate safety measures are in place to ensure the risk is minimal. For your safety, an experimental trial will be terminated if; heart rate exceeds 95% of maximum (220-age) for 3 minutes, gastrointestinal or rectal temperature reach 39.5ºC or 3ºC greater than initial baseline temperature, whichever is the lowest. The regularly seeking responses to subjective scales the research team will also be aware of your level of comfort, physical exertion and well-being you are experiencing throughout each trial.

If you are unable to continue with a trial for any reason at any time let the investigator know as soon as possible and the trial will be stopped (for example raise both hands or stand astride the treadmill). You can of course elect to withdraw at any point throughout the study or within any trial.

COVID 19

You are being asked to participate in this investigation during the COVID19 pandemic. Accordingly, there is a risk of viral transmission between you, the participant, and the researchers as well as via incidental contact due to visiting the University. By agreeing to participate in this study you are also agreeing to follow our COVID19 risk reduction measures whilst on the University premises. We will talk you through our procedures and remind you of them throughout your visit. Please feel free to ask us anything about the investigation and the measures we have in place to reduce the risk of COVID19 at any time. Our procedures are as follows:

- Prior to attending the University you will complete a COVID19 screening questionnaire (sent to you as a word.doc file alongside a physical activity readiness questionnaire, this participant information sheet and the associated consent form). The COVID19 screening tool will be completed prior to each visit and forwarded to the investigator the day before your visit (send to d.thake@coventry.ac.uk). In addition we will hold your contact details should these be required by us to contact you through the University's COVID19 track and trace system.

- Prior to leaving home on the day of an experimental trial an investigator (either Dr Sarah Davey, Dr Ben Lee or Dr Doug Thake) will call your phone to confirm your previously reported COVID19 status. If safe to do so you will the visit the University as timetabled.

- On arrival at the University you will be met outside the building as a previously agreed place. You will be briefed on COVID19 guidance in our buildings (including alcohol hand gel on entry, social distancing and wearing a face mask whilst moving in close proximity, less than 2 m apart, throughout communal spaces) and be escorted to the laboratory.

- Within the laboratory you are assured that investigators will wear appropriate PPE throughout their interaction with you and that all kit and equipment will have been cleansed and prepared to the highest standards according to COVID19 related risk assessments. You will be guided and assisted to minimise the risk of transmitting COVID19 as appropriate throughout your visit.

- After the trial you will be escorted out of the building.

- You agree to inform us of any COVID19 related symptoms, should you experience any, for 14 days after your visit.

Do I have to take part?

No – it is entirely up to you. If you do decide to take part, please keep this Information Sheet and complete the Informed Consent Form to show that you understand your rights in relation to the research, and that you are happy to participate. Please note down your participant number (which is on the Consent Form) and provide this to the lead researcher if you seek to withdraw from the study at a later date. You are free to withdraw your information from the project data set at any time until the data are fully anonymised in our records on 31/06/2021. You should note that your data may be used in the production of formal research outputs (e.g. journal articles, conference papers, theses and reports) so

you are advised to contact the university at the earliest opportunity should you wish to withdraw from the study. To withdraw, please contact the lead researcher (contact details are provided below). Please also contact the Research Support Office [email hls.rso@coventry.ac.uk; telephone +44 (0)24 7765 3805] so that your request can be dealt with promptly in the event of the lead researcher's absence. You do not need to give a reason. A decision to withdraw, or not to take part, will not affect you in any way.

What will happen if I decide to take part?

You will attend the environmental chamber on three occasions. The first visit will be for a familiarisation session (approx. 2 hour). The further two visits will be for experimental trials (up to 3hrs in total for each visit). You are required to bring shorts to each session. Owing to COVID19 showering facilities will not be made available to you, so please bring additional clothing so that you are comfortable on your way home. On the first visit you will be asked a number of questions regarding the physical activity you regularly undertake and your level of fitness. You will also be required to complete a physical activity readiness questionnaire prior to participation on each laboratory visit.

Familiarisation session

On arrival, you will be asked to go to a private changing area, take your clothes off, step onto some weighing scales and record your naked bodyweight. You will then insert a rectal thermistor wire 10cm past the anal sphincter and loosely loop the remaining wire once around your underwear. You will then put on your shorts, return to the laboratory and your height will be measured. You will then step onto a Tanita measurement system that will be used to estimate total body water and fat mass. Skin folds will then be measured using skin fold callipers at the following sites: biceps- vertical fold, on the anterior aspect of the arm over the belly of the biceps muscle, 1cm above the level used to mark the triceps site. Triceps- vertical fold, midway between the acromion and olecranon processes, with the arm held freely to the side of the body. Subscapular- diagonal fold (at a 45° angle), 1 to 2cm below the inferior angle of the scapular. Suprailiac- diagonal fold, in line with the natural angle of the iliac crest taken in the anterior axillary line immediately superior to the iliac crest. Each skin fold measurement will be taken three times in a rotational order, rather than consecutive readings at each site, waiting 1-2 seconds whilst maintaining a pinch before reading the calliper.

A monitoring system to measure your heart rate, skin temperature and breathing rate will then be worn around the chest. A wristband will also be worn to collect wrist temperature. After these items have been attached you will put on a cotton t-shirt and fatigue trousers (both provided). You will then be sized up for the best fitting boot and sock combination (both provided) that you will then wear throughout each subsequent visit.

The EOD suit will then be donned (put on) with the help of the research team. Prior to wearing the helmet, a facemask will be applied for respiratory gas analysis. Thereafter you will be asked to step onto weighing scales before moving into the environmental chamber and walking on the treadmill at 4 $km \cdot hr^{-1}$ for a period of 20 minutes. During the treadmill walk, at 5 minute intervals, you will be asked to report your rating of perceived exertion (overall, lower body and upper body), thermal sensation, thermal comfort and skin wetness for defined body areas (head, face, shoulders and chest, arms, back, legs and feet). In addition you will be asked if you are experiencing any general symptoms including light-headedness, confusion, difficulty breathing and on a separate scale whether you are experiencing any pain. You will have been shown these perceptual scales prior to donning the EOD suit.

After this 20 min period, you will dismount the treadmill and then be weighed. The EOD suit and monitoring systems will then be removed and you will return to the changing area. You will remove the rectal thermistor, wipe it and place it in disinfectant. You will then dry yourself before standing on weighing scales and recording your nude body weight. Thereafter you are free to get changed.

Prior to leaving the laboratory, you will be given a core temperature pill for the measurement of gastrointestinal temperature on your next laboratory visit. You will be required to swallow this at least 3 hours before visiting the laboratory. If visiting the laboratory in a morning slot the pill can be ingested before going to bed the night before. If an afternoon slot the pill can be ingested on waking.

Experimental trials

The two experimental trials will be at least one week apart and always undertaken at the same time of day. The two trials are comprised of wearing the same equipment configuration, an EOD suit + body and head Liquid Cooling Suit (LCS). One trial will be conducted with the body and head LCS actively cooling the participant. The other trial will be conducted with the LCS inactive. Both trials will be conducted at an ambient temperature of 40°C. Some participants will experience the active cooling in their first trial and others will experience it in their second trial. Prior to arrival at the laboratory, you will have ingested a core temperature pill as noted at the end of the section above.

You will report to the laboratory and go to a private changing area, take your clothes off, step onto some weighing scales and record your naked bodyweight. You will then insert a rectal thermistor wire 10cm past the anal sphincter and loosely loop the remaining wire once around your underwear. You will then put on your shorts, return to the laboratory and step onto a Tanita measurement system that will be used to estimate total body water and fat mass.

A monitoring system will then be worn around the chest to measure your heart rate and skin temperature and breathing rate. A wristband will be worn to measure wrist temperature. Six heat flux sensors (3.5cm discs) that also measure temperature will be taped to your skin at the following locations (mid front thigh, lower lateral calf, front chest, apical[below the armpit], upper arm and upper back). After this you will put on a cotton t-shirt and fatigue trousers (both provided). You will then sit at rest for 15 minutes so baseline measurements can be made (at 5 min intervals) from the devices you are wearing (ambient temperature approximately 22°C).

The LCS and then the EOD suit will then be donned (put on) with the help of the research team in a fixed time period (10 min). Prior to wearing the helmet, a facemask will be applied for respiratory gas analysis. Thereafter you will be asked to step onto weighing scales. You will then move into the environmental chamber (40°C / 30% RH), stand for 5 minutes and then mount and walk on the treadmill at 4 $km \cdot hr^{-1}$ for a period of 60 minutes. During the treadmill walk, at 5 minute intervals, you will be asked to report your rating of perceived exertion (overall, lower body and upper body), thermal sensation, thermal comfort and skin wettness for defined body areas (head, face, shoulders and chest, arms, back, legs and feet). In addition you will be asked if you are experiencing any general symptoms including light-headedness, confusion, difficulty breathing and on a separate scale whether you are experiencing any pain. Physiological measures will be continuously transmitted, either directly or via a data logger to a laptop computer. Immediately after the completing the treadmill walk you will then be weighed. The EOD suit and monitoring systems will then be removed and you will return to the changing area. You will remove the rectal thermistor, wipe it and place it in disinfectant. You will then dry yourself before standing on weighing scales and recording your nude body weight. Thereafter you are free to shower and get changed.

In trials where the LCS is active the coolant (water) that is circulated around the suit from an attached reservoir containing ice (1.5 kg of ice and 0.5 kg of water in the reservoir plus 0.35 kg of water already within the LCS). The LCS pump will be switched on when entering the environmental chamber. In trials where the LCS is inactive the reservoir will be filled with 2kg of water to replicate the loading experienced by participants in the active LCS condition.

Data Protection and Confidentiality

Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR) and the Data Protection Act 2018. All information collected about you will be kept strictly confidential. Unless they are fully anonymised in our records, your data will be referred to by a unique participant number rather than by name. All electronic data will be stored on a password-protected computer file on a research team laptop. All paper records will be stored in a locked filing cabinet on the 4th floor of the Richard Crossman building, Coventry University. Your consent information will be kept separately from your responses in order to minimise risk in the event of a data breach. The lead researcher will take responsibility for data destruction and all collected data will be destroyed on or before 31/12/2022.

Data Protection Rights

Coventry University is a Data Controller for the information you provide. You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation and the Data Protection Act 2018. You also have other rights including rights of correction, erasure, objection, and data portability. For more details, including the right to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk. Questions, comments and requests about your personal data can also be sent to the University Data Protection Officer - enquiry.ipu@coventry.ac.uk

What will happen with the results of this study?

The results of this study may be summarised in published articles, reports and presentations. Quotes or key findings will always be made anonymous in any formal outputs unless we have your prior and explicit written permission to attribute them to you by name.

Making a Complaint

If you are unhappy with any aspect of this research, please first contact the lead researcher, [Dr Doug Thake, d.thake@coventry.ac.uk]. If you still have concerns and wish to make a formal complaint, please write to:

Prof Richard Aspinall

Associate Dean for Research

Coventry University

Coventry CV1 5FB

Email: ac8908@coventry.ac.uk

In your letter please provide information about the research project, specify the name of the researcher and detail the nature of your complaint.

C) Worked example of cooling calculations

Heat storage calculation process for each participant

	EODP1	NC	C		HS (NC)	HS (C)		HS difference		Watts
Body mass	5	2.6	1.4		244467	133056		111411		371
95.2	10	3.3	1.6		311775	154920		156855		261
	15	4.2	2.5		403271	239791		163480		182
	20	4.6	3.1		437381	290533		146848		122
	25	5.4	3.6		510917	342239		168678		112
	30	5.9	4.1		560272	393912		166360		92
	35	6.4	4.6		607282	442322		164960		79
	40	7.1	5.1		678520	484048		194473		81

Inlet and outlet calculation process of each participant

Circuit volume (ml)	EODP2	Inlet	Outlet	Increase	°C needed	j/ml		Watts
335	5	12.7	18.1	5.4	4.2	1407	7598	204
	10	14.0	19.6	5.6	4.2	1407	7809	210
Flow Rate (ml/s)	15	16.0	21.7	5.7	4.2	1407	7967	214
9	20	18.0	23.7	5.7	4.2	1407	8073	217
	25	20.5	25.9	5.4	4.2	1407	7580	204
Time to get around the whole suit (s)	30	24.1	28.0	4.0	4.2	1407	5575	150
37	35	30.0	32.3	2.2	4.2	1407	3131	84
	40	33.5	34.8	1.3	4.2	1407	1876	50