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Thermal response during explosive ordnance disposal operations optimising the use of phase change material vests in hot conditions

Smith, Mark Adam

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Thermal Response during Explosive Ordnance Disposal Operations: Optimising the use of Phase Change Material Vests in Hot Conditions

M.A. Smith

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Faculty of Health and Life Sciences, Coventry University, Coventry CV1, 5FB UK

Abstract

Purpose: The aim of this study was to evaluate the thermal physiological and perceptual influence of replacing a torso covering phase change cooling material (PCM) under a Mk6a Explosive Ordnance Device (EOD) suit after one hour of EOD activity representative of that undertaken during explosive ordinance disposal activity in hot environments (40 °C)

Method: Following ethical approval from the Coventry University Ethics committee six non heat acclimated male volunteers (age 22±3 yrs; body mass 78.1±9.3 kg; stature 176.3±6.5 cm) participated in this investigation. Three trials were conducted by each participant at an ambient temperature of 40 °C whilst wearing a 38 kg EOD suit (Mk6, NP Aerospace, UK). The protocol was comprised of three 16 minute 30 second activity cycles; 10 minute rest (helmet, shield, jacket and PCM vest, if worn, were removed and donned in first and last 90 seconds respectively); three 16 minute 30 second activity cycles (a total of 109 min) that took place within a 3 m × 5 m enclosed area. Each activity cycle consisted of treadmill walking, manual activity, crawling and searching, arm ergometry and seated rest. In a randomised cover-over type design participants did not wear PCM (NoPCM); wore one PCM vest throughout (PCM1) or changed the PCM vest in the 10 minute rest period (PCM2). The PCM vests used, phase changed at 25°C and were worn over a cotton t-shirt. Data was analysed using a general linear model analysis of variance (ANOVA). Significant (P<0.05) main effects for condition, time and condition × time interaction were investigated using Tukey post hoc tests.

Results: In all three conditions thermal physiological strain increased with activity duration and was greatest following a ten minute break (P<0.001, main effect for time for all variables). During the first three activity cycles responses were greatest in PCM conditions and tend to be similar within PCM1 and PCM2 conditions. Perceived rate of exertion (RPE),

thermal sensation and thermal comfort followed this same trend ($p<0.001$, Main effect for time). Observations during the ten minute rest period (49:30-59:30,min:sec) identified that the PCM during PCM1 and PCM2 trials had completely melted during the first 3 activity cycles. Physiological strain indices (PhSI) was reduced during the rest period (49:30-59:30,min:sec) by 1.2±0.6 across all three conditions. During the final 3 activity cycles heat storage (S) increased at the greatest rate within PCM1 trials and at the lowest rate with PCM2 trials ($p<0.001$). No significant difference was identified between NoPCM and PCM1 trials post break (NS for core temperature (T_c), mean skin temperatue (T_{msk}), and heart rate (HR)) with significantly reduced strain within PCM2 trials ($p<0.01$ for HR and $p<0.001$ for T_c and T_{msk} in comparison to NoPCM and PCM1). Perceptual strain indices (PeSI) and perceptual data was lowest post break within PCM2 trials in comparison to NoPCM and PCM1 ($P<0.001$). Overall sweat production for trials reflected the physiological response with greatest level of sweat identified in NoPCM and least in PCM2 trials.

Conclusion: Wearing a PCM vest during simulated EOD activity for 50 minutes had no significant impact on heat strain despite the PCM completely melting during this period. Heat strain was reduced during a second 50 minutes bout of EOD activity when a new PCM vest was worn, but not when the melted vest from the first work period was re-applied. Following 50 minutes of EOD activity in 40°C no significant increases were identified in T_{re} or $T_{gi.}$ Irrespective of a PCM being worn HR, T_{msk} and S all increased to the same level. Following a second 50 minutes of EOD activity, rectal temperature (T_{re}) and gastro-intestinal temperature (T_{gi}) increased significantly with $T_{msk,}$ HR and S continuing to rise. No indicators of heat strain ($T_{re,}$ $T_{msk,}$ $T_{gi,}$HR, S or PhSI) was reduced in PCM1 trials compared to control however all were significantly lower when a new charged vest was worn (PCM2).

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Contents

Abbreviations

ANOVA- Analysis of Variance

EOD- Explosive Ordinance Disposal

n -Number of Participants in the sample

RH-Relative Humidity

PPE-Personal protective Equipment

T_c- Core Temperature

T_{sk}- Mean Skin Temperature

T_{gi-} Core Temperature identified via CorTemp® gastro-intestinal pill.

S- Heat Storage

HR-Heart Rate

PSI-Physiological Strain Index

PhSI-Modified Physiological Strain Index

PeSI-Perceptual Strain Index

TS-Thermal Sensation

TC-Thermal comfort

RPE-Rating of Perceived Exertion

1 Introduction

Physical activity in hot environments can cause many physiological changes to the body in comparison to physical activity within a cool environment (Casa, 1999) however metabolic rate has an impact. When exercising the body heats up due to metabolic heat production and when in a hot environment the body's ability to dissipate heat by heat loss pathways (radiant, conduction, convection and evaporation) are impaired (Casa, 1999). This reaction is amplified with increased load carriage due to increased metabolic production and whilst wearing personal protective equipment (PPE) particularly in environments with a high relative humidity (RH). The body can no longer dissipate heat, causing increased heat storage resulting in a subsequent increase in Core Temperature (T_C) and increased thermal physiological strain.

Within a range of occupational and sporting settings personal protective equipment (PPE) is vital to reduce risk from injury and protect the wearer from threats such as impact injury or chemical exposure. A negative factor of PPE, particularly military based PPE such as Explosive Ordnance Disposal (EOD) suits, is their low levels of water vapour permeability and low evaporative efficiency due to their nature of encapsulation. This significantly increases heat storage of individuals wearing them (Hanson 2006). Such PPE also increases metabolic heat production of wearers who have to carry the additional weight. When wearing PPE the low level of water vapour permeability creates a micro-climate between the skin and clothing with the capacity for cooling being lower than that required by the environment creating an Uncompensable heat stress environment (UHS). A UHS environment is defined as when the amount of evaporative heat loss required to maintain a thermal steady state exceeds that of the maximal evaporative capacity of the environment (Cheung *et al.* 2000). Personal protective equipment with greater levels of encapsulation are more likely to cause

UHS environments as there is less capacity for convectional heat loss. EOD suits are likely to have small entrance areas for airflow through the suit such as sleeves. This will help maintain a thermal steady state dependant on the velocity of air movement and ambient temperature.

Physiological responses such as core temperature (T_c), skin temperature (T_{sk}), heat storage (S) and Heart Rate (HR) have all been shown to demonstrate large increases when working in hot environments within PPE (Thake & Price, 2007) as well as perceived rate of exertion (RPE) and perceived thermal sensation and comfort all contributing to physiological strain and reduced time to exhaustion. Previous research (Thake & Price, 2007; Thake *et al.* 2009) has identified that T_c rises in a biphasic pattern during laboratory based physical activity representative of EOD operations within hot environments. T_c rise increases more rapidly between 30 to 45 minutes and is coincident with T_{msk} becoming closer to T_c.

To counterbalance the negative effect that PPE and activity in heat can have on operational performance interventions have been designed and investigated (Vallerand *et al.* 1991). Manipulation of the body's heat storage capacity by training and influencing hydration status (Cheung & Mcllelan, 1998) has been widely investigated. It has been identified that individuals with a higher aerobic capacity have the ability to tolerate a higher T_c level.

Programmes of acclimation and habituation in hot environments within PPE have also been examined to help improve physiological and perceptual responses (Thake *et al.* 2009) within hot environments. Acclimation takes place through increased exposure to hot environments to examine physiological improvements allowing for increased tolerance to exercise within heat. Studies have identified significant reductions in T_c, heat storage and heart rate when an acclimation programme has been adhered to (Thake *et al.* 2009). Whilst acclimation can help to increase tolerance and improve sweat rate to maintain thermal steady state within hot environments this may not prove to always be beneficial within encapsulated PPE where a greater sweat rate may not maintain T_c due to lack of evaporative capacity.

More common methods of intervention to reduce thermal physiological and perceptual strain include equipment configurations and implementation of cooling devices. Thake and Price (2007) identified that a light weight trouser design within an EOD suit can attenuate thermal comfort and increase exposure tolerance time when exercising in heat. They also identified that a dry iced cooling system to actively cool operatives can also reduced thermal discomfort. Frim and Morris (1992) examined three cooling devices (Liquid cooled undergarment, thickly ribbed vest of hydrophilic nylon and an air vest) and reported significant reduction in S, T_c and HR. A thickly ribbed vest becomes beneficial in its ability to create a space between the PPE and body to allow for sweat loss and a flow of passive air through the suit. This may not be beneficial in fully encapsulated PPE as airflow within the suit may not be present. An air vest may prove to be more beneficial as this actively generates ambient air within the suit however may create a greater load as a fan/air generator is required.

It is not always possible or efficient to use some active cooling devices within fully encapsulated PPE due to power supply and range of movement within the field (Bennet *et al.* 1994).Thus the development of passive cooling garments such as ice vests and phase change materials (House *et al.* 2009) have been widely examined. The benefit of such cooling vests within military operations in comparison to other personal cooling devices is the light weight designs and no need to connect to any other apparatus with little effect on operational performance (Smolander *et al.* 2004). Phase change vests are composed of/or incorporate long-chain alkaline substances as a replacement for water based solutions. Thus PCM can be frozen at a higher temperature and are not required to be frozen below 0°C to reach their maximal cooling capacity. PCM cooling is characterized as their ability to absorb energy (heat) as they phase change from solid to liquid (Reinertsen *et al*. 2008). The majority of the cooling capacity (60-70%), of PCM takes place during melting (House *et al*. 2006). A negative effect of such vests includes the increased metabolic heat production due to increased weight and the possibility that they may in fact create an extra impermeable layer for evaporative heat loss. Whilst this may not have a great effect on fully encapsulated body armour, tightly fitted vests will reduce airflow across the skin for convectional cooling in body armour that allows for airflow within the suit. The efficient use of PCM vests has the ability to reduce thermal physiological strain and provide greater operational effectiveness.

It has been identified that EOD personnel often incorporate a rest period after approximately 45 minutes of operation where the opportunity for removal of their helmet and jacket for a brief period of time before recommencing operation is possible. The potential impact on thermal response of such break has not previously been examined. Such rest period also allows time for a potential replacement cooling device (e.g. phase change vest) to help alleviate rapid rise in thermal strain at this time point previously experienced within lab based studies.

1.1 AIM

The aims of this study are;

1. To investigate thermal physiological and perceptual strain whilst wearing an EOD suit when conducting simulated bomb disposal related physical activities in 40 °C air.
2. To assess the impact of torso covering phase change material on thermal physiological and perceptual strain caused whilst wearing an EOD suit when conducting bomb disposal related physical activities in 40 °C air.
3. To evaluate the impact of replacing a recharged phase change material during a break in simulated activity on the subsequent change in thermal physiological and perceptual response caused whilst wearing an EOD suit when conducting bomb disposal related physical activities in 40 °C air.

1.2 Hypotheses

A phase change cooling vest will reduce thermal physiological and perceptual strain experienced whilst wearing an EOD suit conducting simulated bomb disposal related physical activity in 40 °C air.

The addition of a freshly charged vest will reduce increases in $T_{c,}$ T_{msk}, HR and heat storage caused whilst wearing an EOD suit when conducting a second simulated bomb disposal related physical activity sequence in 40 °C air.

2 Literature Review

2.1 Heat Exchange Pathways

Physical activity in heat makes it very difficult for the human body to maintain a thermal steady state. During exercise metabolic heat production takes place within the body. In order to maintain a thermal steady state the body has four methods in which it is able to dissipate heat (Conduction, Convection, radiation & evaporation). Conduction takes place when the body is warmer than the surrounding area and transfers warmth from the body to the cooler air molecules in the environment. Convection provides a similar dissipation of heat however is dependent on the flow of air across the skin surface area with air speed being a key factor. Radiation allows heat to dissipate to surrounding objects when the body is warmer than the surrounding environments to radiant heat loss. The most effective method of heat dissipation by the body is sweat evaporation from the skin surface area.

2.2 Physiological Responses to Exercise in Heat

The ambient environment can affect an individual's ability to maintain a thermal steady state and regulate T_c. While exercising within a hot environment an individual's T_{sk} will increase rapidly and T_c will increase at a slower rate subsequently due to an increase in metabolic production and the bodies' attempts to dissipate heat. The environmental temperature will determine the rate in T_{sk} and T_c increase. Thake and Price (2007) identified that when individuals conduct bomb disposal activity whilst wearing an EOD suit in 40 °C heat that T_c begins to rise more rapidly around 35 to 45 minutes. This is coincident with the rapid rise in T_{sk} becoming closer to that of T_c. As ambient temperature is increased convection, conduction and radiation become inferior methods of heat loss. In hot dry temperatures sweat evaporation can account for up to 98% of heat loss (Casa, 1999). The body's increased sweat response is the key method of dissipating heat. Individuals tend not to rehydrate at similar levels during athletic and occupational performance creating a state of dehydration. It is difficult to identify the difference in performance affects between ambient heat and hydration as both factors run comparable to each other throughout bouts of prolonged exercise (Mcllellan *et al.* 1999). Febbraio *et al.* (2002) showed that euhydrated individuals could exercise for just 33 minutes at 40°C in comparison to 75 minutes at 20°C and 95 minutes at 2°C. The body cannot dissipate heat at high ambient temperatures as effectively particularly when ambient temperature is higher than $T_{C.}$ The thermal gradient between the core and periphery becomes increasingly reduced. Once T_{SK} is higher than that of T_C heat transfer is no longer possible from T_C to the periphery. The body continues to shunt blood to the periphery for cooling as well as trying to provide oxygen to the functioning muscles. This results in decreased venous return and a subsequent increased heart rate and cardiovascular strain (Casa, 1999). An uncompensable heat stress environment (UHS) is created as the body can no longer dissipate heat at the required rate and the individual becomes increasing subject to physiological strain and heat illness. (UHS is defined as when the amount of evaporative heat loss required to maintain a thermal steady state exceeds that of the maximal evaporative capacity of the environment; Cheung *et al.* 2000). This effect is only heightened when conducting physical activity in environments with a high relative humidity (RH). When exercising within hot, wet environments sweat evaporation will only account for 80% of body cooling in comparison to 98% in hot, dry environments (Casa 1999). As RH is of a greater percentage the means of sweat evaporation is significantly reducing the body's cooling capacity adding to thermal physiological strain. Gonzales-Alonso *et al.* (1999) examined the influence of body temperature on the development of fatigue during prolonged exercise in heat (40°C). Seven cyclists conducted three random bouts of cycle ergometer exercise with three different starting oesophageal temperatures. The study showed that in hot environments the time to exhaustion is inversely related to initial temperature and more directly related to the heat storage as subjects fatigued at identical levels of hyperthermia (Esophageal temperature (T_{es}) 40.1°C to 40.2°C).

2.3 Physiological responses to exercise within heat and PPE

Whilst wearing clothing, in particular PPE, a micro environment is created between the skin surface area and the clothing layer. An increased temperature rise in the micro-environment will contribute to preventing heat dissipation from the body and increasing T_c via convection and conduction. Radiation will add heat to the body if the environmental temperature is greater than body temperature and vented to the skin surface area. When this occurs, sweat evaporation becomes the only significant method of heat dissipation and maintenance of thermal steady state. Whilst wearing PPE the micro-climate quickly becomes saturated and will continually increase in temperature. When full body PPE is worn T_{SK} will continue to rise due to its lack of contact with the ambient environment for cooling becoming increasingly close to that of T_C. This micro-climate within the PPE decreases the ability for sweat evaporation due to a fully encapsulated clothing ensemble not allowing air flow across the skin surface area. Sweat can no longer evaporate and RH within the suit increases rapidly causing a UHS environment. Evaporative Cooling is no longer possible and physiological strain is inevitable. The weight and inability to move efficiently whilst wearing PPE will cause an increase in metabolic heat production and increase in $T_{SK} + T_C$ all contributing to thermal strain and the UHS environment. Wearing protective clothing such as NBC suits have shown to increase the production of internal heat and metabolic rate by 13 to 18% whilst conducting treadmill exercise at a self selected speed (Cheung *et al.* 2000) due to an increase in load carriage and a decrease in movement efficiency caused to the wearer.

PPE is vital in protection from injury and health both occupationally and within sporting environments. PPE can provide protection from both impact injury and chemical protection and each ensemble differs in design and encapsulation altering the effect it has on the wearer's thermal steady state. PPE ensembles providing full body protection and encapsulation are generally considered to compromise heat transfer and the ability to maintain thermal steady state. More protective and heavier suits cause a greater metabolic heat production and thermal strain (Cheung *et al.* 2000). The greater the thermal insulation and evaporative resistance of PPE will cause the greater level of heat storage and possibility of a UHS state being created (Hanson 2006).

PPE and clothing types are largely investigated in all ambient environments to try and determine the overall effect on physiological and thermal response. A fully encapsulated impermeable protective clothing layer has been shown to decrease operational work time (38.5 °C T_c cut-off) by 100 minutes in comparison to no clothing whilst conducting moderate work in 37 °C ambient temperature (Table 1, Havenith 1999). A highly impermeable layer will reduce the capacity for cooling and create a UHS environment. Personal protective equipment with an increase in ballistic properties are considered to have a greater weight and thickness. This will serve the function of increased metabolic rate and heat production. Subsequently more strain on the thermoregulatory system is from and an increased humidity within the micro-climate between the periphery and clothing as the body attempts to dissipate more heat.

Table 1 - Time for an operative to reach T_c cut off (38.5 °C) in a 37 °C environment undertaking moderate work within different clothing ensembles (Havenith 1999)

Clothing type	**Nude**	**Normal work gear, cotton, single layer**	**Protective clothing, cotton, three layers**	**Protective clothing, cotton, waterproof outer layer, total three layers**	**Fully encapsulating clothing, impermeable outer layer**
Maximal exposure time (minutes)	120	90	45	30	20

Nuclear, biological and chemical (NBC) protective ensembles worn by military personnel are examples of fully encapsulated PPE which consists of high insulation and low water vapour permeability due to thick fabric design. NBC clothing worn in warm environments (30 °C, 50% RH) significantly reduced (277 ± 47 min to 82.7 ±10.6 min) work tolerance time (18 °C, 50% RH)(Mcllellan *et al.* 1993). The temperature within the micro-climate between the skin and PPE layer would have a correlation with that of the environmental temperature increasingly heating the periphery and $T_{C.}$ This response is heightened due to the encapsulation and low permeability of the NBC suit (Cortili *et al.* 1996). The greater the weight of the ensemble and layers of clothing within the PPE results in a greater effect on heat strain caused by such suits. Wearing NBC with combat clothing underneath increases identified indices of thermal strain whilst conducting intermittent exercise (15 min walking $1.1 m.s^{-1}$/ 15 min seated rest) in comparison to wearing just undershirt and underwear. Heat strain is increased due to increased thermal coverage on the body and increased load, friction and lesser movement available contributing to a reported 13 to 18% metabolic increase (Cheung *et al.* 2000).

A more extreme example of an encapsulated PPE in terms of weight and size are Explosive ordinance disposal (EOD) suits (Mass > 36 kg). The net effect of EOD suits in operational use is reduced by the fact that they provide high levels of encapsulation and are greater in mass due to increased ballistic protection. Thake & Price (2007) assessed the thermal comfort effects of wearing a full EOD bomb disposal suit (FS) in comparison to no suit (NS) and a suit with a light weight trouser design (LS). Participant completed 4 cycles of physical activities similar to that of EOD operations in hot environments (66 minutes, 40.5 ±1.1°C T_{amb}). RPE and physiological strain were significantly higher in FS in comparison to NS and LS. Wearing EOD suits within hot conditions creates a UHS environment and increases thermal physiological and perceptual strain to the operative. The light weight trouser design helps to reduce thermal strain and increase thermal comfort in such environment due to lower levels of metabolic heat production from the decreased weight load and increased mobility and comfort.

2.3.1 Physiological Strain Indices

Individual physiological factors help to identify thermal strain within individuals however Holmer *et al.* (1992) would argue that individual factors such as HR, VO_2, T_c and T_{sk} alone cannot represent a true identification of thermal strain as each factor can rise minimally without causing thermal strain to an individual. Moran, Shitzer and Pandolf (1998) developed a new method of calculating physiological strain on a physiological strain index (PSI) which rates the strain on and index of 0 (No strain) – 10 (Maximum strain) using HR and T_c as key indicators of physiological strain. They suggested that the maximal T_c rise to heat strain from normothermia to hyperthermia was approximately +3°C (up to 39.5°C) and the maximal HR rise to heat strain from normothermia to hyperthermia was 120 BPM (up to 180 BPM).

Tikuisis, Selkirk and McLellan (2002) would argue that the PSI scale does not allow for increases greater than the norms set by Moran, Shitzer and Pandolf (1998). For this reason calculations of PSI were developed (PhSI) which used 60bpm as the standard resting heart rate and used the individuals HR_{MAX} as an indicator more specific to the individual conducting exercise.

2.4 Hyperthermia and Heat Illness

When exercising within PPE and hot environments the subsequent rise in T_C puts increased risk on the participant. Individuals become at serious risk of thermal strain and heat illness when exercise continues and T_c exceeds 40.5 °C due to the body's inability to dissipate heat at the required rate (Coris *et al*. 2004). Coris *et al.* (2004) identified that heat illness can be classified into five different categories (Heat Oedema, Heat cramps, heat syncope, heat exhaustion and heat stroke). Heat exhaustion is most commonly found within individuals exercising in hot environments due to cardiovascular response failing to cope with the given workload. During heat exhaustion we would see individual T_c exceed 38 °C but not exceed 40.5°C. Heat exhaustion occurs as the body attempts to cool itself to reduce the rise in T_c. It is expected that elite cyclists and marathon runners may maintain a steady state within this parameter (Roth *et al.* 1996) safely as whilst metabolic heat production will cause an increase in T_c lightweight and small coverage clothing allows for the body to effectively dissipate heat in accordance with greater thermal tolerance obtained by the athletes through training regimes. Heat stroke is caused when the bodies' thermoregulatory system is no longer able to maintain a thermal steady state. To avoid heat stroke as identified by an elevated T_C (>40.5 °C) during lab based studies, end point criteria's are set to cease continuation of exercise for the participant. Previous lab based studies have used 40 °C as the parameter for cease of exercise however more recently studies have used 39.5 °C (Thake and Price 2007). It has been identified that following a bout of exercise within heat that T_c may continue to rise during the following 15 minutes suggesting that a lower end point criteria will provide a greater level of safety for participants allowing room for T_c peak without elevating above 40.5 °C. Such end point criterion is important for PPE based studies as a continued rise in T_c during removal of PPE may be evident.

2.5 Perceptual Responses to exercise in heat and PPE

When subject to states of thermal strain individual perceptual responses can alter accordingly. It is widely accepted that when individuals T_c rises there is an increase in perceived rate of exertion (RPE) (Borg, 1970) thermal sensation (Young *et al.* 1987) and thermal comfort (Epstein & Moran, 2006). High recordings within perceptual responses are closely associated with a decrease in tolerance time to heat exposure (Cheung & McLellan, 2000).

Tikuisis, McLellan and Selkirk (2002) developed a perceptual strain index (PeSI) in addition to the developed PhSI using thermal sensation and RPE as the calculating variables for an Index running on a scale of 1-10. Twenty six healthy participants were tested within hot conditions (40°C, 30%RH) walking on a treadmill (3.5 km/h^{-1}) whilst wearing semi-impermeable clothing. Subjects were split into two groups consisting of endurance trained and untrained individuals based on body fat and aerobic capacity. It was identified that trained individuals consistently underestimated their physiological strain in comparison to PhSI where as untrained individuals consistently perceived their physiological strain. This would suggest that whilst PeSI is a good indicator for individuals to express their perceptions of their physiological strain in a non-invasive manor it may not be a true representation of the physiological responses that are taking place during exposure. Results ascertained from this study may suggest that trained individuals may be more susceptible to heat strain if allowed to continue over time as they underestimate their level of PSI however this is unproven. As military personnel likely to wear PPE are required to maintain a certain level of fitness they may underestimate their PSI whilst wearing PPE.

Although individuals may underestimate physiological strain, studies have been completed using PeSI as a key calculation for thermal strain and there would be an expected increase over time when conducting exercise within hot environments whilst wearing PPE. Petruzello *et al.* (2009) identified during re-analyses of a lab based study and a fire fighting field based study that even during brief bouts of exercise within heavy impermeable fire fighting clothing can result in significant heat strain identifiable by both PhSI and PeSI.

2.6 Proposed Interventions to reduce heat strain.

To reduce thermal strain and increase operational safety and efficiency a number of cooling techniques whilst exercising in heat and working within PPE have been proposed. Proposed interventions include improving individual's capacity to perform in PPE and heat through acclimation (Cheung & McLellan, 1999) and hydration status in order to alleviate physiological and perceptual strain. Interventions also include direct cooling techniques through the use of equipment configuration (*i.e.* lighter clothing) (Thake & Price, 2007) in order to reduce metabolic heat production and decrease heat storage as well as the integration of cooling devices such as phase change vests (House *et al.* 2009).

Acclimation to heat is a widely investigated method of reducing thermal and physiological strain caused by operations in PPE and heat. Cheung and McLellan (1999a, 1999b) reported that whilst short term heat acclimation can improve physiological response to heat it is long term aerobic fitness that has the greater affect. 15 Subjects consisting of moderately fit (MF) (<50 ml.kg^{-1} max O_2 n=7) and highly fit males (HF) (>55 ml.kg^{-1} max O_2, n=8) participated in exercise (Treadmill walking, 40 °C, 30%RH) whilst wearing a NBC clothing ensemble in a euhydrated and hypohydrated state both pre and post a 2 week daily acclimation period (1 hr Treadmill walking 40 °C, 30%RH wearing NBC clothing). Tolerance time was greater in HF individuals pre-acclimation. Although acclimation period increased individuals sweat rate and decreased T_{msk} of individuals there was no impact on tolerance time. In MF individuals acclimation increased sweat rate but had no affect on overall tolerance time suggesting that an individual's aerobic capacity has a great affect on ability to conduct operations within hot environments due to the ability to tolerate a higher T_c to exhaustion. Selkirk and McLellan (2001) reported that the difference between fit and unfit individuals ability to tolerate higher T_c can be as great as 0.9 °C.

Individual hydration status pre-trial also had a great affect on ability to perform in a UHS environment as in both MF and HF individuals T_c was significantly increased and tolerance time decreased suggesting the appropriate hydration strategies can be an effective technique to reduce individuals thermal strain within UHS environments. Individuals de-hydrated by 2.3% of body mass pre-trial have a significant reduction in tolerance time in UHS environments (euhydrated: 59 ±13 minutes, dehydrated:47.7 ± 15.3 minutess)(Cheung & McLellen, 2000).

PPE configuration alterations have been made to help reduce mass and alter permeability of the ensemble to reduce thermal strain and discomfort for the operative. Thake and Price (2007) examined alterations in EOD suit design by the means of a lighter weight trouser design. Participants (n=4) conducted trials representative of EOD operations (66mins, Ambient temp 40.5°C ± 1°C). Trials consisted of wearing the EOD suit and Lightweight trouser design suit with and without a dry iced based active cooling device and one trial without wearing the EOD suit. Physiological strain was significantly increased whilst wearing the EOD suit and also the introduction of a light weight trouser design with increased mobility can help to optimise thermal comfort. Introduction of a dry ice active cooling system significantly reduced T_{msk} and subsequently T_c (0.6 °C reduction during final activity)resulting in an overall decrease in physiological strain being caused in comparison to suit configurations with no cooling device.

Occupational advancements have been made on a number of other active cooling devices, whilst wearing PPE in hot environments, in order to alleviate thermal strain with UHS environments. Frim and Morris (1992) examined three cooling technologies whilst wearing an EOD suit. The three cooling devices (Liquid cooled undergarment, thickly ribbed vest of hydrophilic nylon and an air vest) were examined within three different environmental conditions (18 °C 40% RH, 34°C 40% RH, 34 °C 80% RH) with subjects conducting simulated EOD operational activities over a 90 minute period. Wearing the liquid cooled vest resulted in Hr, T_c and dehydration levels being reduced similar to conducting activities without the EOD protective ensemble. No significant improvements were made whilst wearing the hydrophilic nylon or air vest.

Commercially available cooling devices are being examined more frequently in order to assess whether off the shelf products can be used to meet the requirements set in military operations to improve operational performance. Cadarette *et al.* (1990) also examined three commercially available cooling devices whilst individuals conducted exercise (3 cycles of 10 minutes rest and 50 minutes walk) in hot environments (38 °C) whilst wearing insulative clothing with low permeability. The three devices consisted of ILC Dover Model 19 cool vest with a mean inlet temp of 5 °C, A LSSI coolhead with mean inlet temp of 14.5 °C and a Thermacor Cooling vest with mean inlet temp of 28.3 °C. Analysed data identified that all three cooling vests provide improved physiological responses to exercise in heat however the ILC model provided only a slightly greater benefit in performance time to exhaustion. This is due to a cooler input temperature allowing for the greatest capacity of cooling by conduction and convection to the body.

2.6.1 Phase Change Materials and Cooling vests

Cooling vests are a simple cooling method that can be worn under personal protective clothing to help alleviate thermal strain. The most common type of cooling vest is an ice vest which usually consists of a vest containing packs of water based solution frozen prior to wearing. The benefit of such cooling vests within military operations in comparison of other personal cooling devices is the light weight designs. As there is limited availability for power sources in operational settings and no possibility to connect to any other apparatus passive cooling vests have little effect on operational performance (Smolander *et al* 2004). The majority of cooling experienced (60-70%) whilst wearing such ice vest occurs during the period of time in which the ice is melting (House *et al*. 2009). As ice vest melting point is 0 °C, re-activation of the ice vest re-freezing would need to take place to lower than 0 °C. Questions have been raised as to whether ice vests may have a negative effect due to vasoconstriction occurring when the ice is in contact with the skin however no recent studies have demonstrated this effect.

Recent studies have seen the development of new phase change long-chain alkaline substances being used within cooling vests as a replacement for water based solutions. Reinertson *et al* (2008) presented the findings of the use of phase change materials within workers conducting simulated work conditions whilst wearing two types of phase change materials (PCM) (the crystalline dehydrate of sodium sulphate and micro capsules in fabrics) under protective clothing. It was reported that phase change materials can have a positive effect on reducing thermal stress and thermal comfort however these responses are in relation to the coverage and distribution of the phase change. Anecdotal evidence suggests that some types of phase change vests are not acceptable within certain professions as the increased stiffness reduces the freedom of movement. A closer analysis of data reported that a PCM vest that covered a greater proportion of the torso with more cooling elements reduced T_{SK} to the greater proportion however individuals reported better thermal sensation and comfort in a vest with less torso coverage and cooling elements. RH was 20% lower and sweat rate decreased within a vest with lower coverage suggesting that a negative trade-off in a PCM with greater coverage can be the extra impermeable layer creating a more humid micro-climate. An extra impermeable layer will have little effect in saturated environments as no heat loss via evaporation between the skin and air will take place however within torso covering armour that is not fully saturated/ impermeable the extra layer may promote a more humid micro-climate.

The benefit of such alkaline solutions is that their melting point can be manipulated un-like water based solutions. If the cooling vest has a greater melting temperature e.g. 20 °C it can be refrozen at that temperature (20 °C) with no need of a freezer being present. Like ice vests the Phase change cooling vests provide their greatest potential of cooling during melting. The added beneficiary of a PCM for example at 20 °C is a reduction in vasoconstriction to the periphery with cold skin contact in comparison to an ice vest.

House *et al.* (2009) examined the use of phase change materials on individuals conducting light stepping exercise (12steps.min^{-1}) for 45 minutes followed by 45 minute rest within hot environments (40°C dry bulb, 29°C wet bulb). Cooling vests with different melting points (0 °C to 30 °C) ($CV_{0,}$ $CV_{10,}$ CV_{20} and CV_{30}) were examined to identify if cooler vests can cause a negative effect due to vasoconstriction of the periphery or if CV_0 would provide the greatest physiological cooling benefit. The findings presented that the greatest cooling affects comes from wearing a cooling vest with the coldest melting point. CV_{10} and CV_0 provided similar cooling benefits. There was no significant difference in skin blood flow during exercise and no evidence of vasoconstriction due to cooler vests being worn. It may be argued that CV_{10} is more beneficial particularly within military operations as there would be a greater opportunity to re-freeze below 10°C than 0°C. Subjective feedback in House *et al.* study also suggested that CV_0 was "too cold" and cold induced erythema was observed (Redness of the skin caused by dilation of the capillaries). Participants reported that CV_{10} was the preferred vest type. The sacrifice of blood flow is outweighed by the benefit created of cooling tissue mass and blood through conduvtive heat transfer when wearing such garments.

Gao *et al.* (2010) examined phase change cooling garments with higher melting points (CV_{24} and CV_{28}) on individuals conducting exercise (Walking 5km/h) within extreme heat conditions (55 °C, 30% RH) wearing fire fighter uniform and equipment. No significant effects on alleviation of T_C rise during exercise and only a reduction in post exercise peak was reported. This supports House (2009) findings that PCM with a lower melting point provides the greatest cooling effect.

2.7 Rationale for current research

The use of PCM has been an effective method of cooling within individuals exercising in heat and PPE. It is also identifiable that whilst phase change with lower melting points may cause a greater effect of cooling benefits from PCM with higher melting temperatures include the ability to re-freeze at a higher temperature. This is beneficial within military based and EOD operations within hot environments where it may not be possible to freeze water based phase change vests. For this reason this study will use phase change cooling vests with a melting point of 25 °C as it is likely that within military based settings water will be available at this temperature or below.

Previous studies on thermal strain within EOD suits have used simulated EOD operation over a continuous period of time with bouts of seated rest whilst wearing the suit (Thake & Price 2007). On conversation with operatives and manufacturers of EOD suits it has been identified that individuals may in fact take a break from operation and remove the helmet and jacket mid operation in order to maintain thermal comfort and reduce physiological strain of wearing such PPE for prolonged periods of time. Previous studies from our lab also demonstrate that T_c rate of rise increases more rapidly around 30 to 45 minutes and are coincident with the rise in T_{sk}. Based on this information the current protocol will have an break at the midway point of the trial (49 minutes 30seconds) where participants are allowed to remove helmet and jackets. This is expected to reduce the rise in T_c and allow the replacement of a new (charged) PCM.

The aim of this study is to assess if replacing phase change material during an integrated break in EOD operation can reduce physiological strain of individuals wearing a MK6 and Ergotec 4010 bomb disposal suit within extremely hot conditions (40°C).

3 Method

3.1 Participants

Six male participants (age 22±3 yrs; body mass 78.1±9.3 kg; stature 176.3±6.5 cm) were recruited to undertake this investigation that was approved by Coventry University Ethics Committee. Participants completed an informed consent form prior to first participation within the study, after a verbal and written explanation of the study and their involvement (Appendix A). Participants were required to be healthy and injury free as determined by the completion of a health screen questionnaire which was read, completed and signed prior to starting each experimental trial including familiarisation. Participants were non-smokers and had no known history of cardio-respiratory disease.

3.2 Experimental Design

The experimental design required participants to conduct one habituation session followed by three experimental trials within a bomb disposal suit (EOD Mk6a) on a counterbalance randomised basis. A counterbalance randomised basis for order presentation would identify if any training effect took place over weekly trials. Each trial consisted of subjects being exposed to ambient temperatures of 40°C ± 1°C. Two of the three trials within the suit consisted of cooling, in the form of commercially available phase change material that has previously been stored in a fridge (5 °C ± 1 °C) for 24hours prior to trial start. The PCM phase changed at 25 °C and was applied to the torso in the means of a vest design. A standard cotton based army camouflage layer of clothing was worn by the subjects underneath the phase change to eliminate the risk of discomfort of direct contact between the skin and PCM. This provided a more representative clothing ensemble to that worn by military operatives wearing the EOD body armour.

Participants attempted to complete a total of 6 EOD related activity cycles (1-3, 3×16:30 minute/seconds = 49:30minute/seconds followed by 4-6, 3×16:30min/sec = 49:30min/sec). A rest period was scheduled for 10 min after the first 3 activity cycles. The EOD suit helmet, jacket and PCM torso garment being worn dependent upon trial was removed for this period of time (removed within 1 min of rest period commencing). At the end of the rest period (8-10 min) the EOD suit helmet and jacket was donned, with the addition of any torso covering PCM garment required dependent upon trial.

The study (figure 1) had three conditions within the MK6a EOD suit in (Figure 1):

1) The same PCM garment worn throughout activity cycle 1-3 and 4-6.
2) One PCM garment worn in activity cycles 1-3 and fresh (Charged) PCM garment worn in activity cycle 4-6.
3) No PCM garments were worn at any stage.

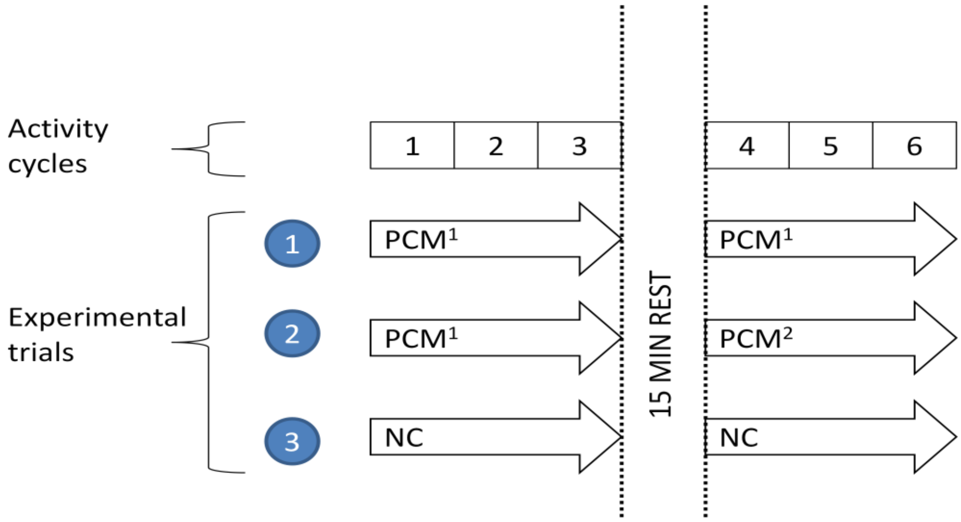

Figure 1: Schematic presentation of experimental design (an activity cycle lasting 16:30 min : sec; PCM = torso covering phase change material garment; 1 and 2 signify separate PCM garments of the same design; NC = no cooling garment; see text for further explanation).

The five activity stations per each 16:30 (min:sec) cycle included treadmill walking (4 km.hr^{-1}; 3:30 min:sec), Manual loading (standardised movements of 1kg weights; 2:30 min:sec),Crawling and Searching (Standardised crawling movements, 2:30 min:sec), Arm Ergometry, (60 watt workload, 3 min:30 sec) and Seated Rest (physical rest; 5min). As identified in figure 2.

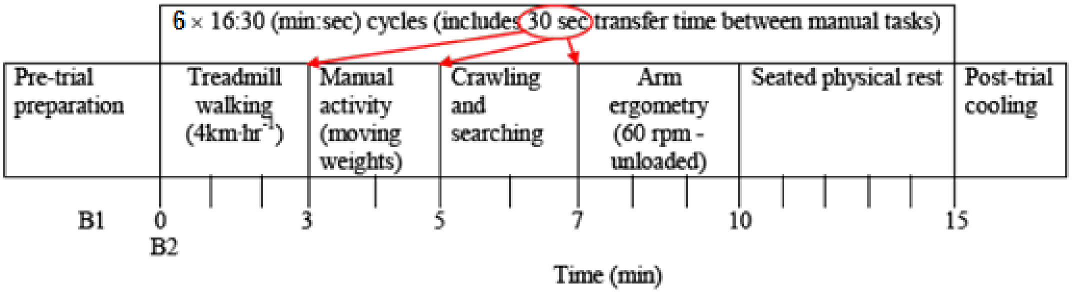

Figure 2: EOD related activity sequence (rest period signified) conducted within each trial (Thake and Price 2007). Patricipants completed a maximum of 6 cycles with an intergrated 10minute break following the 3rd cycle.

The manual loading phase consisted of participants kneeling and moving four 1.25kg weights between two shelves (Shelves 64 and 27cm from ground)(Figure 3). Movement was controlled on the beat of a metronome. (Seiko DM-20, Hattori Seiko Co. Ltd; Japan) set at thirty beats a minute. During the crawling and searching phase participants were required to crawl along a 2.25m ladder design marked on the floor of the environmental chamber (Figure 3). Participants were required to move their hands to the next step of the ladder (24cm) at the beat of the metronome (30 beats per second). Once at the end of the ladder participants were required to search by moving their heads and looking in a set sequence (Left, down, right, down) to the beep of the metronome. Participants were then required to crawl backwards.

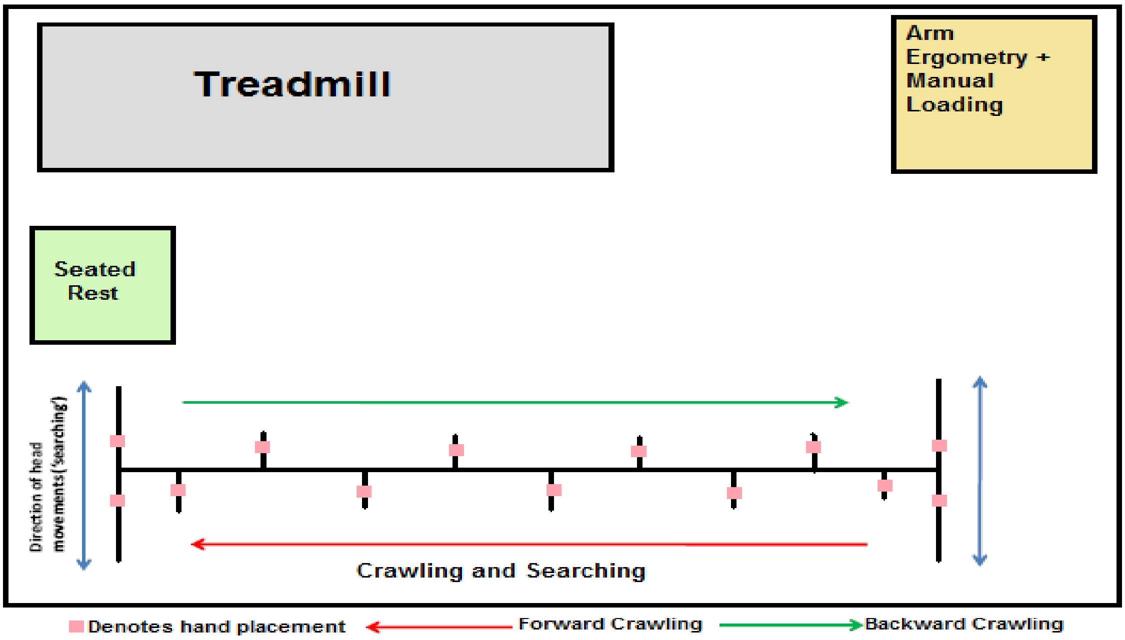

Figure 3: Floor plan of environmental chamber during trials (3m x 5m)(Not to scale).

3.3 EOD Suit

The MK6a EOD bomb disposal suit consists of helmet, bomb disposal jacket with dual fan cooling system, armoured torso shield and trousers with three separate components consisting of leg coverage, pelvis coverage and over trousers. (Total suit weight ≈ 35kg)

The Mk6a was worn over the top of standard military clothing consisting of underwear, socks, cotton t-shirt, combat trousers and leather steel toe cap boots (Mass≈ 2.5kg).Once all scientific instrumentation equipment was added total mass of ensemble increased to ≈39kg.

The dual fan system delivered ≈200 $L.min^{-1}$ of air to the wearers back and ≈100 $L.min^{-1}$ to the head area throughout.

Participants followed the same procedure each time of entering the lab and donning the EOD suit. At an ambient temperature (≈20°C) nude body mass was measured (see section 3:5:1) and the skin thermistors fixed to appropriate sites (See section 3:5:3). A heart rate transmitter band was then attached to the participant (See Section 3:5:2). Participants were dressed into military clothing. EOD trousers were donned first followed by any necessary

PCM vest. Helmet, jacket and chest plate was then applied prior to entering the environmental chamber. A time of 8:45 (min:sec) was kept constant from the period of applying EOD trousers to commencement of trials within each condition.

3.4 Environmental Conditions

All testing was conducted within an enclosed tent heated to a temperature of 40°C ± 1°C (Figure 4) by the means of 6 fan heats kept at set speed and temperature settings identified during pre testing practice sessions. Environmental Temperature and relative humidity was measured and monitored using a digital RS thermometer (Model 206-3722) and a Kestrel anemometer and was recorded during every activity.

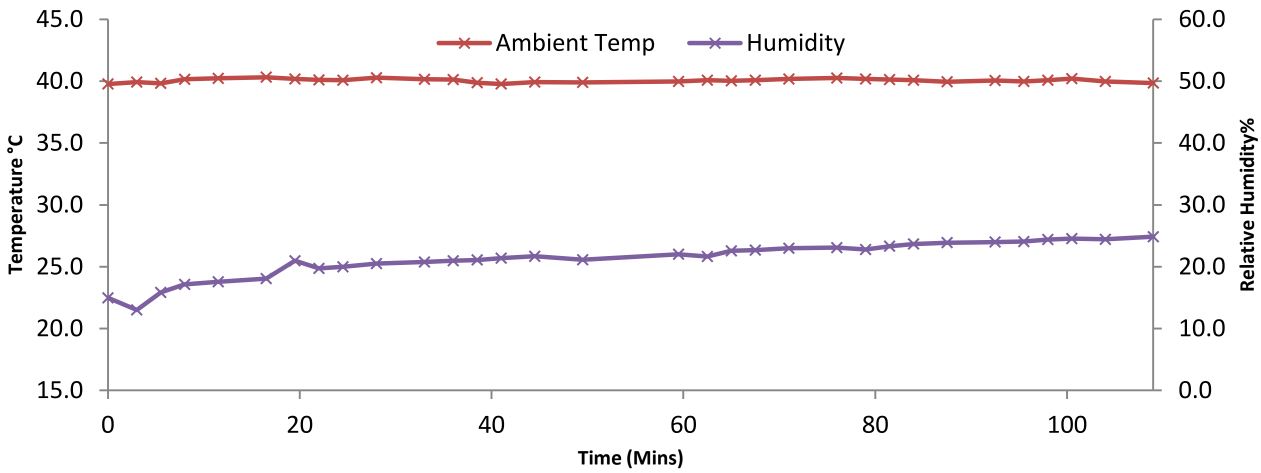

Figure 4. Ambient temperature (°C) and Relative Humidity (%) recorded during all trials. (Mean Values).Error bars omitted for clarity.

3.5 Measurements

3.5.1 Sweat Rate

Body mass was measured pre and post trial both nude and within the EOD suit for each trial. Mean sweat rate was calculated from the change in nude mass between pre and post trial (Equation 1)

Equation 1: Mean Sweat Rate ($L{\cdot}hr^{-1}$) = (Change in mass ÷ Trial Duration) x 60

3.5.2 Heart Rate (HR) Measurements

HR was recorded via a Suunto T6c HR transmitter belt and monitor set to record on two second intervals throughout each trial. Resting HR was recorded 20 minutes prior to testing with the subject seated to minimise the impact of pre-anticipatory rise close to trial beginning. HR was also displayed in real time via the HR transmitter belt sending data directly to a Suunto PC USB pod.

3.5.3 Temperature Measurements

Core (T_c) and Skin (T_{sk}) temperature were recorded throughout trials and logged at 20 second intervals via an Eltek WSR (wireless sensor receiver),interfaced with a PC, receiving T_c and T_{sk} data via an Eltek data transmitter unit connected to Skin and Core thermistors. T_c thermistors consisted of rectal and aural sensor probes. Participants inserted the rectal probe approximately 10cm beyond the anal sphincter. Skin thermistors were placed on 4 sites on the left hand side of the subject's body; lateral calf, medial thigh, chest and upper arm. Mean skin temperature was then calculated using the individual skin temperature sites (Equation 2).

Equation 2: Mean Skin Temperature = 0.30(Chest + Arm) + 0.20(Thigh + Calf) (Ramanathan 1964)

Heat storage ($J.g^{-1}$) of individuals throughout trials was calculated using T_C and T_{SK} as the determining factors (Equation 3).

Equation 3: Heat Storage ($J.g^{-1}$) = $[(0.8 \times \Delta T_C) + (0.2 \times \Delta T_{SK})] \times 3.49$ (Havenith, Luttikholt and Vrijkotte 1995)

T_c of individuals was also measured via the use of CorTemp® ingestible core body thermometer pills (T_{gi}) swallowed two hours prior to trial start, sending direct signals to a RF compatible CorTemp® miniaturized data recorder. This was set to log data every 20 seconds and was monitored continuously in real time throughout testing. Data was then transferred directly from the data record device and exported into Excel for data analysis.

3.5.4 Physiological Strain

Physiological strain index was calculated from T_C and HR using two scales (PSI and PhSI). PSI (Moran, Shitzer and Pandolf, 1998, Equation 4), uses a standard HR_{MAX} of 180BPM and individual resting HR values, and PhSI (Tikuisis, McLellan and Selkirk, 2002, Equation 5), uses individuals predicted HR_{MAX} and a standard resting HR value of 60BPM.

Equation 4: $PSI = 5[(T_{Ct} - T_{C0}) \div (39.5 - T_{C0})] + 5[(HR_t - HR_0) \div (180 - HR_0)$

$_0$ showing baseline value. $_t$ showing value at given time point.

Equation 5: $PhSI = 5[(T_{Ct} - T_{C0}) \div (39.5 - T_{C0})] + 5[(HR_t - 60) \div (HR_{MAX} - 60)$

$_0$ showing baseline value. $_t$ showing value at given time point. $_{MAX}$ showing individuals predicted HR max

3.5.5 Perceptual

Ratings of perceived exertion (RPE) were recorded using the Borg scale (Borg 1970; a 6-20 scale with 6 being no exertion and 20 being maximal exertion (Appendix B). RPE was verbally communicated by the subjects during the treadmill and arm exercise phase of each cycle and individuals report RPE both overall and local body areas including upper back and shoulders, lower back and legs.

Thermal Comfort (Epstein and Moran 2006) and Thermal Sensation (Young, Sawka and Epstein *et al*. 1987) were also recorded verbally by subjects during the treadmill and arm exercise phase as well as rest period during each cycle and during the integrated rest break in the trials. Thermal comfort was recorded on a 1-8 scale (4 = comfortable, 8=very uncomfortably hot and 1=very uncomfortably cold; Appendix B). Thermal sensation was also recorded on a 1-8 scale (4 = comfortable, 8 = unbearably hot and 1 = unbearably cold; Appendix B-Fig 12). Thermal Comfort and Sensation was verbally communicated by individuals for both overall and local body parts including head, back, chest and arms, groin and legs.

RPE and thermal sensation recorded during the treadmill and arm ergometry phase of each cycle were adapted to an 11 (0-10) and 7 (7-13) point scale in order to calculate the perceptual strain index (PeSI). (Tikuisis, McLellen and Selkirk 2002; Equation 6). PeSI normalises increases in thermal sensation and RPE to provide perceptual strain on a scale of 1-10.

Equation 6: $PeSI=5[(TS_t - 7) \div 6 + 5 [RPE_t \div 10]$

$_t$ denotes value at given time point.

3.6 Statistical Analysis

Minitab 15 was used to conduct a general linear model analysis of variance (ANOVA) on each trial condition. Significant ($P>0.05$) main effects for condition, time and condition × time interaction were investigated using Tukey post hoc tests. ANOVA's were initially conducted on the entire data set of trials however for clarity ANOVA's were also conducted on the thirst three and final three activity cycles separately as these can be analysed as new conditions although all related and analysis between the three conditions both pre and post rest period is possible.

All data was organised and managed in Microsoft Office Excel 2007. Means and standard deviation of all data was identified via the last 30 seconds of each activity phase throughout trials. All appropriate equations were input within Excel to identify variables stated within the methods.

4 Results

All data is displayed to highlight differences between conditions (NoPCM, PCM1, PCM2). The integrated ten minute break can be identified on figures between 49.30 minutes and 59.30 minutes. In both PCM1 and PCM2 trials it was observed that the PCM had changed from solid to liquid by the start of the integrated rest period.

All subjects completed all trials throughout testing and therefore performance time is not identified between conditions.

4.1 Temperature Measurements

4.1.1 Core Temperature

Due to error in data of T_{gi} recordings and a participant not being able to swallow the GI pill fewer results were available for analysis (n=4). A resultant fluctuation and error in data due to signal errors results during PCM2 trials is evident (Figure 5). For this reason analysis of T_c via rectal probe will be used when discussing T_{re}.

T_C increased with trial duration in all three conditions ($P<0.001$; Figure 6). PCM 1 and PCM2 are the same condition during the first three cycles and no difference was identified however post break (59:30 onwards) PCM1 showed the greatest rate of increase between all three conditions rising to absolute levels higher to that of NoPCM ($p<0.001$, difference between PCM1 and PCM2). A significantly greater T_{re} is evident with no PCM prior to a break. Following a break PCM1 and NoPCM showed the greatest rise in T_{re} and were significantly greater than 2 PCM (NoPCM: 37.09±0.3,PCM: 38.03±0.3, PCM2: 37.4±0.5; values taken during arm ergometry of last activity cycle). NoPCM trials have a significantly greater overall change in T_{re} ($P<0.001$, difference between NoPCM and PCM1/PCM2) over the 115 minute trial (Figure 5; NoPCM:0.82°C, PCM1:0.52°C, PCM2:0.15°C, rise in T_{re} (°C) between baseline and arm ergometry of last activity cycle). The rate in T_{re} rise from the beginning of trial 4 to the end of trial 6 was significantly higher in NoPCM and PCM1 in comparison to PCM2 (P<0.001; NoPCM: 0.63°C, PCM1:0.51°C, PCM2: 0.24°C, rise in T_{re} (°C) between 10 minutes rest and end trial).

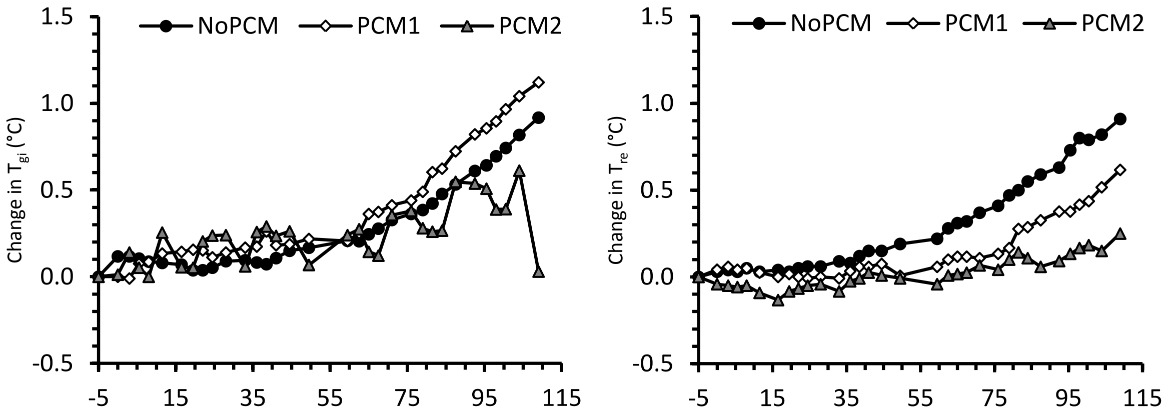

Figure 5. A comparison of T_{gi} (Left n=4) and T_{re} (right n=6) changes in response to EOD related activity whilst wearing a MK6a in 40°C. Error bars omitted for clarity

4.1.2 Mean Skin Temperature

T_{msk} significantly increased with trial time (P<0.001; Figure 6) in all three conditions. A significant difference was also identified between trials over time (P<0.05) at the end of the sixth cycle. A greater rate of T_{msk} rise is identified during the first 49:30 (minutes:seconds) of each trial (2.93±0.56 °C, 3.33±0.28 °C, 3.22±0.78 °C; NoPCM, PCM1, and PCM2). During the last 49:30 (minute:seconds) of EOD operation PCM 1 shows tendencies for a greater absolute value in skin temperature (PCM1-2±0.34 °C, NoPCM-0.95±0.30 °C;). Immediately after the break the 2pcm trial shows a significant drop in T_{msk} (P<0.001) subsequent to a refreshed phase change material being introduced and a significant drop in skin temperature local to a phase change vest (Chest skin surface area). Comparisons can be made between the rate of T_{msk} rise and the subsequent rise in T_C (Figure 6) as T_{SK} becomes closer to that of T_C around 65mins resulting in a significant increase in T_C .

4.1.3 Heat Storage

Heat storage increased significantly over time for each condition ($P<0.001$; Figure 6). Heat storage during the NoPCM trials overall was greater than that of heat storage during PCM1 and PCM2 trials. During the first 49:30 (min:sec; Pre-integrated break) no difference was indentified between PCM1 and PCM2 as these conditions are the same prior to this point however post break during the PCM1 participants stored more heat ($P<0.001$) compared to when a new phase change material was introduced in PCM2. A significantly greater rise in heat storage ($p<0.01$) during the second work period was evident in PCM1 trials in comparison to PCM2 and NoPCM (PCM1:1.4 $J.g^{-1}$, NoPCM: 1.0 $J.g^{-1}$, PCM2: 0.9 $J.g^{-1}$; change in HS between Start of cycle four and end of cycle six).

4 .2 Physiological Measurements

4.2.1 Heart Rate

Heart rate varied over time dependant on the EOD simulated activity sequence (Figure 6).HR was identified as being greatest during crawling and searching phase and lowest during the manual loading phase of activity. HR increased over time for all three conditions ($P<0.001$). During PCM2 trials post PCM refreshment the maximum HR reached was much lower to that in comparison to NO PCM trials (No PCM 150$Bt.min^{-1}$, PCM2 119$Bt.min^{-1}$). PCM1 trial showed a greater HR rise post integrated break reaching levels similar to that of NO PCM by the 6th and final activity cycle. HR was significantly greater during the crawling phase of each activity cycle throughout trials in all three conditions ($P<0.001$).

4.2.2 PSI

PSI increases significantly over time in all three conditions ($P<0.001$; Figure 7) and follows a similar trend as expected with heart rate between simulated activity within cycles. No significant difference is identified between the two PCM trials (PCM1, PCM2) during the first 75 minutes of activity. Following this period PCM1 appears to have a greater increase in physiological strain than PCM2 (NoPCM=5.1, PCM1= 4.4, PCM2= 2.8; PSI during final crawling phase in cycle 6) with NoPCM causing the greatest physiological strain when identified with rectal temperature. This also shows tendencies that during PCM1 trials physiological strain can increase to a greater level than that of NoPCM when worn over a pre-longed period (EOD activity lasting significantly longer than an hour).

4.2.3 PhSI

PhSI follows the same trend as PSI when calculated using both Rectal and CorTemp® pill. PhSI increases over time with activity ($P<0.001$; Figure 7). After a ten minute break if phase change is not replenished and the same PCM are re-applied (PCM1) physiological strain increases at a greater rate than trials with no PCM. PCM2 trials provide the greatest reduction in physiological strain post 10 minute break ($P<0.001$). The integrated rest period reduced PhSI by 1.2 ±0.6 across all conditions.

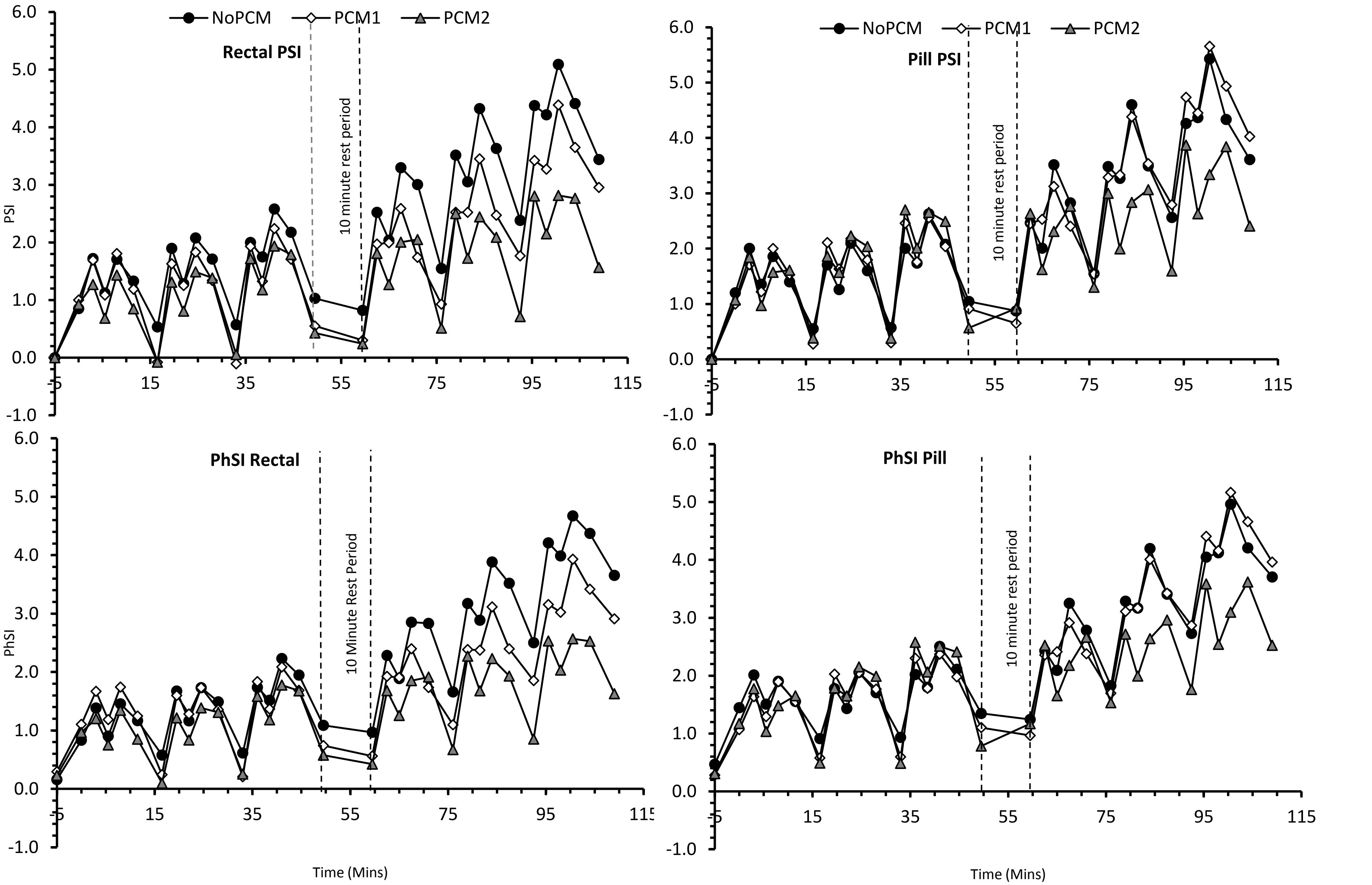

Figure 7: PSI & PhSI responses over an EOD Related activity sequence in 3 conditions. Displayed responses are identified using T_R and CorTemp Pills with heart rate within the appropriate equations. Error bars are omitted for clarity. Refer to text for significant differences.

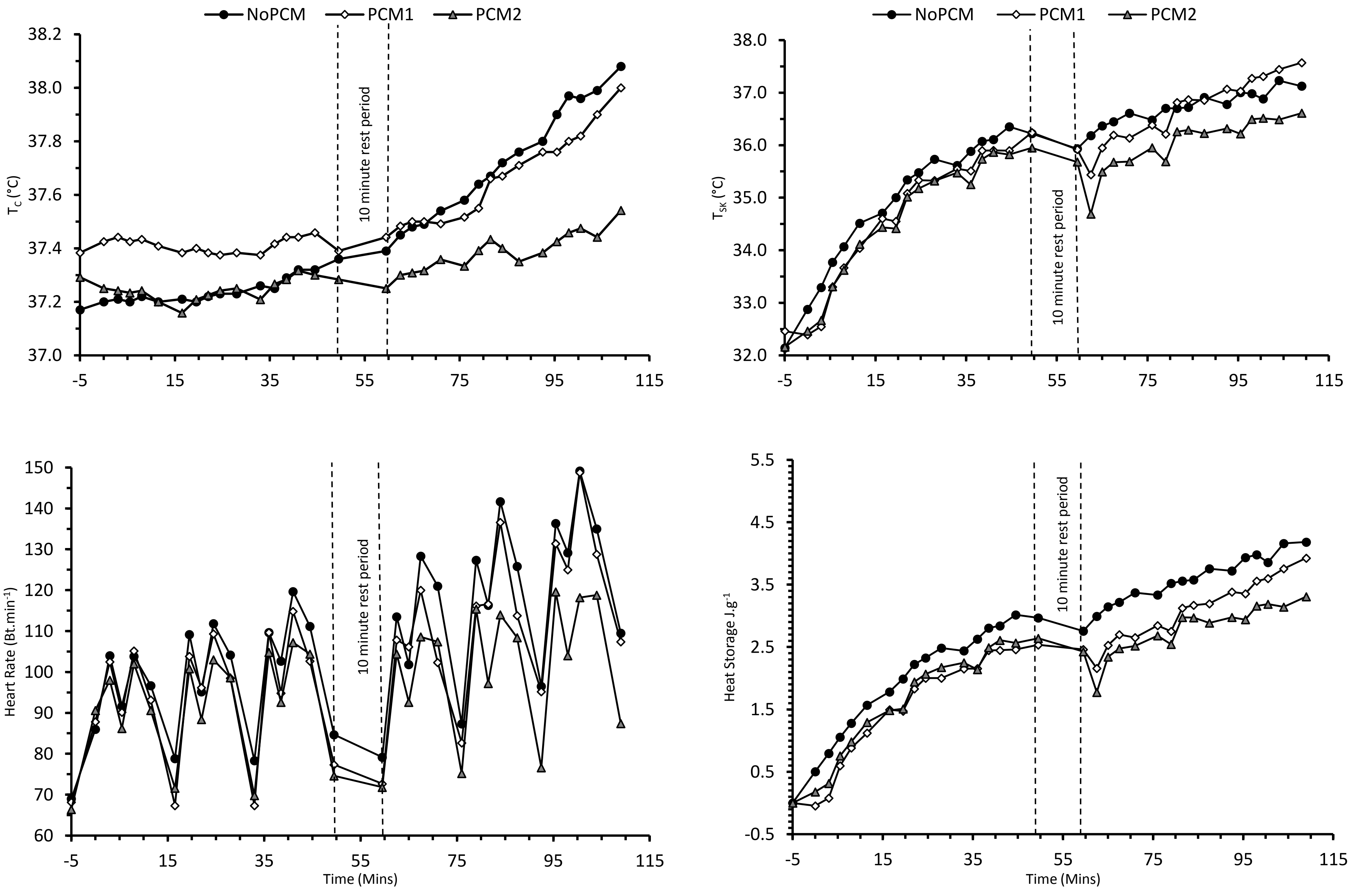

Figure 6. Core Temperature (T_C) Skin Temperature (T_{SK}) Heart Rate and Heat storage responses over an EOD related activity sequence within three conditions (NoPCM, PCM1, PCM2). Error bars are omitted for clarity. Refer to text for significant differences.

4.2.4 Sweat Rates

Mean sweat rate varied between all three conditions (P<0.001; Figure 7). Mean sweat rate was lowest in PCM2 trials and highest in NoPCM trials (NoPCM- 0.82±0.29, PCM1- 0.70±0.38, PCM2- 0.52±0.26; L.hr^{-1}).

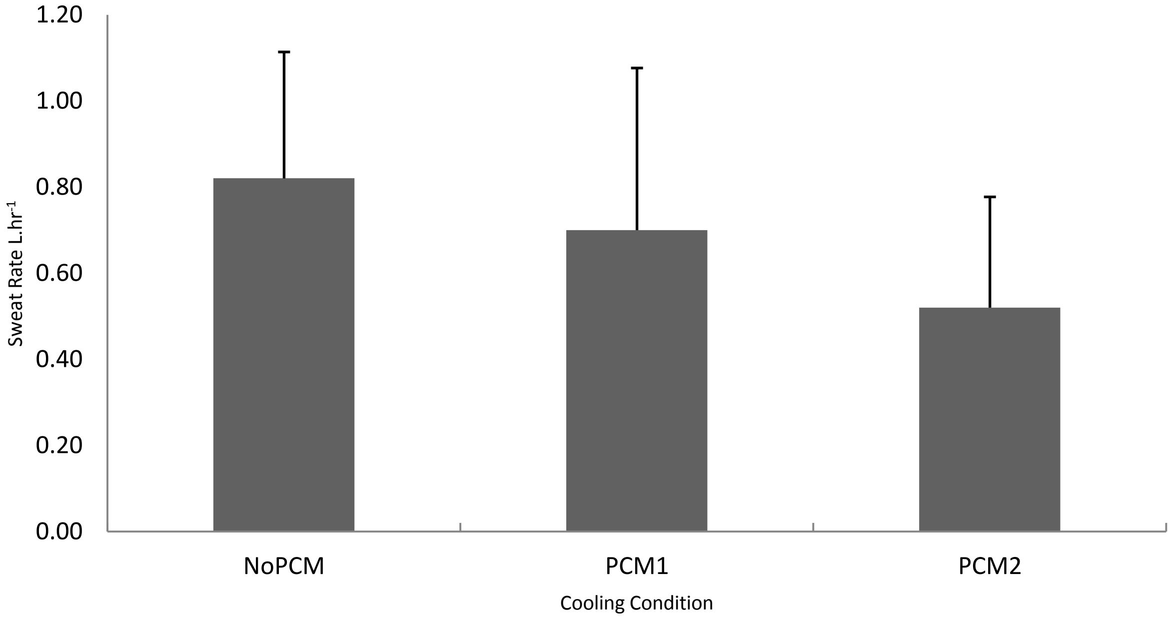

Figure 8. Mean Sweat Rate (L·hr^{-1}) over an EOD related activity sequence in 3 conditions calculated from pre and post trial nude body mass. Values are mean±SD. Main effect for condition; $P \leq 0.001$.

4.3 Perceptual responses

4.3.1 RPE

Overall and Local RPE values increased over time within each condition and varied between conditions (P<0.001; Table 2 and Appendix C). Participants identified that the greatest level of exertion was experienced within the upper back and shoulders (P<0.01). RPE was greatest when NO PCM was worn. PCM1 showed a greater rise in overall RPE (+3, difference between cycle 3 and cycle 6 arm ergometry) post break in comparison to PCM2 (+1.9, difference between cycle 3 and cycle 6 arm ergometry) (P<0.001) and therefore resulted in a similar perceived exertion between PCM1 and NoPCM. This rise is noticeable during the final 49:30 (min:sec) of activity as HR rate increases within PCM1 more rapidly.

Table 2 .Trial differences in RPE (means± SD) pre and post integrated break over an EOD related activity sequence. Recordings are taken during arm ergometry in the 3rd cycle pre-break and in the 6th cycle post break. Difference identified between NoPCM and PCM1 +2 pre break are annotated as follows *(P<0.05) **(P<0.001). Difference identified between PCM2 and 1PCM + NoPCM post break are annotated as follows. # (P<0.05) ##(P<0.001) (n=6).

Condition	Cycle	RPE			
		Overall	Upper Back + Shoulders	Lower Back	Legs
No PCM	**3**	14.2±1.7**	14.7±1.4**	13.2±1.2	12.7±1.5*
	6	17.8±1.3	18.8±1.2	17.2±1.2	16.8±1.6
PCM1	**3**	13.8±1.3	14.8±1.0	13.3±1.2	13.2±2.8
	6	16.8±1.8	17.8±1.3	16.0±1.7	15.3±3.0
PCM2	**3**	12.8±0.8	13.5±0.8	12.2±0.8	12.2±0.8
	6	14.7±1.6##	15.7±1.6##	13.5±1.4##	13.0±1.5##

4.3.2 Thermal Sensation + Thermal Comfort

Thermal sensation and thermal comfort were lowest in PCM2 (vs PCM1 and NoPCM P<0.001; Table 3, Appendix C). Within the first three activity cycles thermal sensation and comfort responses tended to be greatest within the NoPCM trials with PCM1 and PCM2 trials displaying similar results. During the final three cycles the rate of rise in thermal sensation and comfort overall tend to be greater in PCM1 trials bringing overall thermal sensation and comfort to similar levels to that of NoPCM trials.

Table 3. Trial differences in thermal sensation and thermal comfort (mean ± SD) pre and post integrated break over an EOD related activity sequence. Recordings are taken during arm ergometry in the 3rd cycle pre-break and in the 6th cycle post break. (n=6)

Condition	**Cycle**	**Thermal Sensation**						**Thermal Comfort**					
		Overall	**Head**	**Back**	**Chest & Arms**	**Groin**	**Legs**	**Overall**	**Head**	**Back**	**Chest & Arms**	**Groin**	**Legs**
NoPCM	3	6.0±0.9	5.8±1.3	6.0±0.6	5.8±0.8	5.5±0.8	5.5±0.8	5.8±0.8	6.0±1.1	6.0±0.6	5.8±0.8	5.7±0.8	5.5±0.8
	6	7.2±0.8	7.3±0.8	7.3±0.8	7.3±0.8	7.2±0.4	7.2±0.4	7.3±0.8	7.5±0.8	7.5±0.8	7.5±0.8	7.2±0.8	7.3±0.5
PCM1	3	5.4±0.8	5.5±1	5.0±1.1	5.2±0.4	5.7±0.8	5.9±0.7	5.4±0.8	5.5±1	5.1±0.5	5.1±0.5	5.3±1.1	5.3±1.1
	6	7.0±0.6	6.8±0.8	7.2±0.8	6.7±0.8	7.3±0.8	7.2±0.8	7.0±0.6	7.0±0.9	7.2±1.0	7.0±0.6	7.2±1.0	7.2±1.0
PCM2	3	5.2±0.4	5.0±0.9	5.0±0.6	4.8±1.0	5.2±0.8	5.3±0.5	5.2±0.4	5.0±0.9	5.0±0.6	4.7±1.0	5.2±0.8	5.2±0.4
	6	5.8±0.8	5.7±0.8	5.7±0.8	5.3±0.5	5.8±0.4	5.8±0.4	5.8±0.8	5.8±0.8	5.7±0.8	5.5±0.8	5.8±0.8	6.0±0.9

4.3.3 PeSI

Perceptual strain was lowest within PCM2 trials (vs NoPCM and PCM1, P<0.001; figure9). At the end of first work period prior to a break PeSI was significantly greater (vs NoPCM and PCM1, P<0.001) in NoPCM trials(Figure 10; NoPCM:1:38, PCM1: 1.11, PCM2: 1.25, rise in PeSI between start of cycle 1 and cycle 3 arm ergometry). After the rest period between 49.30 and 59.30 the absolute change in perceptual strain was evident within PCM1 (p<0.001) trials (Figure 10; PCM1:1.34, PCM2: 0.7, NoPCM: 1.1, rise in PeSI between start of cycle 4 and cycle 6 arm ergometry). Perceptual strain was reduced by 0.19 ±0.07 during the integrated break across all three conditions.

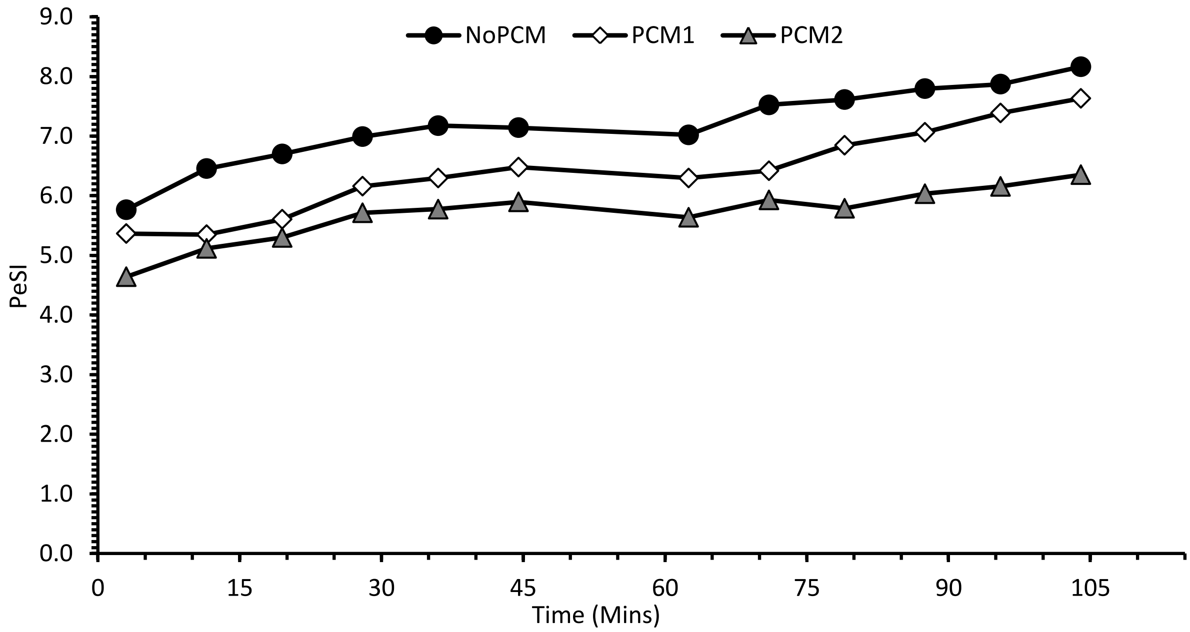

Figure 9. Perceptual Strain Index (PeSI) over an EOD related activity sequence within three conditions (NoPCM, PCM1, PCM2). Error bars are omitted for clarity. Refer to text for significant differences.

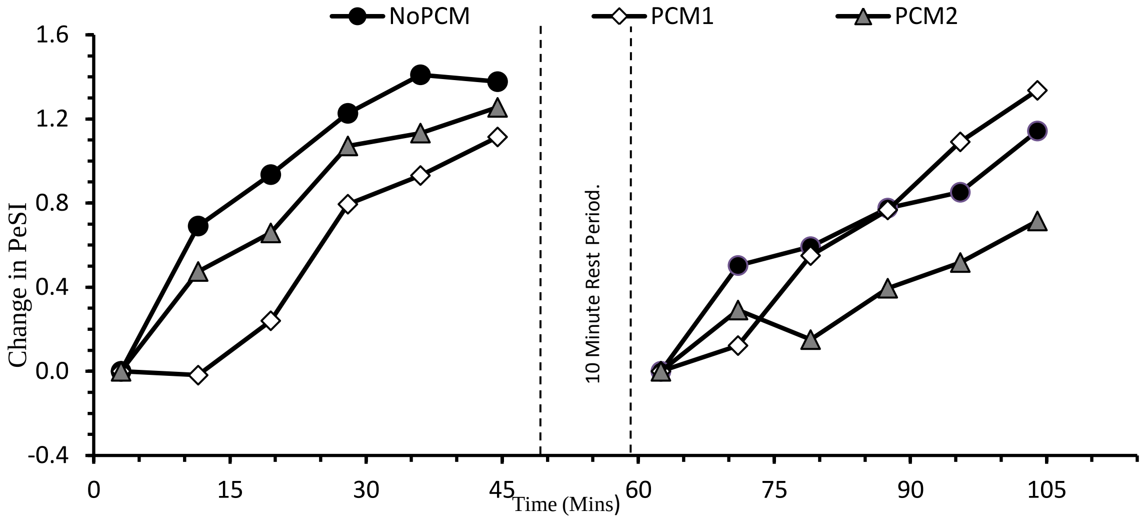

Figure 10. Changes in PeSI from start of pre and Post break workloads over an EOD related activity sequence within three conditions (NoPCM, PCM1, PCM2). Error bars are omitted for clarity. Refer to text for significant differences

4.4 Anecdotal Feedback

Participants reported that they found the searching and crawling phase the most difficult throughout trials. Participants also identified that it is difficult to identify perceived exertion levels between body parts as the total weight of the suit made them feel "exhausted all over".

Participants identified that their positioning whilst conducting an activity determined the sensation of cool in which they were feeling as the PCM vest does not fit tightly to the body. During the crawling phase a participant identified that is when they felt majority of cooling on their back due to the weight of the suit pushing down the PCM.

4.5 Summary of Results

Within all three conditions thermal physiological strain increased with activity duration and was greatest during the final 49:30 of activity (minute:seconds; $P<0.001$, main effect for time for all variables). During the first three activity cycles prior to integrated break these responses were greatest with no PCM trials and tended to be similar within the PCM1 and PCM2 trials. All perceptual data followed this same trend ($p<0.001$, Main effect for time).

Observations during the integrated ten minute rest periods (49:30 to 59:30,minutes:seconds) identified that the PCM during PCM1 and PCM2 trials had completely melted during the first 3 activity cycles. PhSI was reduced during the integrated rest period by 1.2±0.6 across all three conditions.

During the final 3 activity cycles S increased at the greatest rate within PCM1 trials and was alleviated with PCM2 trials ($p<0.001$). Due to increased S no significant difference was identified between NoPCM and PCM1 trials post break (NS for $T_{c,}$ $T_{msk,}$ and HR) with significantly attenuates strain within PCM2 trials ($p<0.01$ for HR and $p<0.001$ for T_c and T_{msk} in comparison to NoPCM and PCM1, Table 3). PeSI and perceptual data was also lowest post break within PCM2 trials in comparison to NoPCM and PCM1 ($P<0.001$, table 4). Overall sweat loss for trials reflected the physiological response with greatest level of sweat identified in NoPCM and least in PCM2 trials and was significant between trials (Table 4).

Table 4.Summary of physiological and perceptual variables taken during arm ergometry within the final activity cycle. Values shown are means ± SD.

	NoPCM	**PCM1**	**PCM2**
Core Temp (°C) $^{\#\dagger}$	37.0±0.3	38.0±0.3	37.4±0.5
Mean Skin Temp (°C) $^{\#\dagger}$	37.2±0.3	37.4±0.3	36.5±0.5
Heart Rate (bt.min^{-1}) $^{\phi\dagger}$	135±25	129±34	119±25
Heat Storage (J.g^{-1}) $^{\#\dagger}$	4.2±0.5	3.8±0.5	3.1±0.9
PhSI $^{\#\dagger}$	4.4±1	3.4±1.7	2.5±0.6
Sweat Rates(L.Hr^{-1}) $^{\phi}$	0.82±0.29	0.70±0.38	0.52±0.26
RPE Overall $^{\#\dagger}$	17.8±1.3	16.8±1.8	14.7±1.6
Thermal Sensation $^{\#\dagger\ \Phi}$	7.2±0.8	7.0±0.6	5.8±0.8
Thermal Comfort $^{\#\dagger\ \Phi}$	7.3±0.8	7.0±0.6	5.8±0.8
PeSI $^{\#\dagger}$	8.2±0.8	7.4±1.1	6.4±0.9

$^{\#,\ \phi}$ main effect for trial ($p\leq0.01$, $p\leq0.001$); † main effect for time ($p\leq0.001$); $^{\Phi}$ interaction trial × time ($p\leq0.05$).

5 Discussion

Replacing a PCM vest during an integrated break of an EOD related activity sequence in 40 °C conditions resulted in significant reductions of individuals T_{re} and HR in comparison to wearing no PCM and one PCM material throughout activity. Reductions were also noted within perceptual indices. Prior to an integrated break PCM1 and PCM2 trials are effectively the same condition and the greatest magnitude of T_c and HR can be identified within the NoPCM trials. Following an integrated break it was identified that should the same phase change vest be re-applied a greater magnitude in rise of T_C, HR and perceptual response can be identified in comparison to wearing no PCM at all. An increase in heat strain may be accounted for by the re-applied PCM becoming a further layer of insulation, reducing airflow across the skin and increasing metabolic heat production with extra weight and reduced movement efficiency with no cooling benefit once completely phase changed and thus having a negative effect on thermoregulation. To the authors knowledge this is the first study to demonstrate that should activity within hot environments go on for a prolonged period of time applying a new (charged) PCM during an integrated break can significantly alleviate thermal physiological and perceptual strain. If an EOD mission is likely to last under 1 hour 15minutes without changing or recharging a PCM vest it is still more beneficial than not wearing one at all. Should trials last significantly longer than 1 hour 15 minutes without changing or re-charging a PCM vest we may see negative thermal effects such as a greater rise in heat storage and perceptual strain.

The following section will assess the magnitude of response whilst wearing PCM within PPE in hot environments (section 5.1). This will be followed by a more in-depth examination of physiological and perceptual response of this study (section 5.2). The final section will discuss the rationale for protocol procedure (section 5.3) followed by potential operation recommendations following this study (section 5.4).

5.1 Changes in Physiological Strain with applied cooling vests.

The beneficial response of replacing a PCM during an integrated break can be identified in its ability to reduce two physiological variables contributing to increase physiological strain, T_c and HR, when exercising within hot environments (Casa, 1999). In the present study HR was reduced by 20±5 bt.min^{-1} at the end of the final activity cycle when PCM was changed at the integrated break (Table 5).T_c was also significantly lower when PCM was changed in comparison to the NoPCM and PCM1 trial (0.56±0.32 °C reduction in T_c compare to NoPCM). Previous studies have also shown that wearing phase change material and cooling vests can reduce HR and T_c however no previous studies have replaced a cooling vest during trials (Table 5). During 45 min stepping exercise (12.steps.min^{-1}) followed by a 45 minute rest period within 40 °C ambient temperature whilst wearing fire fighter ensembles House *et al*. (2009) reported that cooling vests with a lower melting point provide the greatest significant reduction in HR. Cooling vests with a melting point of 30 °C resulted in no significant improvement in heart rate during exercise. Following the 45 minute rest period a cooling vest with the lowest possible melting point of 0°C resulted in a significantly lower HR rate in comparison to all other cooling vests($p<0.05$). House *et al.* (2009) identified that following the protocol all vest types had mostly or completely melted. CV_0 provided the greatest capacity for T_c reduction in comparison to control and all other vest types ($p<0.05$) at the end of the trial. It was identified that during stepping CV_0 provided 40 watts of cooling in comparison to CV_{10} (29 watts). This greater capacity of cooling will allow for reduced temperature within tissue mass and more vasoconstriction to the skin. A subsequent higher level in venous return is resultant in a lower heart rate and reduced cardiovascular strain.

Table 5: A comparison of magnitude of reduction in physiological strain achieved in studies when cooling vests have been used with PPE within hot environments. * denotes P<0.05 **denotes p<0.001

	Participation	**Protocol**	**Environmental Condition**	**T_C Changes**	**HR Changes**
Current Study	6 male university Students	115 Min Bomb Disposal activity sequence. Mark iv body armour. Three Conditions (NoPCM, PCM1, PCM2; 25 °C)	40°C	PCM 2: 0.56±0.32°C** PCM1: 0.08±0.35°C	PCM2: 20±5 bt.min^{-1} ** reduction in. PCM1: 3±15 bt.min^{-1}
House *et al.* (2009)	10 Medically Fit Males	45 min stepping exercise (12 steps.min^{-1}) followed by 45 min rest .Wearing Fire Fighting clothing. Five conditions – Phase change with dif melting points (0 °C, 10°C, 20 °C, 30°C)	40°C dry bulb, 29.5°C wet bulb.	At end of work period CV_0 *significantly lower than control. No Sig between other conditions. Following rest all conditions significantly lower than control. $CV_{0,10,20}$ lower than CV_{30}*.	At end of exercise HR lowest in CV_0 and CV_{20}*. No reduction in CV_{30}. At end of Rest period HR lower in CV_0* compared to all other vests.
Smolander *et al.* (2004)	4 Experienced Fire Fighters	Subjects walked for 30 minutes twice at moderate intensity (4km/hr, 0°Inclination) and twice at high intensity 4km/hr, 4°inclination. With and without ice vest. Wearing full fire fighter ensemble.	45°C , 30%RH	Rest level of average T_C slightly lower in ice vest. Increase in T_C with test was similar with and without vest.	At end of walking for both work levels mean HR was 10bt.min^{-1}* lower when donning ice vest.
Bennet *et al.* (1994)	12 males experienced with fire fighting equipment.	Two Cycles of 30 min seated rest and 30 min treadmill walking (2.5mph). Three conditions- No vest, 4 pack cool vest, 6 pack cool vest. Worn under firefighting protective overgarments.	35±0.9°C dry bulb. 65%RH	No Vest:38.5±0.3 4 pack:37.8±0.4* 6 pack:37.4±0.2* Rate of increase: No Vest:1.2±0.19 4 Pack:0.76±0.17* 6 pack:0.41±0.14*	90 minutes HR: No Vest:129±12 4 Pack:103±15* 6 Pack:84±8* End Trial HR: No Vest:170±15 4 pack:169±15 6 pack:148±15*

Smolander *et al.* (2004) reported that HR was reduced by 10bt.min^{-1} whilst donning an ice vest during exercise within PPE in hot conditions. Four experienced fire fighters exercised at moderate and high intensity walking on a treadmill (4 km/hr 0°Inclination, 4km/hr 4°Inclination respectively) for 30 minutes within 45 °C, 30%RH whilst donning full fire fighter ensembles. No significant difference was identified between T_c response with and without the ice vest during both conditions however resting T_C was lower when an ice vest was donned. This may be explained as previous studies (Thake and Price, 2007) have identified that T_c response and significant rise normally takes place around 30 to 45minutes in similar conditions. Four male subjects conducted an EOD related activity sequence (66 minutes total) whilst wearing an EOD suit (with and without lightweight trouser design, with and without cooling) in 40 °C ambient temperature. The findings suggested that once T_{msk} reached T_c levels between 30 to 45 minutes is when a more rapid increase in T_c is evident. As Smolanders protocol only last 30 minutes it would suggest that maximal peaks in T_c have not been reached and therefore not seen maximal cooling effect that an ice vest may provide. The difference between PPE types can also explain differences within T_c data identified. Fire fighting ensembles may be considerably lighter than an EOD suit due to decreased ballistic properties. This may result in a slower rate in rise of T_C due to reductions in metabolic heat production. Environmental conditions at a higher temperature may also increase T_{SK} and subsequently T_C at a greater rate. Reinertson *et al.* (2008) would argue that this may cause a greater increase in humidity between the individual and cooling vest and have a negative effect on an individual's overall thermoregulation.

Bennet *et al.* (1994) examined the use of cooling vests in a protocol lasting a longer period of time. 12 males experienced in using fire fighting equipment conducted two cycles of 30 minutes rest and 30 minutes treadmill walking (2.5mph) whilst wearing a full fire fighting ensemble within 35°C 65%RH. Individuals conducted the trials whilst wearing no cooling vest, a cooling vest with 4 frozen gel packs and a cooling vest with 6 frozen gel packs. During this longer activity sequence significant reductions in both T_C and HR whilst wearing a cooling vest compared to no vest were identified. After 90 minutes mean HR was 45 $bt.min^{-1}$ lower whilst wearing 6 pack vest and 26$bt.min^{-1}$ lower whilst wearing a 4 pack vest. By the end of the trial Mean HR was only 22$bt.min^{-1}$ and 1$bt.min^{-1}$ (6 Pack and 4 pack) lower than no cooling vest. The 4 pack cooling vest covered 52% less skin surface area than a 6 pack gel vest. This lower capacity for cooling tissue mass and blood via heat transfer will result in increased cardiovascular and physiological strain due to increased vasodilatation to the periphery and decreased venous return.

Smolander *et al.* (2004) identified with the use of a thermal manikin test that an ice vest takes around 45 minutes to melt and around 334kj. This can be dependent upon the specific heat capacity and mass of coolant used in the vest. The present study identified that during the rest period (49:30-59:30,Minutes:Seconds) that the PCM vests had mostly or completely melted within all trials and House *et al.* (2006) also identified that cooling vests had completely melted by the end of his protocol. As the majority of cooling (60-70%) takes place during phase change (House *et al.* 2006) cooling capacity will be significantly diminished once a cooling vest is completely melted. An increase in tissue and periphery temperature triggers an increased vasodilatation to the periphery. Subsequent increased sweat rates create a saturated micro-climate due to the lack of sweat evaporation through impermeable (increased with melted cool vest) PPE layers. As the temperature gradient between the core and periphery is lost the body no longer has a means for cooling resulting in increased cardiovascular and thermal physiological strain. Such conditions can cause detriments to operational performance which can prove to be fatal in conditions such as EOD operations. Physiological and perceptual strain can significantly affect cognition within operational procedure (Radakovic *et al*. 2007). It is difficult to identify once a cooling vest is fully melted under PPE and may be having a negative impact on heat storage and subsequent thermal strain.

The discussed studies have indentified physiological strain reductions due to wearing cooling vests within hot conditions and PPE. As the mentioned studies do not exceed exercise for significantly longer than one hour it cannot be identified whether the cooling vests are starting to cause a negative effect on thermoregulation and contribute to a UHS environment created by PPE with low evaporative efficiency in hot humid environments.

5.2 Thermal Physiological and Perceptual Responses

5.2.1 Thermal Responses

T_{re}, T_{msk}, and heat storage (Figure 6) all increased significantly over time within all conditions. The EOD suit encapsulates the wearer and there is only a minimum amount of cooling via evaporation of sweat via integrated fan systems. As an individual begins to heat up and sweat with little means of evaporation it will continue to cause a more humid condition within the micro-environment created between the EOD clothing and the periphery (Havenith, 1999). As the body attempts to dissipate more metabolic heat and increases in T_{msk} and sweat rate more blood is shunted to the periphery (Casa, 1999). When there is no more capacity for cooling and T_{msk} reaches levels similar to that of T_{re} and heat storage is increased a subsequent rapid increase in T_{re} is evident. This response is heightened when conducting exercise within hot and humid environments due to reduced cooling function and particularly in operations committed to high levels of physical exertion (Casa, 1999). Sawka *et al.* (1985) identified in a study consisting of 13 male participants completing cycle ergometer VO_{2MAX} tests within moderate (21 °C 30%RH) and hot (49 °C 20%RH) environments that an 8% decrease in maximal aerobic power can be identified in hot compared to cool environments. Whilst conducting EOD operations in a heavy suit a compromise between cooling capacity and muscle function is made due to levels of blood shunted to the periphery for cooling counterbalancing blood flow for muscle function.

T_{re} and heat storage were significantly reduced during the first 3 cycles of activity prior to a break (49:30-59:30) during both PCM trials. Statistical analysis identified that there was no difference ($p>0.01$) between the PCM trials prior to an integrated break. When a passive cooling vest is worn within PPE the greatest amount of energy is absorbed during the change from solid to liquid (Reinertson *et al* 2008). Cooling vests will work more effectively with exercise when the ambient temperature is lower than that of the $T_{c.}$ As the external heat load is greater than this and the PCM is only in contact with the torso it is not expected that body temperature would be maintained fully however the rise in temperature reduced when wearing such cooling device.

During the final 3 activity cycles prior to the break it was identified that the greatest rate of rise in T_{msk} and heat storage was evident in the PCM1 trial and greater T_{re} rise in PCM1 and NoPCM trials. It was reported that the PCM was completely melted following the third activity cycle and during the 10 minute rest period and therefore the phase change material has a diminished cooling potential. A possible detriment to PCM which has previously been questioned is the increased weight added to the wearer and subsequent increase in metabolic heat production. An extra barrier is caused to evaporative heat loss (Reinertsen *et al.* 2008) and a subsequent negative impact on thermoregulation. As the PCM had completely melted prior to the start of the final 3 activity cycle the cooling power is diminished and the increased metabolic heat production from increased PCM weight with in-effective cooling will increase rise in heat storage (Figure 6) and increase the onset of thermal strain (Havenith 1999).

PCM2 trials provided the greatest alleviation in thermal strain following a break due to the application of a recharged phase change material. At the end of the integrated break a drop in T_{msk} and heat storage is present with a subsequent drop in $T_{C.}$ This is due to the new PCM providing greater cooling power and allowing for the body to dissipate more heat. A slow rise in thermal response is evident as exercise continues supporting cooling vest studies (House et al 2009; Smolander *et al.* 2004).The cooling capacity is diminished to the extent in which it is unable to manage with the total heat exchange mechanism through the PPE and the bodies capacity to maintain thermal steady state (Reinertson *et al*. 2008). Should operatives exceeded the protocol time we would expect to see a peak in thermal responses again due to the refreshed PCM being completely melted by the end of the final three activity cycles.

In all trials we see the greatest rate of rise in skin temperature during the first 30 to 45 minutes of activity and exposure. This resultant rise is due to heat transfer from the environment and the EOD suit to the cooler skin and increased metabolic heat production via higher intensity exercise with a heavy workload. Thake and Price (2007) also identified this as the body is attempting to dissipate heat through the means of increased blood flow to the periphery until the T_{msk} reaches similar levels of T_C and the ambient temperature with no possible means of cooling. A significant and rapid drop in mean skin temperature (Figure 6) when applying a refreshed phase change at the end of the integrated break would be subsequent to the cool vest having a sudden impact on the area measured local to the surface area occupied by the PCM (Chest). We can also see a variation in T_{SK} results over time which may be identified by the position in which an individual is standing in comparison to the fit of the PCM to the torso. For example anecdotal feedback reported that subjects felt a greater sensation of coolness of their backs compared to their chest (skin measurement) during the crawling activity due to the weight of the suit pushing the PCM tight against the skin. During the crawling activity it will allow for a flow of warm air generated via the built in fans to pass over areas in which the vest does not fit tightly and less air flow to areas of skin in which the vest is pushed against. It is expected that this effect is transient between activity's and does not last for a sufficient amount of time to provide a greater cooling effect.

Sweat rate was highest in NoPCM and lowest with PCM2 trials. It is difficult to identify if sweat rate followed a similar trend as other thermal responses as this can only be identified at the end of the trial. In order to see if sweat rate increased prior to the final 49:30 (min:sec) of activity in PCM1 trials would require nude body mass to be measured during the integrated break before re-donning the PCM.

5.2.2 Heart Rate

In accordance with previous research (Thake & Price 2007, Thake *et al.* 2009) heart rate significantly increased over time with EOD related activity and altered between activity types.

Crawling phases provide the greatest increase of HR for individuals and may be explained due to the extreme weight bearing effect of the suit on the arms and shoulders during this two minute period.

Heart rate was significantly greater in the NoPCM trial compared to PCM2 trials as little capacity for cooling provides a greater strain on the thermoregulatory system whilst wearing an EOD suit due to encapsulation and little evaporative efficiency. As the body has limited heat transfer pathways for cooling it continues to increase blood flow to the periphery in an attempt to dissipate heat as well as increasing blood flow to the functioning muscles. As the demand for heat dissipation and functioning muscles become too great a decrease in venous return triggers the subsequent increase in heart rate and cardiovascular strain (Casa 1999). This effect is heightened when exercising within hot environments particularly with an extreme weight bearing condition and high intensity activity. The cardiovascular system is unable to cope with skin and muscle flow simultaneously within such extreme conditions and maintenance of blood pressure becomes priority over cooling and performance capacity, increasing metabolic inefficiency and hyperthermia.

PCM2 trials result in a lower heart rate (Table 4) once re-charged in comparison and can be explained in terms of the cooling capacity of the trial. There is greater ability for the body to dissipate heat resulting in less strain on the cardiovascular system to shunt blood to the periphery and a reduced effect on venous return. PCM 1 trials identify a much greater rise in HR during the final 3 activity cycles due to the negative effect on thermoregulation of the melted PCM and a greater need for vasodilatation to the periphery.

5.2.3 Physiological Strain

PSI (Moran, Shitzer and Pandolf 1998) and PhSI (Tikuisis, Mcllelan and Selkirk 2002) were both identified using the appropriate calculations with T_C and heart rate as the defining factors of physiological strain. Physiological strain using both variables followed the same trend for both PSI and PhSI. Readings identified on a strain index between the two provided no significant difference between the two calculations ($p>0.05$) (Figure 7). It would be argued that PhSI provided the more accurate measure of physiological strain as it does not use a standardised maximal HR for individuals. Thus allowing for a greater rate of rise which is possible during high intensity exercise within heat and more appropriate to a study of this extent normalises a resting heart rate to 60bt.min^{-1} eliminating the affect of pre-anticipatory rise which may affect resting HR recordings prior to trials. This is evident (figure 7) when PSI drops to a negative recording due to an individual resulting in lower resting HR during the first rest period in comparison to prior to trial start. Therefore the author considers PhSI to be a more appropriate scale within this protocol and environment procedure. Another benefit of PhSI scale would be the development of the PeSI which was designed in accordance with it (Tikuisis, Selkirk and Mclellan 2003) whilst measuring physiological and perceptual strain of individuals wearing semi permeable PPE in hot environments. This provides an index of perceptual strain to be used in accordance with individual's physiological strain.

As expected PhSI increases significantly over time and alters with activity in alignment with HR rate due to the more physiologically demanding tasks such as crawling over all three conditions. Due to the cooling effect of a refreshed PCM prior to an integrated break we would see a reduction in increases of T_C and HR due to the bodies' greater capacity to maintain thermoregulation. This drop in T_C and HR provide a lower level of cardiovascular strain and subsequent lower index of physiological strain for an individual. A greater rise in PhSI is evident in PCM1 (in comparison to PCM2 and NoPCM) during the last three activity cycles due to a greater rise in T_C and heart rate created by a PCM with no more capacity for cooling having a negative effect on thermoregulation. Should activity significantly exceed the length of this protocol we would expect to see PCM1 trials provide a greater level of physiological strain in comparison to wearing NoPCM due to the rise in PhSI and physiological responses being more extreme in PCM1 after 49:30 (min:sec).

5.2.4 Perceptual Responses

RPE overall increased over time with each trial and was significantly different between each condition during the second bout of exercise. The greatest levels of RPE were identified local to the upper back and shoulders in comparison to any other body segment (Table 2, Appendix C). Subjectively this was identified due to the weight load of the EOD ensemble predominantly bearing down on the shoulders of individuals. Although weight load was the same between PCM conditions and only slightly higher than NoPCM trials RPE was reported significantly lower during PCM2 trials. This could be identified in comparison with cardiovascular strain causing a greater level of exertion due to the inability to dissipate heat in the NoPCM trials. Also prior to an integrated break PCM1 trials showed a much greater rise in RPE overall and locally which as before could be explained due to the vest providing an extra layer of insulation and also the possibility that the increase in weight load with no cooling (Reinertson *et al.* 2008) in comparison to NoPCM can increase metabolic heat production and have a negative effect on exertion.

Thermal sensation (TS) and thermal comfort (TC) increased over time within all three conditions. Thermal sensation was reported to be reduced during PCM1 and PCM2 trials during the first three activity cycles and thermal comfort improved. During the final three activity cycles PCM1 trials showed the greatest increase in thermal strain and greatest levels of thermal discomfort in accordance with increases in physiological variables (HR and T_C in particular). A greater rise in TS and TC during PCM1 trials during the second exercise period in comparison to NoPCM trials suggests that should EOD activity exceed a length of time greater than this protocol with no opportunity to remove or replace a PCM that the operatives may be at greater thermal discomfort and feel a great sensation of heat than if they do not wear a PCM at all. We would expect to see the lowest levels of thermal sensation on the chest and back when the cooling vest was donned however this altered throughout cycles. A possible explanation for this is as previously mentioned dependant on posture and activity depends on how much contact and how tightly fit the PCM is against the skin surface area and the subsequent sensation of that area. Arens *et al.* (2005) conducted a study on thermal sensation examining the cooling and warming of body parts within uniform environmental conditions. It was identified that cooling of the back, chest and pelvic region have the greatest effect on overall thermal sensation in comparison to other local body parts and overall sensation readings were very similar to that of the local region. This could identify why little differences were identified between local thermal sensation and comfort during PCM cooling however further examination into more extreme environmental conditions such as those experienced within this study would have to take place.

PeSI followed a similar trend to that of PhSI suggesting that individuals can perceptually identify physiological strain. PeSI increased over time with PCM 2 trials showing the lowest level of perceptual strain. It also followed similar trends as previous physiological and perceptual recordings with PCM1 trials providing a greater rise in strain during the final 3 activity cycles in comparison to both NoPCM and PCM2 trials (Figure 10). When making a comparison between the PeSI and the PhSI, it is identified that individuals overestimate their actual physiological strain within all three conditions. This suggests that although comparisons can be made between the two indices and PeSI is another measurement that can be used to identify perceptual strain the scale would need to be individualised across a range of conditions in order to make a true comparison with physiological strain.

5.3 Rationale for Protocol Design

The Counterbalanced randomised study design showed that no training/order effect had taken place between trials as no significance between trial order was identified during this study through analysis of HR and T_{re} throughout trials and the one week gap between each trial for subjects was sufficient to eliminate any acclimation effects. The completion of a familiarisation session prior to main trials helped to provide any anxiety in which subjects may be adhered to during trials and whilst wearing an EOD suit. Subjects were able to gain a good understanding of standardised procedure between activities. The rest period following the first three activity cycles was an adequate amount of time for a PCM to melt completely. The ten minute period was sufficient to remove the upper body EOD PPE and allow for time to re-apply a new PCM or same PCM where needed.

5.4 Recommendation for Operational Procedure

The physiological and perceptual changes that have been discussed throughout this study whilst wearing cooling vests such as phase change materials have the potential to advise operatives on best operational procedure in order to gain the maximum cooling benefits to reduce thermal, physiological and perceptual strain. The following of such procedure will help to improve physical performance and reduce potential for detrimental effects of heat strain whilst working in extreme conditions particularly within PPE. This study suggests that in order to get maximal cooling benefit that operatives should were possible replace a PCM every 45 minutes during activity with hot environments. This would allow for cooling during PCM melting phase and be appropriate time to remove the PCM before it has any negative effects on the thermoregulatory system. If it is not possible to remove or replace a PCM during operation and the operational procedure is likely to last significantly longer than 1hr 30 minutes it would be advised that no PCM be worn at all due to the negative effects likely to outweigh the beneficial cooling caused during the first 45 minutes of PCM wear. In order to gain maximal benefit it would be suggested that PCM with a lowest possible melting point would provide maximal benefit (House *et al*. 2009) however such a study is yet to be identified following the same protocol. Since thermal strain is associated with decrements in performance of military based tasks (Taylor and Orlansky 1993) following these procedures could prove to have a positive effect.

This study has also identified that an integrated break if possible during operational procedure can help to reduce rates of rise in T_C, T_{SK} and heat storage which would subsequently increase tolerance time. During such integrated break it may also be possible for fluid replacements and cooling device replacements.

6 Conclusion

Whilst conducting bomb disposal activity wearing an EOD suit within hot environments thermal, physiological and perceptual strain is put on participants. Wearing PCM materials can significantly attenuate the rate of rise in thermal strain in which operatives are subject to over three EOD related activity cycles (49:30, Minutes:Secondss) compared to not wearing a PCM. If activity is likely to last an extended period of time (>49:30 Min:Sec) without PCM renewal thermal physiological and perceptual strain will rise at a greater extent to that of NoPCM . Once PCM has phase changed it becomes an extra weight (in comparison to NoPCM) with diminished cooling power and has a negative effect on thermoregulation. If after a ten minute break in operation another (charged) PCM is donned (PCM2) the rate of thermal physiological and perceptual strain is attenuated.

6.1 Limitations of present study and area for future research

A limitation with this current study is the fact that it only identifies effects in physiological responses whilst wearing PCM with a phase change point of 25°C. It would be argued that PCM with a lower melting point would provide a greater capacity for cooling (House *et al.* 2009) and if a PCM takes longer to melt due to environmental heat load and metabolic heat production alterations individuals may in fact be able to continue for longer. Removing a PCM at 45 minutes may be too early as it is yet to fully melt and absorb maximal heat with the added argument that should a phase change material be fully melted it still has capacity for cooling via radiation if the material is a lower temperature of that of T_{SK}. A key limitation with such a study is the in-ability to identify when a cooling vest is completely melted underneath a thick layer of impermeable PPE and therefore lack of knowledge on maximal cooling period. Future research could potentially include adding a thermistor to the PCM to identify temperature and cooling capacity.

The inclusion of participants that have had no previous experience within military situations may not be representative of those within EOD operation. Participants included within this study were identified as 22±3 yrs (body mass 78.1±9.3 kg; stature 176.3±6.5 cm). British army recruits have a mean age of 24±5 years (body mass 71.4±10.6kg; Stature 174±8cm) (Rayson *et al.* 2000). It is believed that aging does not affect performance within heat however the aerobic capacity and body fatness of an individual and reduction in aerobic capacity with ageing that will affect performance within heat and PPE (Kenney and Munce 2003 ; Ho *et al*. 1997).The aerobic capacity difference between participant inclusion and EOD operatives may alter response in relation to this study. It is believed that EOD operatives would generally be within the late 20s by the time experienced is gained to work in such conditions. Such operatives would be expected to go through physical training to competently perform within the increased weight load of such PPE where as participants included within this study has not.

Within a laboratory and controlled environment it is difficult to represent environmental conditions in which operational procedure may be subject to within the field. EOD operation with regions such as Afghanistan and Iraq may be subject to extreme levels of heat, humidity and wind. This study does not have the influence of wind speed on thermal strain within hot environments however it would be expected that an EOD suit with high levels of encapsulation would not allow a high flow of air to the body with increased wind speed. RH rises over the trial duration within this study however RH within field conditions may stay constant at greater extremities and for such reason further investigation into humidity effects of phase change cooling may be appropriate. This study does not represent possible heat load cause by radiation via sunlight. Although an EOD suit encapsulated the majority of an individual sunlight shining via the visor of the helmet may cause extra radiation heat to the localised area of the face.

A limitation of the PCM for this investigation is the “one size fits all” design. A PCM with a tighter fit that is designed to fit an individual more appropriately may alter the thermal response due to increased surface area contact and limitation of airflow between the micro-climate. Other PCM variables that have the possibility to alter thermal response are the stiffness of a PCM and its impact on wearer movement. More friction and restriction of movement can increase metabolic rate and heat production of the wearer (Cheung *et al.* 2000).

During this study a limitation in equipment used was evident with the CorTemp® telemetry pill. Previous studies (O'brian *et al.* 1998) have identified that a core temp telemetry pill is an accurate measurement of T_C. Nine participants took part in trials consisting of warm and cool rest and warm and cool water exercise. The study identified no differences between the telemetry pill in comparison to T_{re} and T_{ES} in both hot and cold conditions. The first limitation evident was the possibility that a participant may not be possible to swallow a telemetry pill. Casa et al (1997) assessed the use of a gastro intestinal telemetry pill as a measure of $T_{C.}$ It was reported that it is a valid measure of T_C however participants must swallow the telemetry pill well before heat exposure to allow for the pill to be within the gastrointestinal tract when food or fluid ingestion will not compromise readings (usually over 1 hour). As participants within this study were not required to be within the laboratory this far in advanced of trials reliance on subjects remembering to swallow the pill the appropriate time for trials was required. Possible fluctuations in results may be due to participants not swallowing the pill in a great enough periods prior to testing. A measure for testing this would include allowing participants to drink cold water and noting if effects on readings take place. It was also identified during trials that telemetry recordings are often interrupted through the thick layer of PPE particularly when placed in close proximity to another electronic device.

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APPENDICIES

APPENDIX A

Informed Consent Form

FACULTY OF HEALTH AND LIFE SCIENCES

Department of Biomolecular and Sports Sciences

The impact of replacing a torso covering phase change material (PCM) garment during rest after conducting activity representative of explosives ordnance disposal (EOD) operations on the subsequent thermal physiological response to identical work.

Principal Investigator: **Mark Smith**

Principal Supervisor: **Dr Doug Thake**

Thank you for showing interest in participating in this study. It is important that before you volunteer to participate you are absolutely clear on the intentions of the study and the protocol involved. All the relevant information is provided below and within the participant information sheet and requires your close attention prior to your participation. Do not hesitate to ask any questions that you may have regarding information provided here or other queries you may have.

PURPOSE OF THE RESEARCH

The main purpose of the current research is to investigate the use of cooling worn within personal protective clothing (EOD suits) that will potentially benefit explosives ordnance disposal (EOD) personnel through maintenance of physical and cognitive working performance in the heat. The aims of the current study are to investigate the impact of cooling (with PCM) on physiological and psychological responses to EOD type activity in 40°C environments. Predominantly the studies will investigate the impact of torso cooling, on cognitive performance and body temperature, and if adding a refreshed cooling device during an integrated break will maximise cooling. Torso cooling will be investigated, with the use of a phase change material vest (worn under the EOD suit, over the skin).

PARTICIPATION IN THIS RESEARCH WILL INVOLVE

Study Outline: The study will require a total of 21 hours commitment, split into seven sessions, with each session lasting a maximum of 2:45hours. There will be one habituation/familiarisation session followed by six experimental sessions. Each session will be separated by one week, and include a 1:44 Hours experimental trial, plus 60 minutes of preparation and cool down/showering time.

This investigation (figure 1) has three conditions:

1) The same PCM garment is worn throughout activity cycle 1-3 and 4-6.
2) Different PCM garments of the same design are worn in activity cycles 1-3 and 4-6.
3) No PCM garments are worn at any stage.

The 3 conditions will be conducted in a 'Heavy-weight' EOD suit and a similar suit with a 'heavier-weight' trouser design (Total Trials = 6).

Participant Requirements: Participants will need to be non-smokers, with no reported illness or injury, non-heat acclimated and physically active (more than 120 minutes of physical exercise per week). Participants will need to be available for a period of seven weeks during mid-February to the End of March (1st Study) and Mid-April to the first week in June (2nd Study). They will need to ensure they; avoid consuming alcohol or undertaking vigorous exercise at least 24 hours before each test day. They will be asked to follow their usual sleep routine combined with their usual dietary habits ensuring they are adequately hydrated, the night before and the morning prior to each test day. Due to the daily fluctuations in body temperature, heart rate, and sweat rate for example (as a result of our internal circadian bio-rhythm), participants will be required and asked to ensure they are available at the same time period on each test day, i.e. if the first session is conducted at 2pm all remaining sessions will be conducted at 2pm.

Measurements: A combination of physiological, subjective, and cognitive measures will be monitored and recorded during the current study. Baseline measures of heart rate, body temperature (core and skin), blood pressure, with local and whole body perceived thermal comfort (PTC), and perceived thermal sensation (PTS), with and without the suit (and/or cooling) will be made. Throughout the trial measurements of these variables at regular intervals with the addition of rate of perceived exertion (RPE) will also be made. N.B. For a full explanation of measurements see the attached *participant information sheet*.

FORESEEABLE RISKS OR DISCOMFORTS

You may experience discomfort from performing EOD type activities in the hot (40°C) conditions, due to the nature of the suit and the duration of activity. You may also feel a little discomfort from the rectal thermistor probe but this should be less noticeable as the trial progresses. There is a possibility of fainting occurring during any point of the trial due to the onset of sweating, and subsequent dehydration. However, in all cases there will be regular monitoring of physical and subjective responses throughout each trial. If deemed necessary by the investigator or if requested to by the participant the trial will be terminated, (see *trial discontinuation criteria* on the *participant information sheet*).

DATA PROTECTION

Any information provided in response to questionnaires, along with all your data, will be kept strictly anonymous. Your name will never be used in conjunction with your data instead each participant will be assigned a code recognisable by the principal investigators only. Paperwork will be stored in a locked filing cabinet and data will be kept on a password-secured computer only accessible to the principal investigators, Mark Smith or Dr. Doug Thake. Data may also be published in scientific works, but your name or identity will not be revealed. Your data may be made available to the participant(s) coaches if required and with prior consent by you the participant.

If you have any questions about your rights as a participant or feel you have been placed at risk you can contact Dr Doug Thake.

I confirm that I have read the above information. The nature, demands and risks of the project have been explained to me.

I have been informed that there will be no benefits / payments to me for participation

I knowingly assume the risks involved and understand that I may withdraw my consent and discontinue participation at any time without penalty and without having to give any reason.

Subject's signature ____________________________________Date _____________

Investigator's signature ____________________________________Date _____________

The signed copy of this form is retained by the student, and at the end of the project passed on to the supervisor.

A second copy of the consent form should be given to the subject for them to keep for their own reference.

Appendix B

Figure 9 :RPE scale. (Borg 1970)

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

Figure 10: Thermal Comfort Scale (Epstein and Moran 2006)

0 Very Uncomfortably cold
1 Uncomfortably Cold
2 Slightly Uncomfortably Cold
3
4 Comfortable
5
6 Slighlty Uncomfortably Hot
7 Uncomfortably Hot
8 Very Uncomfortably Hot

Figure 11:Thermal Sensation Scale (Young, Sawka and Epstein et al. 1987)

0 Unbearably Cold
1 Very Cold
2 Cold
3 Cool
4 Comfortable
5 Warm
6 Hot
7 Very Hot
8 Unbearably Hot

Appendix C

Table 7: Thermal Sensation and Comfot Responses to exercise over EOD related activity sequence (NoPCM). Means±SD
Table 8: Thermal Sensation and Comfot Responses to exercise over EOD related activity sequence (PCM1). Means±SD
Table 9: Thermal Sensation and Comfot Responses to exercise over EOD related activity sequence (PCM2). Means±SD

Condition	Activity	Cycle	Overall	Upper Back + shoulders	Lower Back	Legs
NoPCM	**Treadmill**	1	11.0±2.0	11.0±2.4	10.5±2.0	10.3±2.3
	Arm exercise		12.0±2.6	12.3±2.0	11.2±1.7	11.5±1.5
	Treadmill	2	12.7±1.6	13.2±1.6	12.0±1.3	12.0±1.8
	Arm exercise		13.2±1.7	13.5±1.4	12.0±1.3	12.3±2.0
	Treadmill	3	13.7±1.8	14.3±1.7	13.0±1.4	12.8±1.6
	Arm exercise		14.2±1.7	14.7±1.6	13.2±1.2	12.7±1.5
	Treadmill	4	13.8±1.7	14.2±1.6	13.0±1.9	13.2±1.8
	Arm exercise		15.5±1.8	16.5±1.2	14.7±1.4	13.8±1.7
	Treadmill	5	16.3±1.4	17.2±1.7	15.7±1.2	15.5±1.2
	Arm exercise		16.8±1.7	17.5±1.2	16.0±1.5	15.5±1.6
	Treadmill	6	17.3±2.0	17.8±1.7	16.7±1.2	16.3±1.9
	Arm exercise		17.8±1.3	18.8±1.2	17.2±1.2	16.8±1.6
PCM1	**Treadmill**	1	10.5±1.6	10.7±1.8	10.0±1.3	10.0±1.9
	Arm exercise		11.3±1.5	11.7±1.5	10.8±1.2	10.8±2.0
	Treadmill	2	12.3±1.4	12.8±1.7	11.7±1.4	11.8±1.9
	Arm exercise		12.7±1.6	13.2±1.8	12.0±1.7	12.0±2.0
	Treadmill	3	13.3±1.5	13.8±1.0	12.7±1.6	12.3±2.6
	Arm exercise		13.8±1.3	14.8±1.7	13.3±1.2	13.2±2.8
	Treadmill	4	13.3±2.0	14.0±2.0	13.2±2.0	12.8±3.3
	Arm exercise		13.7±2.3	14.5±1.8	13.5±2.4	13.2±3.5
	Treadmill	5	14.8±2.3	15.3±1.7	14.0±2.6	14.2±3.4
	Arm exercise		14.8±1.8	15.6±2.0	14.2±1.8	13.8±2.4
	Treadmill	6	15.4±1.7	17.0±1.9	15.0±1.9	14.4±2.5
	Arm exercise		16.6±1.9	17.8±1.8	15.8±2.0	15.0±3.2
1.1PCM2	**Treadmill**	1	10.0±2.2	10.3±2.4	9.8±2.3	9.7±2.0
	Arm exercise		11.0±1.0	11.3±0.8	10.8±0.8	10.3±1.2
	Treadmill	2	11.5±1.0	12.2±1.0	11.2±0.8	11.3±0.8
	Arm exercise		12.3±0.5	13.2±0.8	11.8±0.4	11.7±1.0
	Treadmill	3	12.5±0.8	13.2±0.8	12.0±0.9	12.0±1.1
	Arm exercise		12.8±0.8	13.5±0.8	12.2±0.8	12.2±0.8
	Treadmill	4	11.8±0.8	12.7±1.2	11.2±0.8	11.3±0.8
	Arm exercise		12.3±1.2	13.7±0.8	12.0±0.9	11.8±1.3
	Treadmill	5	12.8±0.8	13.7±0.8	12.3±0.5	12.2±0.8
	Arm exercise		13.5±0.8	14.3±1.2	12.5±0.8	12.0±1.4
	Treadmill	6	13.8±1.0	15.0±1.4	13.0±0.9	12.3±1.0
	Arm exercise		14.7±1.6	15.7±1.6	13.5±1.4	13.0±1.5

Table 6: RPE responses to EOD related activity sequence in 40°C whilst wearing MK6a suit. Means±SD

Table 7

Condition	Activity	Cycle	Thermal Sensation: Overall	Head	Back	Chest and Arms	Groin	Legs	Thermal Comfort: Overall	Head	Back	Chest and Arms	Groin	Legs
NoPcm	**Baseline 1**	**0**	4.0±0	4.0	4.0	4.0	4.0	4.0	4.0±0	4.0	4.0	4.0	4.0	4.0
	Baseline 2		3.8±0.4	3.8	3.8	2.7	3.8	3.8	3.6±0.4	3.8	3.8	3.8	3.8	3.8
	Treadmill	**1**	4.2±0.6	4.0	4.0	3.8	4.0	4.0	3.5±0.8	4.0	4.0	4.2	4.0	4.2
	Arm Exercise		5.0±0.8	4.8	5.3	3.1	4.7	4.7	4.6±0.8	4.7	5.0	4.5	4.5	4.7
	Rest		4.5±0.8	4.5	4.5	4.9	4.3	4.5	4.6±0.8	4.5	4.7	4.5	4.3	4.5
	Treadmill	**2**	4.8±0.8	4.7	5.2	4.5	4.7	4.7	4.3±0.9	4.7	5.2	5.0	4.7	4.8
	Arm Exercise		5.7±1.0	5.5	5.5	3.8	5.0	5.2	5.1±0.5	5.5	5.5	5.7	5.2	5.2
	Rest		5.0±0.8	5.2	5.0	5.6	4.8	5.2	5.1±0.5	5.3	5.3	5.2	5.0	5.2
	Treadmill	**3**	5.5±0.9	5.5	5.7	5.1	5.3	5.3	5.0±0.5	5.5	5.7	5.7	5.3	5.3
	Arm Exercise		6.0±0.5	5.8	6.0	4.7	5.5	5.5	5.6±0.8	6.0	6.0	5.8	5.7	5.5
	Rest		5.7±0.9	5.5	6.0	5.9	5.2	5.5	5.7±1	5.5	6.0	5.8	5.3	5.5
	10min Break	**Rest**	4.7±0.8	4.5	4.3	5.6	4.7	5.0	4.8±0.6	4.8	4.7	4.7	4.7	4.8
	Treadmill	**4**	5.2±0.8	5.5	5.0	4.6	5.0	5.2	4.9±1.2	5.3	5.3	5.5	5.2	5.3
	Arm Exercise		6.2±0.8	6.2	6.2	4.9	5.7	6.0	5.8±0.8	6.3	6.0	6.0	5.7	6.0
	Rest		6.0±0.8	6.0	5.5	6.2	5.8	6.2	5.9±0.6	6.2	6.0	6.0	6.0	6.0
	Treadmill	**5**	6.5±0.5	6.7	6.7	6.0	6.5	6.7	6.2±0.5	6.7	6.7	6.7	6.7	6.7
	Arm Exercise		6.7±0.8	6.8	6.7	6.1	6.5	6.8	6.5±0.8	6.8	6.8	6.8	6.5	6.8
	Rest		6.7±0.5	6.7	6.7	6.8	6.5	6.7	6.7±0.5	6.8	6.8	6.8	6.5	6.0
	Treadmill	**6**	6.8±0.8	7.2	7.2	6.7	6.8	7.0	6.8±0.5	7.2	7.2	6.5	6.8	7.0
	Arm Exercise		7.2±0.8	7.3	7.3	6.7	7.2	7.2	7.1±0.8	7.5	7.5	7.5	7.2	7.3
	Rest		6.8±0.8	7.0	7.2	7.3	6.7	7.0	7.0±0.8	7.3	7.3	7.3	7.2	7.2

Table 8

Condition	Activity	Cycle	Thermal Sensation						Thermal Comfort					
			Overall	Head	Back	Chest and Arms	Groin	Legs	Overall	Head	Back	Chest and Arms	Groin	Legs
PCM1	**Baseline 1**	**0**	4.0±0	4.0	4.0	4.0	4.0	4.0	4.0±0	4.0	4.0	4.0	4.0	4.0
	Baseline 2		3.7±0.5	3.7	3.3	3.3	3.7	3.7	3.8±0.4	3.8	3.5	3.5	3.8	3.8
	Treadmill	**1**	3.3±0.5	3.8	3.0	3.2	3.7	3.5	3.7±0.5	3.8	3.3	3.2	3.7	3.8
	Arm Exercise		4.2±0.4	4.5	3.5	4.0	4.0	4.5	4.2±0.4	4.3	3.5	4.0	4.2	4.3
	Rest		4.0±0.0	4.2	3.4	3.4	4.0	4.2	4.0±0	4.0	3.4	3.4	4.0	4.2
	Treadmill	**2**	4.5±0.5	4.7	4.0	4.0	4.5	4.7	4.7±0.5	4.7	4.2	4.2	4.7	4.5
	Arm Exercise		5.2±0.4	5.0	4.3	4.5	4.8	5.0	5.0±0.6	4.8	4.3	4.3	4.8	5.0
	Rest		4.8±0.4	5.2	4.2	4.6	4.2	4.6	4.8±0.4	5.0	4.6	4.2	4.4	4.6
	Treadmill	**3**	5.2±0.4	5.0	4.7	4.8	5.0	5.0	5.3±0.5	5.2	4.8	4.8	5.0	5.0
	Arm Exercise		5.3±0.8	5.5	5.0	5.2	5.7	5.8	5.3±0.8	5.5	5.0	5.0	5.2	5.2
	Rest		4.8±0.4	5.3	5.2	4.8	5.7	5.5	5.0±0	5.3	4.7	5.0	5.2	5.2
	10min Break	**Rest**	4.2±0.4	4.3	4.0	4.2	4.7	4.8	4.2±0,4	4.3	4.0	4.0	4.5	4.7
	Treadmill	**4**	5.0±0.6	5.0	4.7	5.0	5.2	5.2	4.8±0.8	4.8	4.5	4.8	5.0	5.2
	Arm Exercise		5.7±0.8	5.8	5.5	5.3	5.7	5.8	5.7±0.8	5.7	5.5	5.3	5.5	5.5
	Rest		5.7±0.8	5.8	5.5	5.3	5.5	5.7	5.7±0.8	5.7	5.3	5.3	5.5	5.7
	Treadmill	**5**	6.0±0.9	6.2	6.0	6.0	6.0	6.2	5.8±0.8	6.0	6.3	6.2	6.0	6.2
	Arm Exercise		6.4±1.1	6.4	6.4	6.2	6.4	6.4	6.6±0.9	6.6	6.6	6.8	6.4	6.6
	Rest		6.4±1.1	6.4	6.2	6.2	6.4	6.4	6.4±1.1	6.4	6.2	6.4	6.0	6.4
	Treadmill	**6**	6.8±0.8	6.6	6.6	6.6	6.4	6.4	6.8±0.8	6.8	6.8	6.6	6.6	6.4
	Arm Exercise		7.0±0.7	6.8	7.0	6.6	7.2	7.2	7.0±0.7	7.0	7.0	7.0	7.0	7.2
	Rest		7.0±0.8	7.3	7.0	6.8	6.5	6.8	7.0±0.8	7.0	7.0	7.0	6.5	6.5

Table 9

Condition	Activity	Cycle	Thermal Sensation						Thermal Comfort					
			Overall	Head	Back	Chest and Arms	Groin	Legs	Overall	Head	Back	Chest and Arms	Groin	Legs
PCM2	**Baseline 1**	**0**	4.0±0	4.0	4.0	4.0	3.0	4.0	4.0±0	4.0	4.0	4.0	4.0	3.8
	Baseline 2		3.7±0.5	3.7	3.3	3.3	3.6	3.7	3.8±0.4	3.7	3.7	3.8	3.8	3.7
	Treadmill	**1**	3.3±0.5	3.5	3.2	3.0	2.8	3.7	3.7±0.5	3.8	3.7	3.3	3.8	3.5
	Arm Exercise		3.8±0.4	4.2	3.5	3.5	3.8	4.0	3.8±0.4	4.0	3.8	3.5	4.0	3.8
	Rest		3.8±0.4	4.2	3.7	3.5	3.9	4.0	3.8±0.4	4.2	3.7	3.3	4.0	3.8
	Treadmill	**2**	4.2±0.8	4.3	4.0	3.5	3.6	4.3	4.5±0.5	4.3	4.0	4.0	4.7	4.1
	Arm Exercise		4.3±0.8	4.7	4.2	4.2	4.4	4.7	4.3±0.8	4.5	4.2	4.0	4.3	4.3
	Rest		4.3±0.5	4.3	4.3	4.2	4.3	4.3	4.3±0.5	4.3	4.2	4.0	4.2	4.3
	Treadmill	**3**	4.7±0.8	4.7	4.5	4.3	4.2	4.8	4.8±0.8	4.7	4.7	4.2	4.3	4.6
	Arm Exercise		5.2±0.4	5.0	5.0	4.8	5.1	5.3	5.2±0.4	5.0	5.0	4.7	5.2	5.0
	Rest		5.0±0.	5.3	4.8	4.7	5.1	4.8	5.0±0	5.0	4.8	4.3	4.7	4.8
	10min Break	**Rest**	4.2±0.4	4.0	4.2	4.0	4.1	4.2	4.2±0.4	4.0	4.2	4.0	4.2	4.1
	Treadmill	**4**	3.5±0.8	3.7	2.8	2.8	3.5	4.3	3.7±0.5	4.2	3.3	3.3	4.0	3.7
	Arm Exercise		4.5±0.5	4.7	4.0	3.8	4.4	5.0	4.5±0.5	4.7	4.2	4.2	4.7	4.5
	Rest		4.3±0.5	4.3	4.0	3.5	4.2	4.7	4.5±0.5	4.5	4.2	4.0	4.7	4.3
	Treadmill	**5**	4.7±0.5	5.0	4.2	4.0	4.7	5.2	4.8±0.4	4.8	4.5	4.2	4.8	4.7
	Arm Exercise		5.3±0.5	5.5	5.2	4.5	5.3	5.2	5.3±0.5	5.5	5.2	4.8	5.2	5.2
	Rest		4.8±0.8	5.0	4.8	4.5	4.9	5.2	4.8±0.8	5.3	4.8	4.8	4.8	5.0
	Treadmill	**6**	5.7±1.	5.5	5.2	5.2	5.6	5.2	5.7±0.5	5.5	5.3	5.3	5.2	5.4
	Arm Exercise		5.8±1	5.7	5.7	5.3	5.7	5.8	5.8±0.8	5.8	5.7	5.5	5.8	5.7
	Rest		5.5±0.8	5.5	5.3	5.2	5.4	5.5	5.5±1	5.8	5.7	5.5	5.3	5.6