Thermoregulation in the Encapsulated Environment

Reducing Thermoregulatory Strain Experienced by Warfighters when Wearing Fully Encapsulating Protective Clothing with Additional Investigations of Thermoregulatory Control.

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ABSTRACT

Operating in a hot environment when wearing clothing that is moisture vapour restrictive and thermally insulative, such as chemical and biological (CB) protective equipment, places a thermal burden on the wearer. The first two experiments addressed the general aim of this thesis, which was to quantify the thermoregulatory strain associated with wearing chemical, biological, radiological and nuclear (CBRN) individual protective equipment (IPE). CBRN IPE comprises of a suit (material of a low air permeability) and moisture vapour impermeable (MVIP) ancillary items such as a respirator, gloves and overboots, which increase insulation and impede evaporative cooling. The thermal burden associated with wearing military body armour (BA) was also quantified. Subsequent aims to investigate thermoregulatory control were explored in the third and fourth experiments. This thesis tested the general hypothesis that: improving the moisture vapour permeability (MVP) of CBRN ancillary items would alleviate thermoregulatory strain when worn in a hot, desert-like environment, and assessed whether a reduced thermoregulatory strain would be equal between the improved items.

The aim of the first study was to quantify the thermal burden imposed by each MVIP ancillary IPE, and that of the MVIP BA during exercise and recovery in a hot and dry environment. The thermal burden of each item was quantified by the measured reduction to thermoregulatory strain (internal and surface body temperature, heart rate, whole body sudomotor response and perceptual measures) when the item was not worn, thereby simulating the idealistic situation of a 100 % MVP material. To isolate only the thermal burden of the items, and not the metabolic cost associated with wearing the items, when an item was not worn a weight equivalent to the mass of the item was secured to the area from where the item had been removed. During the first experiment, at the sponsor's request, the thermal burden of items were assessed cumulatively such that items were progressively not worn and the thermal load on the wearer gradually lessened as fewer items were worn over the different conditions. It was found that not wearing any one of the MVIP ancillary items decreased thermoregulatory strain, perception of thermoregulatory strain or both. The BA, represented by a soft armour liner (BAL) with a mass of 170 g reflecting the shape and impermeability of BA but without the weight, alleviated the greatest thermoregulatory strain on participants when not worn. This was evident by a 16.1 % ($p < 0.001$) improvement to the rate of whole body sweat evaporation and an enhanced rate of cooling of rectal temperature (T_{re}) by 0.31 °C.hr^{-1} ($p < 0.05$) during the 20-minute recovery period at the end of the protocol compared to the adjacent condition when the BAL was worn.

Participants also felt less hot and less uncomfortable at some points during the protocol when the BAL was not worn. The least improvement to thermoregulatory strain occurred when the overboots were not worn as the only measure to be improved was a 35.2 minute (14.8 %, $p < 0.05$) increase to the predicted tolerance time (TT) to a T_{re} of 40 °C, or 28.5 minute (13.7 %, $p < 0.05$) improvement to a T_{re} of 39.5 °C. Improving the MVP of the gloves or respirator also improved whole body physiological and perceptual thermoregulatory measures to a greater degree than improving the MVP of the overboots, but to a lesser degree than the BAL.

The aim of the second study was to again quantify the thermal burden associated with each item but individually, not in a cumulative order, to obtain the true thermal burden of the item that was unaffected by reducing the overall thermal load placed on the body during later conditions, as in the first study. It was found that not wearing the gloves best alleviated thermoregulatory strain on participants, attenuating the rate of rise of T_{re} during continuous work by 0.37 $°C.hr^{-1}$ (20.3 %, $p < 0.001$) culminating in an extended TT during continuous work by 9.2 minutes (21.3 %) in a 60-minute period ($p < 0.05$) compared to when the gloves were worn during the fully encapsulated condition. Perceptually, participants also felt less uncomfortable at some time points when the hands were exposed. Again, not wearing the overboots minimally reduced thermoregulatory strain. Improving the MVP of the BAL or respirator also reduced whole body thermoregulatory strain to a greater degree than improving the MVP of the overboots, but to a lesser degree than the gloves. Compared to the second study, underestimations of the thermal burden of the last items not to be worn during the first study (gloves and overboots) occurred during exercise, most likely because these items had less of a thermal load over which to demonstrate an improvement in the first study.

The first two studies highlighted that whole body thermoregulatory strain could be reduced during exercise-induced hyperthermia when wearing CBRN IPE, when only small body surface areas, such as the hands or face, were exposed, and might have influenced whole body thermoregulatory responses such as sweat rate or skin blood flow (SkBF). Thus, the aim of the third study was to determine whether exposing either the hands or the head to a hot, desert-like environment would result in the greatest change to local sweat rate (LSR) and SkBF at the torso, forearm and thigh, as well as whole body thermal perception during exercise. To isolate the influence of temperature perturbations only at the treated sites (the head or hands) on thermoregulatory responses, measures were analysed at the same mean body temperature ($\overline{T}_b$) during each condition. Thus, the influence of skin temperature (T_{sk})

from the untreated tissues (*i.e*. not the head or hands) on the changes to LSR and SkBF was minimal between conditions, and any differences would then be attributable to the perturbed local T_{sk} at the treated sites. However, no significant differences in LSR or SkBF at the torso, forearm or thigh, or whole body perceptual measures when $\overline{T}_b$ was 37.5 °C during exercise, were identified during exposure of either the head or hands. The lack of significant findings was attributed to either thermal sensitivity being altered with the introduction of exercise or the methodological shortcomings of the study such as: the magnitude of the stimulus not being sufficient to elicit a measurable response; the equipment not being sensitive to detect small differences; or the day-to-day variations in the thermoregulatory response outweighing any measurable differences. During the third study it was noted that post-exercise, SkBF declined at all sites and LSR declined at all sites except the chest, even though $\overline{T}_b$ remained elevated and these areas covered.

Therefore, the aim of the fourth study was to determine the influence of non-thermal mechanisms on LSR and SkBF responses post-exercise, and whether any of these mechanisms could result in the regional variations seen in the third study. It was found that as there was a homogenous sweat pattern response at regional sites (chest, back, forearm and thigh), the mechanism governing the sudomotor response was most likely systemic and was influenced by oesophageal temperature (T_{oe}), exercise and / or posture. The regional LSR responses identified in the third study might have been due to an artifact of the confounding effects of clothing and / or mechanical pressure imposed on the sweat capsules. Further research was necessary, that standardized the duration of exercise pre-posture and clamped T_{oe} post-exercise, to investigate the finding that the greatest decrease to LSR was during standing and sitting with the magnitude of the response being less during lying (lateral, prone and supine).

In conclusion, efficient thermoregulation is compromised in the encapsulated environment but can be improved by reducing the thermal burden of any of the ancillary items but particularly the MVIP gloves. To the sponsor, this might pose an attractive avenue for future improvements as air permeable prototype gloves have already gone through the initial product development and human testing phase as annexed in this thesis.

Overall, the general null hypothesis was rejected and the experimental hypothesis was accepted that improving the MVP of CBRN ancillary items alleviated thermoregulatory strain when exercising in a hot, desert-like environment, and that the reduced thermoregulatory strain was not equal between items.

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~ Let us run with perseverance the race that is set before us ~ Hebrews 12:1

DECLARATION

Whilst registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award.

Christie Nicole Garson

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LIST OF ABBREVIATIONS

α – alpha

°C – degree Celsius

μm – micrometer

BA – body armour

BAL – body armour liner

$\dot{C}$ – rate of convection

CB – chemical and biological

CBRN – chemical, biological, radiological and nuclear

CBV – central blood volume

CC – combat clothing

CDH – cell dehydration

cm – centimeter

cm^2 – square centimeter

dH_2O – distilled water

DPM – disruptive pattern material

Dstl – Defence Science and Technology Laboratory

$\dot{E}$ – rate of evaporation

ECG – electrocardiogram

e.g. – *exempli gratia*; for example

EHI – exertional heat illness

E_{max} – maximum evaporation possible from the environment

E_{req} – amount of evaporation required to maintain heat balance

E_{res} – evaporative loss from respiration

et al. – *et alia*; and others

f_{cl} – clothing area factor

F_{pcl} – reduction factor for vapour transfer

g – grams

G – gloves

h_c – convective heat transfer coefficient

h_e – evaporative heat transfer coefficient

hr – hour

h_r – radiative heat transfer coefficient

HR_t – heart rate taken at any time during the protocol

HR_0 – initial heart rate

ΔHR – change in heart rate

HSI – heat stress index

h_{tot} – total heat transfer coefficient

i.e. – *id est*; it is

I_a – thermal insulation of the boundary air layer

I_{cl} – intrinsic clothing insulation

IHG – isometric handgrip

i_m – vapour permeability index

IPE – individual protective equipment

I_T – total clothing insulation

$\dot{K}$ – rate of conduction

K – Kelvin

kg – kilogram

kJ – kilojoule

km – kilometer

kPa – kilopascal

L – litre

L – Lewis number

LBPP – lower body positive pressure

LDU – laser Doppler units

LSR – local sweat rate

$\dot{m}$ – rate of body mass loss

$\dot{M}$ – metabolic rate

m^2 – square meter

ΔMAP – change in mean arterial pressure

mg – milligram

min – minute

mL – millilitre

mm – millimeter

mmHg – millimeter of mercury

MoD – Ministry of Defence

MODREC – Ministry of Defence Research Ethics Committee

MVIP – moisture vapour impermeable

MVP – moisture vapour permeable

NBC – nuclear, biological and chemical

nL – nanolitre

O – overboots

P_a – partial pressure of water vapour in the air

Pa – Pascal

p_{CO2} – density of carbon dioxide

PEI – post-exercise ischaemia

p_{O2} – density of oxygen

PSI – physiological strain index

P_{sk} – saturated water vapour pressure at the skin

PU – perfusion units

Q – cardiac output

rΔ – change in recovery data

$\dot{R}$ – rate of radiation

R – respirator

RQ – respiratory quotient

R_a – vapour resistance of the boundary air layer

R_{cl} – vapour resistance of the clothing

rh – relative humidity

RPE – rating of perceived exertion

R_T – clothing vapour resistance

s – second

$\dot{S}$ – rate of heat storage

SCCM – standard cubic centimeters per minute

SD – standard deviation

SEM – standard error of the mean

SFEC – Science Faculty Ethics Committee

SkBF – skin blood flow

ΔSR – change in sweat rate

SSNA – skin sympathetic nerve activity

SV – stroke volume

T_a – air temperature

$T_{ambient}$ – ambient temperature

T_{arm} – arm temperature

T_{au} – aural temperature

$\overline{T}_b$ – mean body temperature

$\Delta\overline{T}_b$ – change in mean body temperature

T_c – core temperature

$\overline{T}_{c}$ – mean core temperature

T_{calf} – calf temperature

T_{cheek} – cheek temperature

T_{chest} – chest temperature

T_{finger} – finger temperature

T_{gi} – gastrointestinal temperature

T_{oe} – oesophageal temperature

ΔT_{oe} – change in oesophageal temperature

T_{re} – rectal temperature

T_{ret} – rectal temperature taken at any time during the protocol

T_{re0} – initial rectal temperature

ΔT_{re} – change in rectal temperature

T_{sk} – skin temperature

$\overline{T}_{sk}$ – mean skin temperature

ΔT_{sk} – change in skin temperature

T_{thigh} – thigh temperature

TT – tolerance time

USG – urine-specific gravity

VAS – visual analogue scales

$\dot{V}O_2$ – rate of oxygen uptake

$\dot{V}O_{2max}$ – maximal rate of oxygen uptake

W – external work

W – Watts

WMA – World Medical Association

DISSEMINATION OF CONTENT

Garson, C. N., Tipton, M. J., & House, J. R. (2016). Thermoregulatory strain in a prototype, lightweight CBRN ensemble in comparison to a common CBRN ensemble. *Defence Science and Technology Laboratory, Scientific Report*

Garson, C., Tipton, M. J., & House, J. R. (2015). Making chemical and biological protective gloves vapour permeable reduces thermoregulatory strain better than making armour, respirator or overboots permeable. *Extreme Physiology and Medicine, 4(Suppl 1),* A65.

> This abstract was also presented as an oral presentation at the 15th International Conference on Environmental Ergonomics, Portsmouth, United Kingdom.

Garson, C., Dennis, M., Tipton, M. J., & House, J. R. (2015). Individual and cumulative benefits of making body armour and chemical and biological protective gloves, respirator and overboots from moisture-vapour permeable materials. *Extreme Physiology and Medicine, 4(Suppl 1),* A96.

> This abstract was also presented as a poster presentation at the 15th International Conference on Environmental Ergonomics, Portsmouth, United Kingdom.

Garson, C. N., Tipton, M. J., & House, J. R. (2015). An investigation as to whether making the respirator, body armour, gloves or overboots completely moisture-vapour permeable results in reductions to physiological and perceptual thermoregulatory strain. *Defence Science and Technology Laboratory, Scientific Report,* ISBN: 978 1 86137 657 2.

Garson, C., Tipton, M. J., & House J. R. (2014). A partitioned approach to reducing thermoregulatory strain whilst wearing fully encapsulating chemical protective equipment and exercising in desert-like conditions. *Conference Proceedings of the International Congress on Soldiers Physical Performance,* Boston, United States of America, p 48. (Poster Presentation).

CHAPTER I: INTRODUCTION AND STATEMENT OF THE PROBLEM

The World Meteorological Organization named the 2000s the "Decade of Extremes" with the year 2014 being recorded globally as the hottest year (Coumou & Rahmstorf, 2012; Hanna & Tait, 2015). Heat-related deaths initially occur with heat sensitive populations such as the elderly, those suffering from chronic diseases and psychiatric disorders as well as those that are house-bound and avoid contact with others (Stafoggia *et al*., 2006; Kenny *et al*., 2010). Additionally, geographic locations unaccustomed to extreme heat such as Europe and Russia have recently seen large numbers of heat-related deaths (Barriopedro *et al*., 2011; Hanna & Tait, 2015). Predictions of the trajectory of climatic extremes show that there is likely to be an increase in the frequency and severity of extreme weather patterns, directly impacting vulnerable populations (United Nations, 2005; Kenny *et al*., 2010). It is not only the vulnerable that are affected but also fit and healthy personnel working in occupations such as the Fire and Rescue Services, Chemical and Energy Industries and the military who are required to wear clothing that protects against hazardous environments. The clothing, whilst alleviating one form of risk, can introduce another in the form of heat illness due to the impairment in thermoregulatory capacity caused by the protective clothing.

History is littered with examples of heat illness and deaths from heat stroke within the military. During the First World War 426 incidences of death from heat stroke were recorded in one month, with survivors reporting their comrades suffering from delirium, hot and dry skin and convulsions (Leithead & Lind, 1964). Current statistics of UK military personnel suffering from exertional heat illness (EHI) equated to approximately 4.4 cases per month in a sampling period taken over 88 months (Stacey *et al*., 2015). Approximately one third of the cases of EHI occurred in hot environments such as Iraq, Cyprus and Brunei with the majority of cases occurring in the UK mostly during the summer months (Stacey *et al*., 2015). Warfighters exposed to, or in threat of being exposed to CBRN agents are at an elevated risk of suffering EHI due to wearing IPE. In the military, CBRN IPE comprises of a hooded jacket and trouser combination that can be worn over a t-shirt and undershorts or over combat clothing (CC) if donning the equipment in an emergency. Additional ancillary protective equipment such as a full-face respirator, butyl gloves with cotton glove liners and overboots that are worn over combat boots and socks must also be donned to ensure protection from harmful substances. Thus, CBRN IPE is fully encapsulating to provide adequate protection against contaminating agents and imposes a thermal burden even when worn in cool climates depending on the work load the warfighter is subjected to and the physical characteristics of the clothing, such as thermal resistance and water vapour permeability. The thermal burden is exacerbated during exercise in the heat, with warfighters often working in uncompensable heat stress conditions in which internal body temperature continues to rise (McLellan *et al*., 1992; Amos & Hansen, 1997). McLellan *et al*. (2013b) summarized that TT when wearing encapsulating protective clothing is largely dependent upon three factors; i) starting core temperature (T_c), ii) T_c at exhaustion and iii) the rate of rise in T_c throughout the duration of the exposure. These factors are also affected by other variables as illustrated in Figure 1 below.

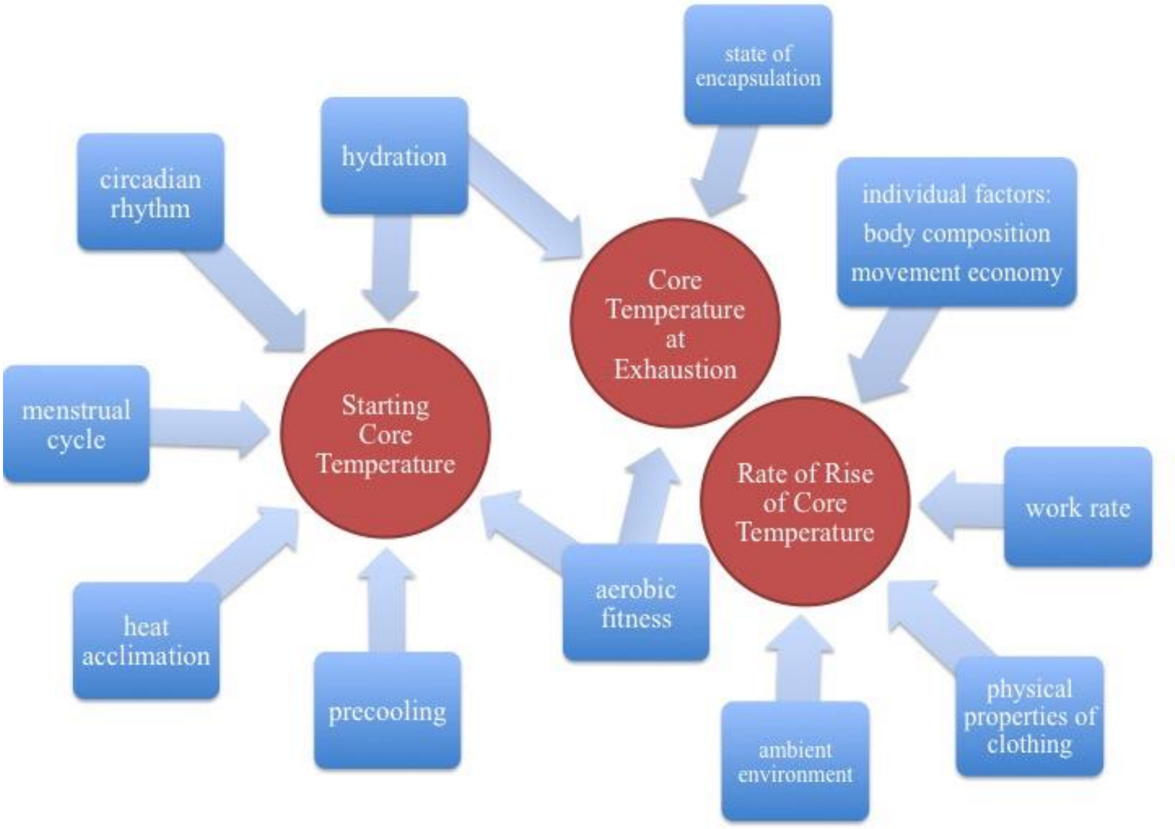

Figure 1: Factors affecting tolerance time when wearing individual protective equipment (McLellan *et al*., 2013b).

By 1993, 130 of 190 member countries of the United Nations signed the U.N. Chemical Weapons Convention, yet in spite of this Hewish (1997) and Pearson (1994) asserted that approximately 30 countries have CB development programs containing chemical research initiatives and stockpiles of chemical arsenals. The wound to kill ratio of CBRN weapons is approximately 30:1 compared to 3:1 for conventional weapon warfare, thus resulting in a greater casualty rate, although less fatalities, as well as being relatively inexpensive (Stokes & Banderet, 1997).

Therefore, with advancements in CBRN warfare, global weather patterns and current combat theatres comprising of primarily hot, desert-like environments, reducing the thermoregulatory strain associated with wearing CBRN IPE is a high priority for the military.

Following from the above-mentioned rationale, the aims for this thesis were three-fold. Firstly, to quantify the physiological and perceptual thermoregulatory strain imposed by each CBRN ancillary item (respirator, gloves and overboots) and BA during exercise and recovery in a hot, desert-like environment. Secondly, to quantify the effect of exposing the head (covered by the respirator and hood during a CBRN threat or attack) or the hands (covered by gloves during a CBRN threat or attack) to a hot, desert-like environment on thermoregulatory strain, particularly thermoregulatory responses of LSR and SkBF, and whole body perceptual responses during exercise. Finally, to investigate the impact of manipulating posture during post-exercise recovery on whole body thermoregulatory responses (LSR and SkBF) as measured at the torso, forearm and thigh. These aims were explored through a combination of experimental procedures that are described in four chapters.

In Chapters 4 and 5 experiments are described that investigated the thermal burden of protective equipment using two different methodologies to highlight which protective item (respirator, gloves, overboots or BA) imposed the greatest and the least physiological and perceptual thermoregulatory strain on the wearer. The methodology of the first study (Chapter 4) followed the experimental design of the CBRN ensemble tests conducted on a thermal manikin (Havenith *et al*., 2013) that were largely directed by the Defence Science and Technology Laboratory (Dstl). The experiments described in the second study (Chapter 5) again aimed to determine the thermal burden of CBRN ancillary items by using an adapted experimental design that isolated the thermal contribution from each individual item, rather than quantifying the cumulative thermal burden of ancillary items.

The results from the experiments undertaken in Chapters 4 and 5 highlighted that exposing small surface areas of the body, such as the face or hands, could elicit seemingly disproportional gains in the reduction of both physiological and perceptual thermoregulatory strain. Therefore, an investigation was undertaken (details contained in Chapter 6) that compared the contribution of exposing the head *vs*. the hands on whole body perceptual responses and thermoregulatory responses of LSR and SkBF at unexposed sites. In Chapter 7 the thermoregulatory responses (LSR and SkBF) obtained post-exercise during the experiments in Chapter 6 were further explored. LSR and SkBF seemed to respond to a change in exercise and posture and appeared contradictory to the thermal state of the whole body, such that for an elevated or plateaued T_{re}, cooling mechanisms of LSR and SkBF declined. A thorough investigation was undertaken, critically assessing specific methodologies employed that prompted the thermoregulatory responses.

Finally, the results are discussed, as are the assumptions, limitations and delimitations of the studies and recommendations for further work are presented.

CHAPTER II: REVIEW OF LITERATURE

The literature presented in this review was primarily searched using Google Scholar and PubMed. Articles were obtained from electronic databases or the British Library's inter-library loan services. Initially, abstracts were evaluated to assess whether the content was appropriate and relevant to the topic, after which the full article that had been peer-reviewed and cited was obtained whilst the quality of the journal was noted. The content, methodology, data and conclusions were critically examined.

2.1 Thermoregulation in a Hot Environment

Human thermoregulation aims to maintain a stable T_c of approximately 37.0 °C at rest by balancing the amount of heat produced with the amount of heat lost. Kerslake (1972) proposed the following heat balance equation:

$$\dot{M} - W = \dot{E} + \dot{R} + \dot{C} + \dot{K} + \dot{S}$$

Where: $\dot{M}$ is the metabolic rate ($W.m^{-2}$)

W is the external work ($W.m^{-2}$)

$\dot{E}$ is the rate of evaporation ($W.m^{-2}$)

$\dot{R}$ is the rate of radiation ($W.m^{-2}$)

$\dot{C}$ is the rate of convection ($W.m^{-2}$)

$\dot{K}$ is the rate of conduction ($W.m^{-2}$)

$\dot{S}$ is the rate of heat storage ($W.m^{-2}$)

There are a number of factors affecting heat balance such as the ambient environment, clothing, the intensity of work and individual factors such as body composition and the degree of acclimation (McLellan *et al*., 2013b; Figure 1). For heat balance to be achieved the following must hold true:

$$\dot{M} - W - \dot{E} - \dot{R} - \dot{C} - \dot{K} = 0 \qquad [W.m^{-2}]$$

The body's normal response to exercise is a rise in T_c due to increased metabolic heat production as a consequence of muscular activity. To maintain heat balance, heat loss occurs by radiation, convection, conduction, and most prominently by the production of sweat resulting in evaporative cooling where permissible. Evaporative cooling is the major mechanism engaged to defend against hyperthermia (Nielsen & Nielsen, 1965; Åstrand & Rodahl, 1977). In a hot environment, where the ambient temperature is warmer than that of the skin, radiation, convection and conduction may result in heat gain, thereby negating the heat loss mechanisms associated with these parameters. Lind (1963) suggested that during exercise at a constant work rate, thermal equilibrium could be achieved without excessive strain on the thermoregulatory system and the condition was "easily tolerable" or "compensable" but that in warmer environments, when body temperature rises, a "neutral zone" of climates whereby thermal equilibrium could be achieved was established at different work rates. Beyond the neutral zone of climates, achieving thermal equilibrium was forced higher than the level of the neutral zone (Lind, 1963; Figure 2).

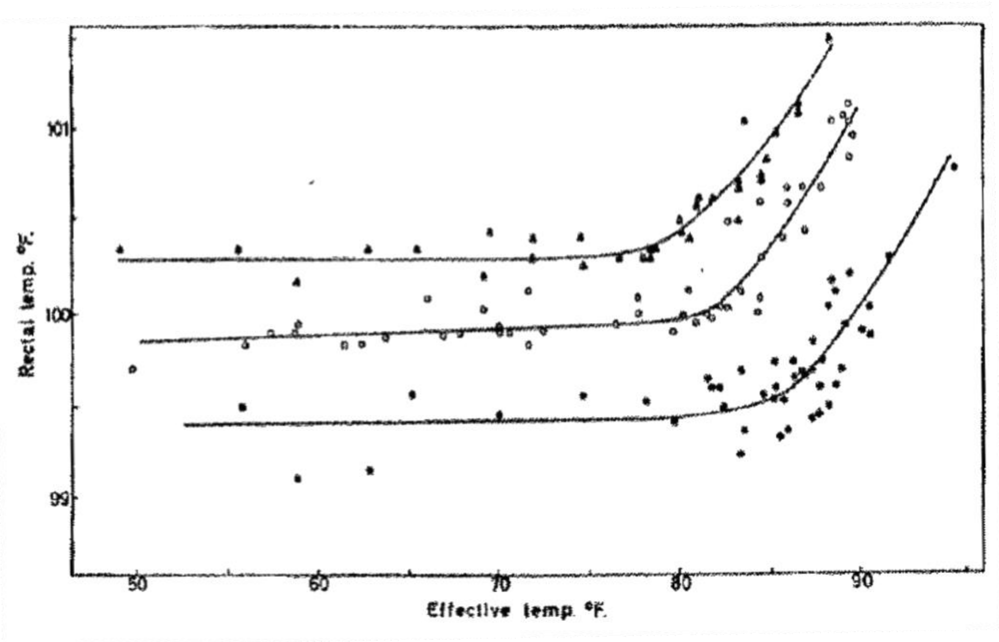

Figure 2: Rectal temperature at three levels of thermal equilibrium in different climates during continuous work at three different intensities: 100 kcal.m^{-2}.hr^{-1} (filled circles), 167 kcal.m^{-2}.hr^{-1} (empty circles) and 233 kcal.m^{-2}.hr^{-1} (filled triangles) (Lind, 1963).

"Uncompensable" heat stress refers to the point where thermal equilibrium is unachievable, as the mechanisms employed for cooling the body (*e.g.* sweat evaporation) are inadequate to stop the rate of rise of T_c as the requirements to evaporate sweat exceed the maximum evaporative capacity of the environment (Lind, 1963; Montain *et al*., 1994). The body thermoregulates in response to afferent information regarding T_{sk} and T_c that is relayed to the preoptic/anterior hypothalamus which co-ordinates the appropriate efferent response. This can occur through modulation of behaviour (posture, activity), cardiovascular (increased heart rate, stroke volume [SV] and cutaneous vasodilatation with splanchnic vasoconstriction to redirect blood to the periphery for cooling [Rowell *et al*., 1969; Kenney, 2008]) and sudomotor (increased rate of sweating to dissipate heat [Rowell *et al*., 1969; Boulant, 1998; Boulant, 2000]) responses. The magnitude of physiological thermoregulatory responses depends upon thermal feedback from deep tissues as well as superficial tissues such as the skin (Grant, 1951; Parsons, 1993).

2.1.1 The Cardiac Response to Thermal Loading

During passive heat stress, cardiac output (Q) doubles to maintain arterial pressure whilst SkBF increases 40 times from 200 $mL.min^{-1}$ up to 8000 $mL.min^{-1}$ accompanied by an elevated heart rate and a redistribution of blood flow from the splanchnic regions to the periphery (Rowell *et al*., 1969; Kenney, 2008). During exercise in the heat, two competing cardiovascular demands are placed upon the body: firstly, to maintain energy metabolism, the exercising muscles require more arterial (oxygenated) blood and secondly, redistribution of blood flow to the periphery for cooling (Rowell *et al*., 1970). To accommodate these demands, Q is increased by way of an elevated heart rate and SV. This system can remain compensatory until a T_{re} of approximately 39.5 °C, after which the body enters a preliminary crisis stage before whole body failure where tachycardia results in a lowered ventricular filling, decreasing Q and culminating in cerebral ischaemia (Hubbard & Armstrong, 1988). However, the value of 39.5 °C T_{re} is not fixed and T_{re} of up to 40.6 °C have been found in elite athletes without heat illness (Richards *et al*., 1979).

Rowell *et al*. (1966) showed that exercise of a moderate to severe intensity in the heat (43.3 °C), compared to exercise in a normothermic environment (25.6 °C), resulted in elevated heart rates, significant decreases in Q (which was more pronounced as exercise intensity increased), decreased central blood volume (CBV) and decreased SV among participants. During exercise that did not exceed 15 minutes, the authors attributed the decreased SV to a lowered CBV and cardiac filling pressure from the redistribution of SkBF from the core to the periphery for cooling. Rowell *et al*. (1966) therefore concluded that humans have a limited capacity for working in the heat primarily due to the inadequacy of meeting Q requirements for both exercise and heat dissipation.

To test the hypothesis that a reduced SV during exercise in the heat was directly due to an elevated SkBF, Gonzalez-Alonso *et al*. (2000) conducted an experiment with euhydrated male trained cyclists. The participants cycled at 72 % of their maximal rate of oxygen uptake ($\dot{V}O_{2max}$) either in the heat (35.0 °C) or cold (8.0 °C) for 30 minutes. The authors found that whilst T_{oe} was similar between the hot and cold environments, SkBF was greatly increased when exercising in the hot environment as expected, yet SV was not different between the conditions. Thus, the authors concluded that in the exercising and euhydrated individual a reduced SV was not solely dependent on an increased SkBF but rather an interaction of multiple factors such as: T_c; Q in combination with a lower visceral blood flow; blood volume; and elevated sympathetic activity such as elevated noradrenaline levels. In support of the conclusion by Gonzalez-Alonso *et al*. (2000), Lee *et al*. (2015) conducted experiments with non-trained individuals cycling for 20 minutes at 69 % $\dot{V}O_{2max}$. It was found that heart rate was higher but SV lower when both the skin and core were warm compared to when the skin was cool but the core was warm. Furthermore, it was found that heart rate was higher but SV unchanged when the skin was warm and the core was cool compared to when both the skin and core were cool. Thus, the authors concluded that SV would only be reduced during exercise when T_c was elevated above 38.0 °C with an elevated T_{sk} and heart rate.

2.2 Thermal Burden of Protective Clothing

Clothing can influence heat balance through reducing heat loss from the skin such as during exercise, when wearing clothing of a high vapour resistance, heat loss is impeded through restricting the evaporation of sweat (Amos & Hansen, 1997; Havenith *et al*., 1999). Some textiles insulate an area by trapping air in the layer between the skin and the material, and this layer is known as the microclimate. During movement, if the air layer is large enough, ventilation from the pumping actions of the clothing reduces the insulation (McCullough, 1993) and can result in improved performances under conditions of uncompensable heat stress (Gonzalez *et al*., 2006). The number of clothing layers can also affect heat balance as each layer has its own microclimate within the clothing ensemble reducing the rate of heat transfer away from the skin to the environment (McLellan *et al*., 1992). Likewise, evaporation that takes place further from the skin is less efficient in cooling the surface of the skin compared to evaporation from the skin directly (Havenith *et al*., 2013b). Motion and postural shifts can result in a bellows effect that pumps air throughout clothing layers and the microclimate (Teitlebaum & Goldman, 1972; Havenith, 1999). Wearing clothing in a cool environment can result in a heat pipe effect whereby sweat evaporates from the skin and recondenses at the inner surface of the outer garment, releasing heat through the garment but without a loss of water (Havenith *et al*., 2008). Finally, radiation from the ambient environment of a short wavelength can be absorbed by textiles, with darker materials absorbing more heat radiation than lighter materials, and can also penetrate multiple clothing layers, depositing heat and increasing T_{sk} depending on ventilation and sweating (Lotens, 1995).

2.2.1 Defining Clothing Parameters

Clothing can restrict heat and moisture transport between the skin and the environment by providing a barrier that serves to protect against extreme heat and cold but also impedes heat loss during exercise. The barrier encompasses the clothing materials, any air layers enclosed by the materials as well as the still air layer on the outer surface of the clothing (Havenith, 1999). The intrinsic clothing insulation (I_{cl}) incorporates the resistance to heat transfer between the skin and the clothing itself, independent of the external environment. Each clothing layer has a still air layer on its boundary surface. The thermal insulation of the boundary air layer (I_a) that is influenced by the external environmental can also be calculated. This calculation, when considering clothing, encompasses the following: the clothing area factor (f_{cl}), which is the ratio of the clothing surface area to the surface area of the body; the radiative heat transfer coefficient (h_r); as well as the convective heat transfer coefficient (h_c). A heat transfer coefficient simply describes the heat flux (the rate of heat energy transfer through a surface) and the thermal gradient (driving force).

The equation for total insulation (I_t) is as follows (Parsons, 1993):

$$I_T = I_{cl} + (I_a / f_{cl}) \qquad [m^2.°C.W^{-1}]$$

Where: I_T is the total clothing insulation ($m^2.°C.W^{-1}$)

I_{cl} is the intrinsic clothing insulation ($m^2.°C.W^{-1}$)

I_a is the thermal insulation of the boundary air layer ($m^2.°C.W^{-1}$) and when clothed is calculated as $I_a = 1 / (f_{cl}h)$ where $h = h_r + h_c$

f_{cl} is the clothing area factor

Therefore, the driving force of the thermal gradient divided by the total clothing insulation determines dry heat loss. The equation for dry heat loss is presented below (Havenith *et al*., 2013):

$$\text{Dry Heat Loss} = (T_{sk} - T_a) / I_T \qquad [W.m^{-2}]$$

Where: T_{sk} is skin temperature (°C)

T_a is air temperature (°C)

I_T is clothing insulation including air layers ($m^2.°C.W^{-1}$)

Less data are available for calculation of evaporative heat resistance of clothing compared to dry heat resistance calculations. There are two common methods for determining the evaporative resistance of clothing systems: using a reduction factor for vapour transfer (F_{pcl}) when wearing clothing compared to a nude state; and using a vapour permeability index (i_m).

The equation for calculating the vapour resistance of the clothing (R_T) using the reduction factor for vapour transport is as follows (ISO 7933):

$$R_T = 1 / (h_e \times F_{pcl}) \qquad [m^2.kPa^{-1}.W^{-1}]$$

Where: R_T is the clothing vapour resistance ($m^2.kPa.W^{-1}$)
h_e is the evaporative heat transfer coefficient ($m^2.kPa.W^{-1}$)
F_{pcl} is the reduction factor for vapour transfer

Calculation of h_e includes h_c and the Lewis number (L) given by 16.7 °C.kPa^{-1}. Whilst F_{pcl} is a reduction factor for evaporative heat loss when wearing clothing compared to a nude state and is calculated as follows (Havenith *et al.*, 1999):

$$F_{pcl} = R_a / (R_a + R_{cl})$$

Where: R_a is the vapour resistance of the boundary air layer ($m^2.kPa^{-1}.W^{-1}$)
R_{cl} is the vapour resistance of the clothing ($m^2.kPa^{-1}.W^{-1}$)

The equation for calculating the R_T using the vapour permeability index (i_m) is as follows (ISO, 9920):

$$R_T = I_T / (i_m \times L) \qquad [m^2.kPa^{-1}.W^{-1}]$$

Where: R_T is the vapour resistance of the clothing ($m^2.kPa^{-1}.W^{-1}$)
I_T is the clothing insulation including air layers ($m^2.°C.W^{-1}$)
i_m is the vapour permeability index
L is the Lewis number (16.7 °C.kPa^{-1})

Therefore, the driving force of the pressure gradient divided by the total clothing vapour resistance determines evaporative heat loss. The equation for evaporative heat loss is presented below (Havenith *et al*., 2013):

$$\text{Evaporative Heat Loss} = (P_{sk} - P_a) / R_T \qquad [\text{W.m}^{-2}]$$

Where: P_{sk} is the saturated water vapour pressure at the skin (kPa)
P_a is the partial pressure of water vapour in the air (kPa)
R_T is the clothing vapour resistance (m^2.kPa.W^{-1})

During times of CBRN threat or attack, the warfighter is required to don CBRN IPE. Wearing this protective equipment results in an increased metabolic heat production due to carrying the additional weight (approximately 6 kg), however over 50 % of the additional heat production can be attributed to contributing factors other than the weight of the clothing, such as friction and restriction of movement (Dorman & Havenith, 2009). The CBRN protective ensemble is fully encapsulating and typically comprises of a suit with a hooded jacket and trouser combination with ancillary items such as a respirator, gloves and overboots. There are two types of clothing materials that affect water vapour transport:

i. MVIP: offering a high degree of protection from contaminating agents whilst allowing no water vapour to pass through the material thereby causing the clothing microclimate to saturate when the wearer is sweating, increasing thermoregulatory strain by limiting evaporation. The CBRN ancillary items (respirator, gloves and overboots) are MVIP. MVIP items are also insulative and thus contribute further to thermoregulatory strain by impeding heat loss across a temperature gradient, although can protect against local heat gain (for a while) when the gradient is for heat gain.
ii. MVP: there are varying degrees of MVP and in this thesis the definition of a 100 % MVP material is a theoretical material offering no evaporative resistance thereby allowing sweat to freely evaporate, although currently no CBRN protective equipment or fabric is 100 % MVP.

Clothing, and particularly CBRN protective clothing, provides a barrier for water vapour and heat exchange from the skin to the environment, attenuating the capacity for heat loss (Havenith, 1999). Moreover exercising, particularly in a hot environment, and wearing protective clothing places an even greater thermoregulatory strain upon the individual due to the insulative and moisture-vapour restrictive properties of the material impeding metabolic heat dissipation through evaporation of sweat. During prolonged exercise in the heat when wearing CBRN clothing the increased sweat production saturates the microclimate (Amos & Hansen, 1997). This imposes a thermoregulatory strain on the individual by restricting evaporative cooling as when the partial pressure of water vapour in the air (P_a) of the clothing's microclimate equals or exceeds the saturated water vapour pressure at the skin (P_{sk}), no net evaporation of sweat occurs (Amos & Hansen, 1997).

Gagge *et al*. (1941) introduced the Clo unit. One Clo represents the thermal insulation of a business suit when a resting individual is kept comfortable at 21 °C and possess a value of 0.155 $m^2.°C.W^{-1}$. Thus, the indices affecting an estimation of insulation include surface area of the individual, the temperature gradient between the material and the skin as well as the conductivity of the material. The estimated thermal resistance for the entire (Canadian Forces) CBRN ensemble is 1.53 Clo (McLellan, 2008). Due to the vapour-restrictive protective materials, if exercise continues at the point of microclimate saturation, T_c will continue to rise and the individual will operate in an uncompensable heat stressed state if the protective garment is not made from extremely air-permeable and MVP materials (McLellan *et al*., 1992; Amos & Hansen, 1997). This high evaporative burden imposed by the CBRN IPE places the individual at risk of developing heat illness (Nunneley, 1989; McLellan, 1993). A warfighter suffering thermoregulatory strain could jeopardize the success of military operations with critical elevations in T_c resulting in hospitalization and even death (Carter *et al*., 2005). Thus, modifications to the current CBRN IPE, as well as other protective ensembles, are desirable to enhance evaporative cooling in warfighters and those working in high-risk occupations such as the Fire and Rescue Services and Chemical and Energy Industries whilst maintaining adequate protection.

2.2.2 Sweat Secretion in a Hot and Humid Environment

Current combat theatres include the Middle East, with hot and dry (desert-like) ambient conditions, where daytime air temperatures average 40.5 °C with a relative humidity (rh) of 20 % (Def Stan 00-35, 1999[1]). Peak temperatures can reach 49.0 °C in the afternoon with humidity as low as 3 %. The following equation is for the heat stress index (HSI), which is often used to assess thermal strain when wearing protective equipment (Gonzalez, 1988; McLellan *et al*., 2013b):

[1] Def Stan 00-35 is a MoD Defence Standard produced by the Meteorological Office and provides climatic information worldwide (2000).

$$HSI = E_{req} / E_{max}$$

Where: E_{req} is the amount of evaporation required to maintain heat balance (W)

E_{max} is the maximum evaporation possible from the environment (W)

In a hot desert environment, the low level of humidity favors water vapour exchange with the environment (high E_{max}) however, in a humid environment the E_{max} is low and therefore not all the sweat produced is evaporated but rather drips off the skin and, from a thermoregulatory perspective, is wasted as no cooling takes place (Nielsen, 2011). This reduces the efficiency of sweating, resulting in an accumulation of body heat storage and placing the individual in an uncompensable heat stress state. The predicted HSI for a warfighter working at a moderate intensity (metabolic rate of 500 W) in a chemically hazardous (therefore wearing fully encapsulating clothing) hot (40 °C) and dry (15 % rh) environment is 2.8. Bearing in mind that a HSI above 1.0 represents a positive rate of heat storage placing the worker in a state of uncompensable heat stress (McLellan *et al*., 2013b). These predictions assumed a constant T_{sk} of 37.0 °C. Interestingly, a state of uncompensable heat stress would be reached even during very light (metabolic rate of 170 W) exercise at the same hot and dry environmental conditions (McLellan *et al*., 2013b). Whereas a state of compensable heat stress when wearing CBRN IPE could only theoretically be achieved during very light exercise (170 W, or less) in a 30 °C, or cooler, and 50 % rh, or drier, environment whereby the predicted HSI = 0.8. Furthermore, Rissanen (1998) calculated that warfighters are at risk of heat strain when wearing CBRN IPE with an estimated thermal insulation of 2.0 Clo, even in temperatures as low as -20 °C after one hour of heavy work (metabolic rate of 510 W to 680 W).

The ambient conditions actually experienced by the warfighter when wearing the CBRN ensemble are soon that of a hot and humid environment due to microclimate saturation within the clothing even if working in a hot or cold, dry environment. Ladell (1945) discovered that in a hot environment (above 31 °C) maximal sweat secretion rates of approximately 3.0 $L.hr^{-1}$ could be reached however; this large rate of sweat output could not be maintained due to “sweat gland fatigue”. Randell and Peiss (1957) challenged the notion of sweat gland fatigue and identified that in a humid environment, the excessive amount of sweat covering the skin, due to limited evaporation, caused the epidermal cells to swell, obstructing the sweat ducts and resulting in a gradual decline of sweat production, rather than “fatigue” of the glands. This “hidromeiosis”, was more prevalent in hot and humid environments (Brown & Sargent, 1965).

2.2.3 Methods of Reducing the Thermal Burden of Protective Equipment

Between September 2007 and December 2014 389 UK military personnel suffered EHI equating to approximately 4.4 cases per month diagnosed by UK military physicians (Stacey *et al*., 2015). Surprisingly, it was noted that wearing occlusive (protective) clothing actually lessened the susceptibility to EHI, possibly due to structured implementation of strict work / rest schedules due to a heightened awareness of the risks associated with thermal uncompensability during load carriage and wearing impermeable or multi-layered protective clothing (Stacey *et al*., 2015). Nevertheless, there remains a need to reduce thermoregulatory strain associated with fully encapsulating protective clothing to ensure soldier wellbeing and overall success of military missions, particularly those that make contact with chemical agents. This is of importance as during actual operations in a hostile environment it is less likely that work / rest schedules would be implemented or clothing worn in a relaxed posture, for example with the hood down and respirator not worn.

Laboratory-based research into the reduction of thermoregulatory strain has lead to significant advancements in methods of reducing thermoregulatory strain when wearing CBRN protective equipment. Examples of which include: eliminating the need to wear CC underneath the protective overgarment thereby reducing the evaporative and insulative burden associated with multi-layered clothing (Farnworth & Crow, 1983; Nunneley, 1989; McLellan *et al*., 1992); improving the evaporative efficiency of the protective suit (McLellan *et al*., 1992); hand and forearm cooling (House *et al*., 1997); as well as the incorporation of microclimate liquid and air cooling (Bomalaski *et al*., 1995; Cadarette *et al*., 2006); and air vents (McLellan *et al*., 2013a). Air vents are closed when exposure to hazardous agents is imminent or the agents have been detected and remain open when no threat is perceived allowing for greater air ventilation throughout the microclimate supporting evaporative and convective heat transfer (McLellan *et al*., 2013a). While opening of the air vents attenuated the rate of rise of T_{re} by 0.5 °C.hr^{-1} and increased TT by approximately 13 minutes (39.4 %) during exercise in the heat, the benefits of improved air ventilation with the vents open are unable to be achieved during, or indeed after, an attack when the vents are closed. Research has also elicited recommendations for altering states of dress reflecting the level of threat detected (McLellan, 1993) as well as structured work / rest regimes that aim to minimize thermoregulatory strain incidents (McLellan *et al*., 1993).

Air cooling systems have been shown to lower thermoregulatory strain by 50 % in helicopter pilots wearing survival suits when ambient air was pumped into the suit using a battery-powered blower (Reffeltrath, 2006). However, in a CBRN contaminated environment, air ventilation through the microclimate using external air is impossible without extensive filtering that is difficult to achieve in the hostile environment. Therefore, although the methods mentioned above have, in the laboratory, reduced thermoregulatory strain, the practicalities of implementing the systems are problematic. For example, cooling systems often require a power supply comprising of large and heavy batteries and pumps or large quantities of water sometimes in the form of heavy ice packs to be readily available which, when the additional weight and subsequent increases in metabolic heat production are accounted for, nullify some, if not all, of the cooling benefits (McLellan *et al*., 2013b).

2.3 Regional Variations in Thermoregulation

Local sweat rate is affected by T_{sk} (Nadel *et al.*, 1971a) and upon entering a hot environment, T_{sk} of exposed and covered skin increases. Initially this substantial elevation in T_{sk} slows the rate of heat gain as T_c is defended from rising through T_{sk} buffering against heat gain from the environment. As T_{sk} rises, the saturated water vapour pressure increases whilst the ambient water vapour pressure remains unchanged, thereby increasing the gradient that drives evaporation (Taylor *et al*., 2014a). Nakamura *et al*. (2008) found that the change in T_{sk} (ΔT_{sk}) during local application of a cold or warm stimulus varied between body sites such that the ΔT_{sk} was greatest at the thigh compared to the abdomen, chest and face. The authors proposed that regional variations in SkBF accounted for the higher ΔT_{sk} at the thigh compared to the other areas measured.

Smith and Havenith (2011) reported that for male athletes exercising at 55 % of $\dot{V}O_{2max}$ in warm conditions (25 °C, 50 % rh and 2 $m.s^{-1}$ air velocity), the total sweat rate (per square meter) differed at each body region. For example, sweat rate at the forehead reached 697 $g.m^{-2}.hr^{-1}$, 86 $g.m^{-2}.hr^{-1}$ at the palm, 202 $g.m^{-2}.hr^{-1}$ at the dorsal foot and 677 $g.m^{-2}.hr^{-1}$ at the lower back. Studies often report high regional sweat rates occurring centrally such as the lower back, with lower regional sweat rates occurring at peripheral sites such as the arm and thigh (Smith & Havenith, 2011; Smith *et al*., 2013). However, when these values are corrected for the measured surface area, sweat production at the face (5.29 $g.hr^{-1}$) for example is approximately 2.6 times less than sweat production at the hands (13.78 $g.hr^{-1}$). It is pertinent to mention however that whilst sweat was collected from the majority of the surface area of the hands (totaling 1340 cm^2, by using gloves), sweat was only collected from parts of the face such as the forehead, parts of the cheeks and the chin (totaling 207 cm^2, by using absorbent pads). To our knowledge there is no literature directly measuring the surface area of the face only, but it is estimated to be approximately 490 cm^2 (manikin Newton, Thermetrics, USA). Thus, the absorbent pads only collected sweat from approximately 42 % of the face and therefore the sweat production at the face, when corrected for total surface area, would be greater than 5.29 $g.hr^{-1}$ (perhaps 12.6 $g.hr^{-1}$) and would therefore be closer to the value obtained for the hands. Surface area is important to consider when exposing areas in a hot and dry environment as the primary mechanism for cooling in such environments is through evaporation of sweat and therefore the greater amount of surface area exposed, the greater amount of sweat that has been produced at the site can evaporate. The primary body areas of interest in the study are those covered largely by MVIP CBRN ancillary items (Table I).

Table I: Estimated surface areas of body areas covered by CBRN protective items.

CBRN Ancillary Item	**Body Area**	**Surface Area (% of total body surface area)**	**Reference**
Respirator	Face	2.7	Manikin Newton (Thermetrics, USA)
Respirator and Hood	Head	7.2	Yu *et al*. (2010)
Gloves	Hands	4.6	Yu *et al*. (2008)
Overboots	Feet	8.1	Yu and Tu (2009)
Body Armour	Torso	39.5	Weiner (1945)

Although sweat gland recruitment occurs simultaneously during exercise in the heat (Taylor *et al*., 2009), the approximately 2.03 million sweat glands that the human body possesses are not homogenously distributed (Szabo, 1962; Knip, 1969; Taylor & Machado-Moriera, 2013) with the hands and feet possessing high densities of sweat glands compared to the head and torso for example (Taylor & Machado-Moreira, 2013; Table II).

Table II: The maximum, theoretical evaporative cooling during light to moderate exercise in the heat based upon surface area, average sweat gland densities and estimated sweat gland outputs of certain body areas (Taylor & Machado-Moreira, 2013).

Body area	Sweat gland density (glands.cm^{-2})	Surface area (% of total body)	Relative contribution from evaporative cooling whilst thermally loaded with maximum evaporation permitted (%)
Head	186	7.4	13.8
Hands	684	4.6	6.0
Feet	616	6.5	3.6
Torso	383	28.6	32.7
Arms (forearm and upper arm)	195	14.2	11.6
Legs (lower legs, thighs and buttocks)	163	38.6	32.0

Table II shows the theoretical relative contribution from evaporative cooling from local sites whilst being thermally loaded during exercise when maximum evaporation is permitted. The values were calculated using the surface areas of each region from the standard reference adult with regional sweat rate data assuming 2.43 kJ.mL^{-1} heat loss with whole body sweat rates of 1.0 L.hr^{-1} (Taylor & Machado-Moreira, 2013). The hands and feet have a small surface area yet possess a high density of sweat glands and would therefore contribute greatly to reducing the thermal burden if complete evaporative cooling was permitted from those areas. Calculating that the relative contribution of evaporative cooling from the upper limbs during exercise is near 18 % and the contribution from the hands accounts for over one third of that evaporative cooling, whilst only occupying approximately 24 % of the total upper limb surface area, the hands appear disproportionally effective at dissipating heat if maximum evaporative cooling was permitted. Table II also shows that whilst the torso may possess a lower density of sweat glands, it has a large surface area and therefore permitting complete evaporation of sweat from the torso during exercise in the heat could theoretically contribute greatly, approximately 33 % of the total contribution, to a reduced thermal strain.

Cutaneous sweat evaporation cools the skin and subsequently the blood in the vasodilatated blood vessels close to the skin, and thus cooled blood is returned to the core. Therefore regional variations in SkBF are important to consider. Caldwell *et al*. (2014) quantified blood flow to the right hand compared to the left foot in six male and moderately hyperthermic (T_{oe} between 38.4 °C and 38.5 °C) participants during rest. Peak values of 18.4 mL.100mL^{-1}.min^{-1} were obtained for the right hand (local T_{sk} of 40.3 °C), with peak left foot values reaching only 12.8 mL.100mL^{-1}.min^{-1} for a higher local T_{sk} (41.4 °C). A greatly increased blood flow in the hand is made possible by the high densities of capillaries in the hands ranging from 47 vessels.mm^2 (dorsal hand) to 77 vessels.mm^2 (palmar hand) (Grant & Bland, 1931) as well as the large diametric arteriovenous anastomoses reaching up to 125 µm (Hales, 1985). While these results highlight the importance of the hands for dissipating heat at least compared to the feet, it is interesting to note that maximal blood flow to the hands and feet, was only accomplished when whole body hyperthermia existed on some level (Caldwell *et al*., 2014) and not necessarily based upon T_{sk} alone as previously thought (Taylor *et al*., 1984). This was highlighted when the relationship between vascular conductance and the local treatment temperature were assessed at three distinct stages of T_{oe}; 36.1 °C (mild hypothermia), 37.0 °C (thermoneutral) and 38.5 °C (moderate hyperthermia). Significant increases to vascular conductance at the hands and feet only occurred in response to increased local temperature during moderate hyperthermia.

2.4 Thermoreception

Autonomic regulation of body temperature is influenced by input from cutaneous temperature receptors that also constitute the development of conscious sensation of the ambient environment (Hardy, 1961; Hensel, 1973). Temperature sensing free nerve endings found at the skin surface, known as thermoreceptors, transmits nerve impulses through the spinothalamic pathway to the primary somatosensory area in the postcentral gyri of the parietal lobes of the cerebral cortex (Tortora & Derrickson, 2006). Each region of the somatosensory area receives feedback from different parts of the body allowing for precise localization of somatic sensation. The sensory cortical homunculus shown in Figure 3 illustrates the relative contributions different areas of the body have on sensation as determined by electrical stimulation under local anaesthesia (Penfield & Boldrey, 1937). The homunculus is not exclusive to thermal sensation alone but also includes other sensors for touch such as pressure, vibration, stereognosis (tactile perception of the form of an object) and proprioception. In their widely cited paper, Penfield and Boldrey (1937) highlight that the hands and face provide greater sensory feedback to the brain in comparison to the trunk for example.

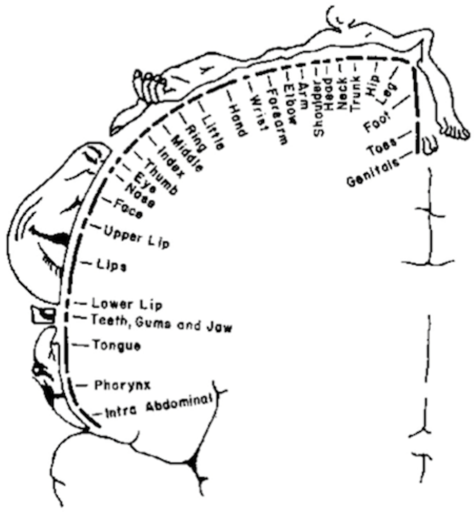

Figure 3: The sensory cortical homunculus as described by Penfield and Boldrey (1937) where the length of the bars on the periphery of the cortex represents the relative cortical areas (Penfield & Boldrey, 1937).

Hensel (1981) proposed a holistic approach to thermal responses whereby whole body thermal comfort, sensation and local thermal comfort depend largely upon afferent input from cutaneous, deep body and central nervous system receptors. There are both cold- and warm-specific receptors within the cutaneous somatosensory system that generate a steady-state discharge until the detection of a changing surrounding temperature whereby the discharge becomes dynamic (Hensel & Boman, 1960; Hensel, 1973). The cold- or warm-sensitive thermoreceptors lay approximately 200 μm beneath the surface of the skin forming a small sensitive area of approximately 1 mm in diameter (Fanger, 1970; McGlone & Reilly, 2010). Importantly, it should not be assumed that the density and sensitivity of thermoreceptors are evenly distributed throughout the skin (Nadel *et al*., 1973; Cotter *et al*. 1996; Cotter & Taylor 2005). For example on the lips there are approximately 19 cold spots.cm^{-2} with approximately 8 cold spots.cm^{-2} on the forehead (Strughold & Porz, 1931). It is estimated that there are approximately five times more cold than warm spots on the human body (McGlone & Reilly, 2010) with regional values such as approximately 1.0 warm spots.cm^{-2} on the nose and 0.3 warm spots.cm^{-2} on the chest (Parsons, 1993).

2.4.1 Thermal Comfort

The work of Fanger (1970) identified that for an individual to report whole body thermal comfort; there must be a balance of heat within the body while sweat rate and mean skin temperature ($\overline{T}_{sk}$) are within whole body comfort limits and additionally there must be a lack of thermal discomfort at discrete sites that can be influenced by humidity (Newton *et* *al*., 2007). Hygrosensation is the ability to detect skin wettedness and as the human skin does not specifically possess humidity receptors, it has been suggested that hygrosensation is detected through other sensory cues such as temperature or pressure (Bentley, 1900; Filingeri & Havenith, 2015).

Fukazawa and Havenith (2009) investigated the effects of local skin wettedness on whole body thermal comfort. In their experiment, participants exercised lightly in a climatic chamber at 22 °C and 50 % rh. Whole body thermal comfort in relation to skin wettedness was maintained at 0.4, which although being slightly higher than previous experiments (Gagge *et al*., 1969), was found to be thermally comfortable for participants wearing clothing. The measure of skin wettedness is dimensionless and was presented as a decimal fraction whereby 1.00 represents the maximum level of possible skin wettedness (skin surface being covered entirely by sweat) and 0.06 was the minimum level, which represents insensible sweating (Nishi & Gagge, 1977). Local body areas were subjected to increased skin wettedness through covering with an impermeable fabric (while the rest of the body was clothed in a permeable fabric with the exception of the head, hands and feet). It was found that different areas of the body possess different local thermal comfort limits and that generally the periphery possesses a higher sensitivity of thermal discomfort to skin wettedness (arms and thighs approximately 0.32) compared to the torso (approximately 0.40 to 0.45). These results taken together with the sensory cortical homunculus (Penfield & Boldrey, 1937) suggest that perhaps the extremities such as the hands, feet and face may possess a higher sensitivity of thermal discomfort to skin wettedness than even the arms and thighs.

Gueritee *et al*. (2015) investigated the limits to thermal comfort in cooling water (from 34.5 °C to 19.5 °C) using a partitioned clothing approach, whereby local areas were exposed and participants would state when the loss of overall thermal comfort occurred and which area of the body was driving that whole body thermal discomfort response. Interestingly, when starting from a largely uniform whole body T_{sk} (achieved by water immersion), it was the chest and back that were primarily responsible for the loss of overall thermal comfort rather than the extremities as was hypothesized by the authors. The findings were attributed to the chest and back cooling by more than the normal T_{sk} distribution in thermoneutral air, compared to the extremities that are adapted to experiencing colder conditions. Contrarily, Zhang (2003), whose participants wore a full-length leotard and socks (0.32 Clo) with air sleeves placed over various body sites that delivered either warmed or cooled air, identified that in a cold air environment overall thermal comfort tended to follow the local thermal comfort of the extremities (hands and feet). The magnitude of the change in temperature at the local sites from the normal T_{sk} distribution in thermoneutral air might have accounted for the differences in results between the studies (Gueritee *et al*., 2015). Zhang (2003) also explored thermal comfort in warm conditions and found that overall thermal comfort followed the local thermal comfort of the head and face.

2.4.2 Thermal Sensation

Some researchers attribute perceived thermal sensation to the stimulation of thermoreceptors (Hensel, 1981) and Stevens (1960) proposed that, from a psychological perspective, the magnitude of the sensation increases with the magnitude of the stimulus. Parsons (1993) reviewed the parameters affecting thermal sensation found by others and summarized that an individual's perceived whole body thermal sensation is determined by: the rate of change in discrete T_{sk}; the intensity of the temperature stimulus; the pre-existing thermal state of the body; the surface area exposed to the stimulus; the duration of exposure; and position of the stimulus on the body. T_{sk} also drives perceived thermal sensation in a humid environment due to the elevated T_{sk} as a result of the reduced heat loss from the skin in a high rh environment (Newton *et al*., 2007). Zhang (2003) found that in a cold environment overall thermal sensation, similar to overall thermal comfort, tended to follow the local thermal sensation of the hands and feet whereas in a warm environment, again similar to overall thermal comfort, overall thermal sensation tended to follow the local thermal sensation of the head and face.

It is difficult to distinguish the relative contributions of T_c or T_{sk} on thermoregulatory responses although it is generally accepted that T_c provides a greater weighting, particularly with initiating autonomic responses (Simon *et al*., 1986). It is even more difficult to determine the relative contributions of T_c or T_{sk} on perceived thermal responses of comfort or sensation. Whilst Chatonnet and Cabanac (1965) proposed that T_{sk} primarily drives cold perceptions and T_c primarily drives warm perceptions, the authors did not independently manipulate either T_{sk} or T_c in their study. Frank *et al*. (1999) successfully manipulated T_{sk} and T_c independently by a water-perfusion mattress set to 14 °C, 34 °C or 42 °C (manipulating T_{sk}) with intravenous infusion of cold (4 °C) fluid (manipulating T_c). It was found that T_c and T_{sk} contributed equally to whole body thermal comfort (1:1), but that for vasomotor response the T_c/T_{sk} ratio was 3:1 and for metabolic heat production the ratio was 3.6:1. The influence of T_c on perceived thermal sensation has also been researched, and McIntyre (1980) concluded that while perceived thermal comfort is largely dependent upon skin wettedness, perceived thermal sensation is initially a product of T_{sk} and then T_c. However, Gagge *et al*. (1967) stated that even before T_{sk} or T_c change, immediately upon a change in air temperature there are disruptions to perceived thermal sensation. Thus, the study of thermoreception is ongoing and the mechanisms determining perceived thermal sensation, thermal comfort or skin wettedness are not fully understood but appear to be influenced by both T_{sk} and T_c, as well as by the six parameters defining the human thermal environment: air and radiant temperature, humidity, air movement, metabolic heat generation and clothing (Parsons, 1993).

2.5 Differential Thermal Sensitivity

2.5.1 Differential Thermal Sensitivity During Rest

In the resting man, T_c primarily drives autonomic responses to hyperthermia, such as increased heart rate, SkBF and sweating, however as mentioned, the thermoregulatory system also receives afferent input from skin thermoreceptors (Nadel *et al*., 1971a; Wyss *et al*., 1974; Simon *et al*., 1986). Nadel *et al*. (1971a) found that when discrete skin areas were heated, T_{sk} exerts a "modifying effect" on the whole body thermoregulatory response. Kissen *et al*. (1971) first identified that during resting hyperthermia, cooling a small body surface area such as the head and neck (approximately 8 % of total body surface area by air passing through two inlet ports under a helmet) significantly reduced thermoregulatory strain (heart rate, SV, Q and sweat rate) to a greater extent than cooling an area of approximately 60 % (torso and legs cooled by air passing through small holes in a protective garment). The study also highlighted that cooling the head and neck inhibited the discharge of facial thermoreceptor neural impulses, attenuating whole body sudomotor mechanisms. This effect would be counter-productive to the minimally clothed individual operating in a hot environment where evaporative cooling is imperative to maintain heat balance, however the reduced sweat rate in response to facial cooling could be beneficial to the warfighter encapsulated in CBRN clothing. This is because much of the sweat produced when wearing CBRN IPE is unable to be evaporated due to the moisture vapour restrictive properties of the clothing and therefore a lower sweat production could result in less wasting of body fluid.

Two years after the experiments by Kissen *et al*. (1971), Nadel *et al*. (1973) conducted experiments to assess the differential thermal sensitivity of the skin focusing on specific areas (face, chest, abdomen, upper arms, lower arms, upper legs and lower legs). These areas were exposed to thermal irradiation (with an intensity of either 350 $W.m^{-2}$ or 700 $W.m^{-2}$) for periods of three to seven minutes interspersed with recovery periods of three to five minutes. The rate of change of sweating at the thigh was measured during each irradiation exposure while the minimally clothed participant rested in a supine position in an ambient environment controlled between 30.5 °C to 36.0 °C. The results indicated that, when adjusted for surface area, the face displayed a thermal sensitivity *i.e*. more sweat was produced per cm^2, that was approximately three times greater than that of the thigh, abdomen and chest, while the lower legs were found to possess a lowered thermal sensitivity by down to one half of the sensitivity at the thigh. This elegant experiment was the first of its kind to assess differential thermal sensitivity of the skin and postulated that, compared to any other area of the human skin; the face possesses a higher proportion of warmth receptors per unit area and therefore is responsible for a greater sudomotor response during heating. Furthermore, warm stimulation to the face had previously been shown to induce a greater peripheral vasodilatory response compared to when the same stimulus was applied to the chest or lower leg (Belding *et al*., 1948). Importantly the authors noted that T_{oe} remained unchanged (approximately 37.0 °C) during each irradiation exposure thus confirming that the altered sudomotor response at the thigh was attributable to increased T_{sk} at local sites and was not a function of T_{oe} directly.

In a follow up study Crawshaw *et al*. (1975) investigated the differential thermal sensitivity when certain areas of the skin (forehead, chest, abdomen, back, thigh and lower leg) were actively cooled by conduction using a water-cooled thermode (6 °C). Sweat rate was measured at the thigh whilst minimally clothed participants rested for up to two hours in an ambient environment of 39.0 °C. During this study Crawshaw *et al*. (1975) also measured subjective cold sensation when various areas were exposed to cold stimulation (which lasted three minutes at each site). The results indicated that, while T_{oe} (approximately 37.5 °C) and $\overline{T}_{sk}$ (approximately 36.8 °C) remained constant, the areas stimulated resulted in reduced T_{sk}, reduced rate of sweating at the thigh and increased estimates of cold sensation. However, again it was noted that not all sites reacted uniformly. The forehead proved to be highly sensitive per unit area regarding both autonomic and affective responses compared to any other area stimulated and therefore was in line with previous research (Hardy & Oppel, 1937; Stevens *et al*., 1974).

More recently the experiments of Nadel *et al*. (1973) and Crawshaw *et al*. (1975) have come under scrutiny by Cotter and Taylor (2005) who suggested that the failure to apply thermal clamps to unstimulated areas have methodologically limited the investigation into differential skin thermosensitivity as temperature changes at the treated sites could influence the temperature at untreated sites subsequently affecting the whole body sudomotor response. Cotter and Taylor (2005) proposed that through an open-loop approach using a water-perfused suit, T_c and $\overline{T}_{sk}$ could remain unchanged, or "clamped" above the threshold for sweating, whilst discrete areas were stimulated by conduction. In this way, a true investigation into differential skin thermosensitivity could be achieved without thermally perturbing the untreated tissues that could affect the whole body sudomotor response.

Cotter and Taylor (2005) found that during moderate active skin cooling by 11 °C, the face was two to three times more sensitive *i.e.* suppressed sweating during cooling, than the chest, abdomen, arm, thigh or foot. The face was five times more sensitive than the hand during active local warming by 4 °C. Cotter and Taylor (2005) suggested that, in conjunction with the experiments conducted by Kissen *et al*. (1971), the augmented sensitivity of the face to local cooling could result in a lowered whole body sudomotor response thereby detrimentally amplifying heat storage when wearing minimal or largely MVP clothing. In this way, local cooling of the face, while effectively reducing the perceived heat load, could exacerbate whole body heat storage by reducing the whole body sudomotor response. Whereas cooling the hands may not reduce the perceived heat load as much as cooling the face but, may more effectively reduce the actual heat load as the hands are less thermosensitive compared to the face and therefore influence the whole body sudomotor response less (Cotter & Taylor, 2005); particularly as the hands and forearms have been identified as effective zones for conductive heat extraction from the body (House *et al*. 1997). It is unclear why there are differences in thermosensitivity between the hands and face but one possible reason could be due to cerebral anatomy. When expanding on the work of Penfield and Boldrey (1937) who showed that the sensory capacity of certain body areas correspond with specific regions on the somatosensory cortex (Figure 3); Erpelding *et al*. (2012) identified that the degree of temperature sensitivity may be correlated with cortical thickness. Therefore as the sensory capacity of different parts of the body are at different regions on the somatosensory cortex, it is possible that the thickness of the cortex is different between the part associated with the hands compared to the face, thus eliciting varying degrees of temperature sensitivity.

2.5.2 Differential Thermal Sensitivity During Exercise

Ouzzahra *et al*. (2012) assessed the distribution of subjective thermal sensitivity (at 16 sites on the anterior and posterior torso and arm) during light exercise (cycling at approximately 30 % of $\dot{V}O_{2max}$) and at rest in response to local cold stimulation using a thermal probe (surface area of 25 cm^2) set to 20 °C. T_{re}, T_{sk} and perceived thermal sensation were measured. The authors found that, perceived thermal sensitivity to a cold stimulus was not homogenous between the 16 sites during both rest and exercise but were more pronounced during rest, with the lateral anterior torso proving to be the most sensitive area to cold and the posterior forearm the least. The heterogeneous distribution of cutaneous thermoreceptors (Nadel *et al*., 1973; Cotter *et al*. 1996; Cotter & Taylor 2005) was provided as a possible explanation as well as varying rates of ΔT_{sk}, hair density and differential sensory thermoreceptor feedback to the cerebral cortex (Penfield & Boldrey, 1937; Burke & Mekjavić, 1991).

Explanations for the decreased thermosensitivity during exercise compared to rest, whilst no differences in $\overline{T}_{sk}$ were identified, included: contributions of noradrenaline (Kozyreva, 2006); activation of the stress analgesia mechanism (Lewis *et al*., 1980); or arousal (Bentley *et al*., 2003). During acute exposure to cold, blood concentrations of noradrenaline are increased resulting in a decreased sensitivity to a cold stimulus (Kozyreva, 2006). Lewis *et al*. (1980) found reduced pain responsiveness when stress was induced in rats through electric foot shocks. The stress was found to activate an analgesia mechanism. On investigating the degree of arousal on painful thermal stimuli, Bentley *et al*. (2003) found that during deeper stages of sleep, a higher intensity of painful thermal stimulus was required to wake participants compared to lighter sleep stages. During the Ouzzahra *et al*. (2012) study, whether the decreased subjective sensitivity during exercise compared to rest was related to a 0.5 °C higher T_c during exercise was not determined, but the authors postulated that movement could affect the amount or selection of afferent information that is fed back to the cerebral cortex and thalamus (Ghez & Pisa, 1972; Rushton *et al*., 1981). The importance of the findings from Ouzzahra *et al*. (2012) is noted, however only measures of perceptual thermal sensitivity, not physiological parameters such as LSR or SkBF were obtained.

2.6 Special Consideration of Thermoregulation at the Hand *Versus* the Face

The face has a surface area of approximately 2.7 % of total body surface area (manikin Newton, Thermetrics, USA[2]) while the surface area of one hand is approximately 2.3 % of total body surface area (Yu *et al*., 2008), yet for similar surface areas, the whole body response of thermal stimulation to either the face or the hands can differ noticeably. The innervation of the face compared to the torso, hands and feet is different. The thermal

[2] To our knowledge no human anthropometric data exists for the surface area of the face in isolation to head measurements.

neurons of the face are located in the nucleus caudalis of the trigeminal nerve and relay thermal information directly to the thalamus (Dostrovsky & Hellon, 1978); whilst the sensory information from the trunk and limbs first pass through first and second order neurons before terminating in the thalamus. As demonstrated in rats and primates, there is extensive convergence of thermo-afferent signals from the trunk and limbs (Hellon & Mitchell, 1975) with only minimal convergent processing of facial afferents (Poulos & Molt, 1976). This differential relaying of thermal information to the thalamus, in conjunction with differential cortical thickness (Erpelding *et al*., 2012) discussed earlier, may explain why there are physiological and perceptual differences observed when either the face or hands are exposed to a stimulus.

Furthermore, the hand comprises of both glabrous (palm and ventral finger) and non-glabrous (dorsal surface) skin that possess differing thresholds of heat detection, *i.e.* glabrous skin has a lower threshold for heat detection compared to non-glabrous skin (Granovsky *et al*., 2005). Indeed, the head also comprises of glabrous skin sites such as the lips, which have been noted to possess the lowest heat detection threshold throughout the whole body (Stevens & Choo, 1998), but the majority of the head is covered by non-glabrous skin. Non-homogenously distributed cold- and warm-spot density may also provide an explanation for the differential thermal sensitivity found at different body regions when a stimulus is applied to the skin surface. The open-loop study by Cotter and Taylor (2005) found that the hands displayed a low thermosensitivity for sweating, yet in an earlier study Cotter *et al*. (1996) identified that the hands (as well as the feet and head) possess a high sensitivity for local thermal sensation. The high local sensitivity however, does not impact largely on whole body sensation or comfort measures, which subsequently has minimal impact on thermoregulatory responses (Cotter *et al*., 1996). Therefore, there appears to be incongruity between local thermal perception and thermoregulatory sensitivity.

Thus manipulating temperature at discrete areas such as the hands and face, whilst having similar surface areas, result in different local and whole body perceptual and physiological thermoregulatory responses.

2.7 Control of the Thermoregulatory Response of Sweating

An increase in T_c and T_{sk} as a result of exposure to a warmer ambient environment, and / or increased metabolic heat production caused by muscle activation during exercise, results in an increased expulsion of sweat from eccrine glands (Benzinger, 1959; Nadel *et al*., 1971a; Nadel *et al*., 1971b; Saltin & Gagge, 1971). Preceding the production of sweat, cholinergic sudomotor nerves that innervate sweat glands release the neurotransmitter acetylcholine, as well as various peptides, that bind to muscarinic receptors on the gland initiating a cascade of events that culminate in sweat expulsion (Randall & Kimura, 1955). It is generally well accepted that input from peripheral thermoreceptors relay information directly and rapidly to the hypothalamus (Kuno, 1956; Shibasaki *et al*., 2006). Furthermore, the anterior hypothalamus also detects slight disturbances to thermal homeostasis (such as an increase in circulating blood temperature) and initiates the heat loss response with the commencement of sweating and peripheral vasodilatation (Benzinger, 1959; Nielsen & Nielsen, 1965; Smiles *et al*., 1976). Therefore activation of the sudomotor response is closely associated with increased T_c and T_{sk}, input from thermoreceptors and stimulation of the anterior hypothalamus.

Non-thermal mechanisms governing the sudomotor response have also been widely investigated (Figure 4) and experiments have included identifying the contribution of central command (van Beaumont & Bullard, 1966; Vissing *et al*., 1991; Shibasaki *et al*., 2003b), metaboreceptor (Shibasaki *et al*., 2001; Shibasaki *et al*., 2003a) and mechanoreceptor stimulation associated with exercise (Kondo *et al*., 1997; Journeay *et al*., 2004) as well as osmoreceptor (Fortney *et al*., 1981; Takamata *et al*., 1995) and baroreceptor stimulation (Dodt *et al*., 1995; Wilson *et al*., 2001).

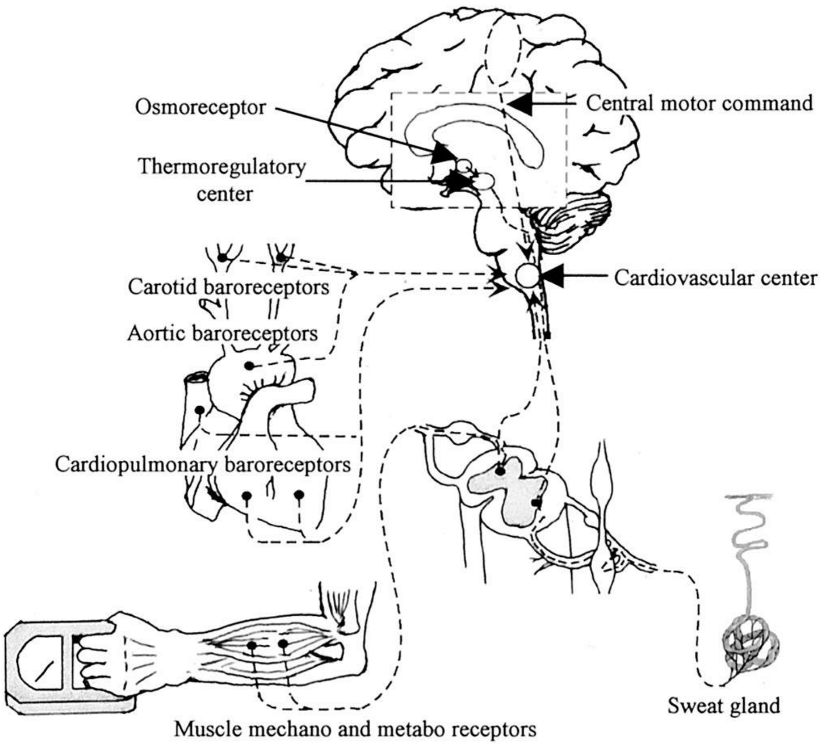

Figure 4: Possible mechanisms governing non-thermal regulation of the sweating response (Taken from Shibasaki *et al*., 2003a. Used with author's permission).

A phenomenon first identified by van Beaumont and Bullard (1963) showed that sweating, in a warm environment, began within 1.5 seconds to 2.0 seconds after the onset of heavy muscular exercise, therefore preceding any noticeable increases to T_c from internal metabolic heat production. The authors further explored this response with participants performing an isometric contraction lasting approximately 75 seconds, in which venous return from the working muscle was occluded using an inflatable blood pressure cuff (van Beaumont & Bullard, 1966). This prevented the warmed, metabolite-rich blood from the working muscle reaching the anterior hypothalamus that would subsequently detect the altered thermal homeostasis and initiate the sudomotor response for heat dissipation. It was identified that as the onset and cessation of sweating at the contralateral limb when the left arm was occluded followed a similar pattern of response when the left arm was not occluded, the authors postulated that the sweating response was largely mediated by neurogenic stimulation and that detection of altered blood temperature by the hypothalamus might not be essential in initiating the sudomotor response.

Vissing *et al*. (1991) investigated the influence of skin sympathetic nerve activity (SSNA) on normothermic and mildly heat stressed participants during isometric handgrip (IHG) exercises pre-limb occlusion. SSNA comprises both sudomotor and vasomotor activity and is microneurographically recorded from cutaneous peripheral nerves (Vallbo & Hagbarth, 1967; Vallbo *et al*., 2004). The exercised limb was occluded in an attempt to trap muscle metabolites. As post-exercise SSNA levels returned to pre-exercise levels after being elevated during exercise, the authors concluded that, central command provided a greater influence on the modulation of SSNA compared to muscle metaboreceptors. When a neuromuscular blockade was applied through injection of vecuronium, thereby limiting the influence from muscle metaboreceptors yet maintaining influence from central command, SSNA was again increased during an attempted IHG exercise. These results suggested that central command provided a large influence on sympathetic outflow to the skin and could greatly modulate the sweating response (Vissing & Hjortsø, 1996). However, SSNA measures all activity from the cutaneous peripheral nerves isolated and can therefore govern a variety of end organ responses such as cutaneous vasodilatation or piloerection and not just sweating (Shibasaki *et al*., 2003a). Although approximately 80 % of all SSNA activity has been associated with sweat expulsion during mild heating in humans (Sugenoya *et al*., 1998).

The loading or unloading of baroreceptors has also been indicated as a mechanism by which there is non-thermal regulation of the sweating response. Investigations into baroreceptor stimulation usually involve the use of tilt tables (Dodt *et al*., 1995; McInnis *et al*., 2006) however, Jackson and Kenny (2003) investigated the role of loading baroreceptors through application of lower body positive pressure (LBPP) of + 50 mmHg on the post-exercise threshold for sweating and vasodilatation. LBPP was used to induce an increase in mean arterial pressure, particularly as the quality of data from tilt models has been questioned as there is often a failure to clarify which specific baroreceptor population has been stimulated by the tilt (Shibasaki *et al*., 2003a). For example, venous pooling that occurs post-exercise would unload both cardiopulmonary and arterial baroreceptors, yet the head-up tilt is known to unload only cardiopulmonary baroreceptors. LBPP on the other hand results in stimulation of both cardiopulmonary and arterial baroreceptors through application of increased barometric pressure to the lower extremities. This conserves mean arterial pressure and CBV post-exercise due to micro-vascular compression in the lower limb tissues (Fu *et al*., 1999).

Jackson and Kenny (2003) required that participants complete a 15-minute bout of exercise (or no exercise in the control condition) after which participants were moved to a pressure box and donned a water-perfused suit in which initially 20 °C water was perfused to stabilize T_{sk} and T_{oe}. After 65 minutes, water at 47 °C was then perfused through the suit whilst the onset of sweating (as measured from a capsule placed on the upper back) and vasodilatory (as measured by a laser Doppler probe placed on the forearm) responses were measured. The results indicated that the threshold for the onset of sweating and vasodilatation were significantly elevated post-exercise compared to when no exercise was undertaken, however when baroreceptors were loaded by LBPP post-exercise, the threshold for the onset of vasodilatation and sweating was no longer elevated. This was the first study to show that the post-exercise increase in the threshold for sweating was reversed after a bout of upright exercise by loading baroreceptors. It has also been suggested that perhaps the magnitude of heat stress that participants are exposed to may influence whether or not unloading baroreceptors modulates the sweating response particularly as Shibasaki *et al*. (2006) concludes that in experiments where sweating was already initiated, non-thermal factors provided a greater influence on the sweating response compared to studies where participants began the experiment in a normothermic state.

Dehydration results in a loss of blood volume if fluid is not replenished, causing reductions to blood pressure that would be sensed by baroreceptors (cardiopulmonary, carotid or aortic baroreceptors). Plasma hyperosmolality can impair the sweating response particularly during exercise in the heat when plasma volume is decreasing due to sweating-induced dehydration (Nielsen, 1974; Fortney *et al*., 1984). Takamata *et al*. (1995) induced cell dehydration (CDH) in passively heated participants (lower limb immersion in 42 °C water) through a 3 % sodium chloride infusion before providing water to drink that was heated to 38 °C. It was found that compared to control participants (euhydrated), LSR at the chest for CDH participants increased to a lesser extent per unit rise in T_{oe} as well as the T_{oe} threshold for sweating was greatly elevated. Takamata *et al*. (1995) explored the relationship between sweating responses, plasma osmolality and plasma volume and discovered that within minutes of drinking the water there were rapid elevations to sweat rate for the CDH group even before any changes to plasma osmolality or plasma volume could occur. This led the authors to consider that an oropharyngeal reflex under hyperosmotic conditions could modulate the sweating response. Fortney *et al*. (1981) manipulated the plasma volume whilst maintaining plasma osmolality during passive heating and discovered that under hypervolemic conditions (plasma volume expansion of 7.9 %), there were no significant alterations to the sweating response however under hypovolemic conditions (plasma volume reduction of 8.7 %), whole body sweat rate was decreased.

Therefore, studies have explicitly shown that control of the thermoregulatory response of sweating does not depend solely on thermal factors such as T_c and T_{sk} but can include non-thermal regulation.

2.8 Summary

This review of the literature has included discussions on thermoregulation in a hot environment and when wearing protective clothing. Additionally, the review has included discussions of regional variations in thermoregulation, thermoreception and thermosensitivity with differences particularly noted for the hands *vs*. the face. Finally, the control of the thermoregulatory response was discussed with emphasis on non-thermal regulation of sweating. The overall aim of the work reported in this thesis was to investigate reducing the physiological and perceptual thermal burden associated with wearing CBRN protective items, some of which completely restrict evaporative cooling from certain body areas. Therefore much emphasis was placed on regional variations to thermoregulation. The aim was also to determine the additional methodological deliberations that should be considered when attempting to quantify the thermal burden when varying proportions of the body are covered with MVIP materials, as well as considerations on the mechanistic control of thermoregulation.

The general hypothesis of this thesis was that improving the MVP of CBRN ancillary items would alleviate thermoregulatory strain to varying degrees between items when worn in a hot, desert-like environment.

CHAPTER III: GENERAL METHODS

3.1 Ethics

The first study received a favourable ethical opinion from the Ministry of Defence Research Ethics Committee on the 2nd of January 2014 (470/MODREC/13). The second study was granted a favourable ethical opinion by the University of Portsmouth Science Faculty Ethics Committee (SFEC) on the 15th of October 2013 (SFEC 2013-044). The third study was granted a favourable ethical opinion by the University of Portsmouth SFEC on the 19th of January 2015 (SFEC 2014-100) with a minor amendment to the protocol receiving favourable opinion from SFEC on the 6th of March 2015 (SFEC 2014-100 B). The fourth study received ethical approval from the University of Ottawa Health Sciences and Science Research Ethics Board under the guidance and advice of Professor Kenny (University of Ottawa). All procedures are in compliance with the University of Portsmouth Department of Sport and Exercise Science Schedule of Approved Procedures[3] and the Declaration of Helsinki[4].

3.2 Environmental Chamber Conditions

For the first, second and third studies, environmental conditions of Pinsent Chamber (Extreme Environments Laboratory, Department of Sport and Exercise Science, University of Portsmouth) were set to 40.5 °C air temperature and 20 % air rh. The actual temperature and rh for each study are provided in each chapter. The values chosen (40.5 °C and 20 % rh) represent the mean conditions between 08:00 and 21:00 for countries in the Defence Standard A2, hot and dry, category[5]. An air temperature of 40.5 °C is also sufficient to enable the onset of sweating and a rh of 20 % provides an adequate gradient for water vapour exchange that promotes evaporative cooling from an exposed site. The environmental conditions were measured using a wet-bulb globe thermometer (Edale Instruments Ltd, UK) and electronically logged every minute (Squirrel 1000, Grant Instruments [UK] Ltd, UK). The environmental conditions for the fourth study were controlled at 40.0 °C air temperature in an environmental chamber (Can-Trol Environmental Systems Ltd, Markham, ON, CA) at the Human and Environmental

[3] University of Portsmouth, Schedule of Approved Procedures, Department of Sport and Exercise Science, November 2012.

[4] World Medical Association (WMA) Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects. 64th WMA General Assembly, Fortaleza, Brazil, October 2013.

[5] Ministry of Defence Standard 00-35 produced by the Meteorological Office that provides climatic information worldwide.

Physiology Research Unit, School of Human Kinetics, University of Ottawa in Canada, whilst humidity rose steadily from 20 % rh until reaching approximately 45 % rh by the end of each trial. The environmental chamber at the Human and Environmental Physiology Research Unit, University of Ottawa does not have an integrated rh system and therefore rh was not precisely controlled.

3.3 Participants

All participants for all four studies were male volunteers. Only two female volunteers were used for pilot testing for the fourth study (Appendix 14). In general females were not used primarily because the menstrual cycle and the use of oral contraceptives are known to impact temperature regulation depending on which phase of the menstrual cycle the female is currently experiencing (Tenaglia *et al*., 1999).

To estimate sample sizes, *a priori* power analysis was conducted (Version 2.00, StatMate, US) based upon the standard deviation (SD) of 25.5 minutes (12.6 %) of the TT for nine, male volunteers engaging in light, intermittent exercise in a climate of 40 °C and 30 % rh whilst wearing Canadian nuclear biological and chemical (NBC) battle dress uniform (McLellan & Ayogi, 1996). Based upon the power analysis, a sample size of six participants in each condition had a 50 % power to detect differences between means of 22.63 minutes (11.2 %) with a significance of 0.05. A 50 % power means that there is a 50 % chance of making a Type II error (false negative). Therefore, a more appropriate approach would be to calculate the sample size required for 80 % power. In the example provided above, this would mean that a sample size of n = 12 would be required to elicit a statistical power of 80 %. In this thesis, the number of participants varied between the studies: for the first study n = 12, for the second study n = 13, for the third study n = 15 and for the fourth study n = 9. Originally the fourth study had ten participants but one participant was excluded due to both sweat capsule and laser Doppler probe detachment.

Before volunteering to partake in a trial, all participants were provided with a written briefing and attended an oral briefing detailing the specifics of the experimental protocol and explaining any potential discomforts or disadvantages to participating. If content, participants then signed an informed consent form and also completed an exercise and health history questionnaire. Individuals were excluded subject to being on current medication or any serious medical conditions that were determined by the independent medical officer for example: hypertension, heart disorders or musculoskeletal injury.

3.4 Experimental Procedures

3.4.1 Prior to Testing

Prior to testing, for the first three studies, anthropometric measures of skin-folds (Harpenden, Cranlea Ltd, UK), nude body mass (Model I10, Ohaus Corporation, US) and height (Stadiometer, SECA Ltd, UK) were acquired. For the fourth study, anthropometric measures of body fat were determined by hydrostatic weighing using the Siri (1956) equation (data kindly obtained by Martin Poirier and Brendan McNeely from the University of Ottawa). Nude body mass (Model CBU150X, Mettler Toledo Inc., CH) and height (Model 2391, Detecto Scale Company, MO, US) were also acquired. Four skin-fold sites: biceps, triceps, subscapular and supra-iliac were measured using calipers (Harpenden, Cranlea Ltd, UK) for estimation of body fat (Durnin & Womersley, 1974).

For the first and second study, all experiments took place in the morning, between 08:00 and 13:00. This was to eliminate any influence of the circadian rhythm on thermoregulation which may show a variation as much as 0.5 °C, affecting subsequent performance and prompting early withdrawal (lessening the time to reach a T_{re} of 39.0 °C) of participants (Kräuchi & Wirz-Justice, 1994; Gonzalez-Alonso *et al*., 1999). For the third and fourth study experiments took place either in the morning (between 08:30 and 12:30) or in the afternoon (between 13:00 and 17:00) as these experiments lasted 90 minutes or less and the pilot studies conducted (Appendices 11 and 14) confirmed that for these specific protocols, early drop out based on a high T_c during the afternoon session would be minimal. Furthermore, during the third study when participants conducted repeated measures, individuals partook in the experiment in either the morning or the afternoon session only for all five conditions to eliminate any diurnal effects within participants. On each test day, participants were instructed to eat a light breakfast and arrive at the laboratory in a euhydrated state. During the fourth study, urine-specific gravity (USG) was measured from the participants' urine sample using a handheld total solids refractometer (Model TS400, Reichter Inc., Depew, NY, US) to assess hydration level. All experiments only began once the participant was euhydrated *i.e*. USG $\leq$ 1.02. Participants were asked to refrain from alcohol the day prior to testing to avoid alcohol-induced dehydration (Roberts, 1963), and caffeine for two hours prior to testing particularly as caffeine can modify hormonal and cardiovascular measures (Daniels *et al*., 1998).

3.4.2 Measurements

3.4.2.1 Core Temperature

During all studies T_{re} was used as the measure of T_c whereby participants self-inserted a rectal thermistor (Edale Instruments Ltd, UK) to 15 cm beyond the anal sphincter. Additionally during the fourth study T_{oe} was used as the primary measure of T_c whereby the experimenter inserted a general-purpose thermocouple (Mallinckrodt Medical Inc., MO, US) 40 cm through the nasal cavity and down the oesophagus of the participant whilst the participant sipped warm (approximately 30 °C) water through a straw. During the pilot work for the fourth study, aural temperature (T_{au}) was also measured. The aural thermistor (Grant Instruments (UK) Ltd, UK) was secured in the participant's right ear using an impression silicone (Otoform K2, Algeos, UK) and was insulated from the ambient environment using non-absorbent cotton wool, which was secured in place using a net bandage (SurgiFix, Smith & Nephew, AU). T_{re} data were transmitted wirelessly every second in real time to a data acquisition system (Sharktooth System, MIE Medical Research Ltd, UK). T_{au} data were sampled at a rate of 1 second to a data acquisition system (Squirrel, Grant Instruments (UK) Ltd, UK) while T_{oe} data were sampled at a rate of 15 seconds to a data acquisition system (Model 34970A, Agilent Technologies Canada Inc., ON, CA) and simultaneously viewed in real time using LabVIEW software (Version 7.0, National Instruments, TX, US).

For calculation of rate of change of T_{re}, data that were approximately linear were used. Therefore when participants either exercised at a constant rate or recovered for a period greater than 10 minutes, the T_{re} trace was approximately linear. An example is illustrated in Figure 5 below. Calculating the rate of change of T_{re} during stepping from the start of the stepping period at 20 minutes would be inaccurate as the data were not linear. However, from 30 minutes into the protocol, that being 10 minutes into the stepping period, the data were approximately linear and the rate of change of T_{re} could be calculated. Similarly, during recovery, the rate of change of T_{re} would only be calculated from 90 minutes, that being 10 minutes into the recovery period when the data were approximately linear (Figure 5).

The rate of change of T_{re} was calculated as follows:

$$Rate = \Delta T_{re} / t \ [°C.hr^{-1}]$$

Where: ΔT_{re} is the change of rectal temperature [°C]

t is the time over which ΔT_{re} occurred [hours]

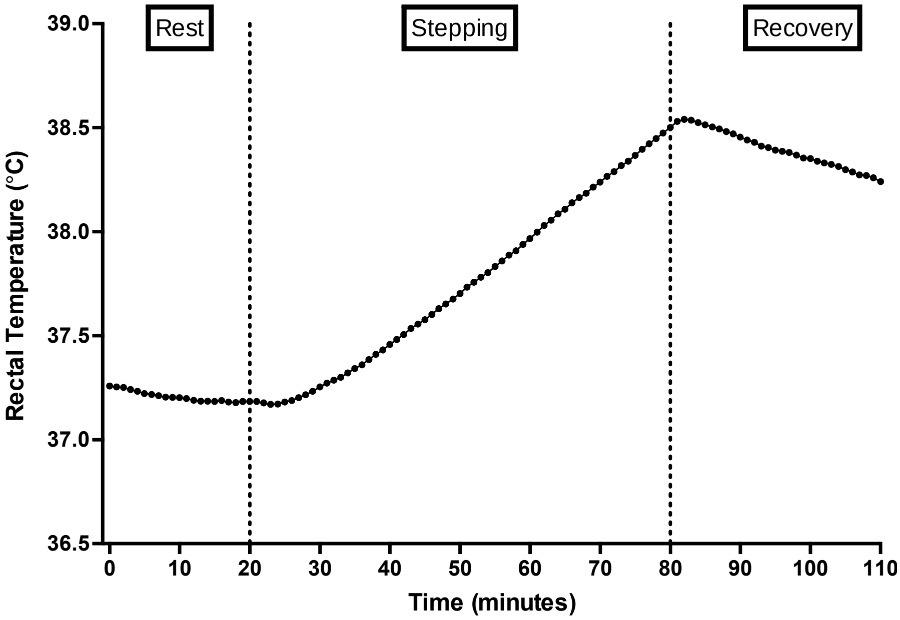

Figure 5: Mean rectal temperature during rest, exercise and recovery when wearing fully encapsulating protective equipment with the head exposed and a fan directed at the head in 40.5 °C and 20 % rh air (n = 10).

Participants ceased exercising when T_{re} > 39.0 °C (Section 3.4.4) and predicted TT to a T_{re} of 40 °C was calculated by adding the linear rate of rise of T_{re} during the final exercise period, to the final temperature point obtained and noting the time whereby T_{re} would have reached 40 °C.

3.4.2.2 Skin Temperature

Participants were instrumented with skin thermistors during the first, second and third studies (Grant Instruments (UK) Ltd, UK) and thermocouples (Concept Engineering, CT, US) during the fourth study at four sites: calf, thigh, chest and upper arm, to estimate $\overline{T}_{sk}$ according to the equation presented by Ramanathan (1964) as follows:

$$\overline{T}_{sk} = 0.3 * (T_{chest} + T_{arm}) + 0.2 * (T_{thigh} + T_{calf}) \ [°C]$$

The work of Olesen (1984) concluded that as little as two to four skin sites, but usually three placed at the chest, forearm and calf, could be used for estimation of $\overline{T}_{sk}$ in a warm environment provided that intra-site variability is presumed to be low. The skin thermistors were attached to the participant using Tegaderm™ tape (3M, Bracknell, UK) and secured using Transpore™ tape (3M, Bracknell, UK). During the first three studies additional skin thermistors were secured to the right finger pad and right cheek for estimations of finger pad (T_{finger}) and cheek (T_{cheek}) skin temperatures. During the first three studies, T_{sk} data were transmitted wirelessly every second in real time to a data acquisition system (Sharktooth System, MIE Medical Research Ltd, UK) and during the fourth study data were sampled at a rate of 15 seconds to a data acquisition system (Model 34970A, Agilent Technologies Canada Inc., ON, CA) and simultaneously viewed in real time using LabVIEW software (Version 7.0, National Instruments, TX, US).

3.4.2.3 Mean Body Temperature

$\overline{T}_b$ was calculated according to the equation presented by Colin *et al*. (1971) by combining $\overline{T}_{sk}$ in conjunction with T_{re} in a weighted formula as follows:

$$\overline{T}_b = 0.79 * (T_{re}) + 0.21 * (\overline{T}_{sk}) \ [°C]$$

Colin *et al*. (1971) conducted 91 experiments in five hot environments where body heat storage was determined by the record of weight loss using the Houdas *et al*. (1970) equation[6] whilst participants lay resting in a supine position. Colin *et al*. (1971) determined that a weighting of 0.79 for the T_c component in the $\overline{T}_b$ equation would generally elicit an accuracy of 0.1 °C compared to the calculated body heat storage (Houdas *et al*., 1970).

3.4.2.4 Heart Rate

During the first two studies heart rate was monitored by a three-lead electrocardiogram (ECG) attached to the chest with gel electrodes (Blue Sensor SP, Ambu, DK). During the final two studies heart rate was monitored using a heart rate monitor (RS800, Polar Electro Oy, FI). The ECG data were transmitted continuously to a data acquisition system (Sharktooth System, MIE Medical Research Ltd, UK) and minute averages were exported, while 5 second samples were minute averaged when the Polar heart rate monitor was worn.

[6] body heat storage = $\lambda (\dot{m} \cdot t - \Delta m)$

where λ is the latent heat of vaporisation of sweat assumed to be 2.52 $kJ.g^{-1}$, $\dot{m}$ is the slope of the weight loss curve at the end of the exposure, t is time and Δm is the weight loss (Houdas *et al*., 1970).

3.4.2.5 Physiological Strain Index

Heart rate was used in conjunction with T_{re} to estimate the physiological strain index (PSI). The PSI developed by Moran *et al*. (1998) takes into account both the changes in T_{re} and heart rate at a given time point in the context of an existing physiological database (100 men exercising at 4.82 km.hr^{-1} at a 2 % grade in 40 °C, 40 % rh for 120 minutes). The tool has been validated on seven men exercising lightly for 180 minutes wearing partially protective clothing in hot (43 °C) and dry (20 % rh) as well as hot (35 °C) and wet (50 % rh) environments and was sensitive enough to detect changes between the similar exposures. The equation for PSI is as follows:

$$PSI = 5\,(T_{ret} - T_{re0})\ ^{*}\ (39.5 - T_{re0})^{-1} + 5\,(HR_t - HR_0)\ ^{*}\ (180 - HR_0)^{-1}$$

Where: T_{ret} and HR_t are rectal temperatures and heart rate measures taken at any time during the protocol

T_{re0} and HR_0 are initial measures

The PSI scale ranges from 0 to 10 and yet values below 0 are reported in the first and second studies. Upon consultation with Professor Moran, it was highlighted that values below 0 are obtained when the starting T_{re} or heart rate is taken as the initial T_{re} or heart rate measure instead of using resting T_{re} or heart rate to depict T_{re0} and HR_0. The impact that this consideration has on the results obtained is large upon initial exposure to a hot environment but lessen as the protocol progresses and thermoregulatory strain increases (Appendix 2). This occurred as individuals' T_{re} and heart rates got closer to the maximum values of 39.5 °C and 180 beats.min^{-1} respectively. Additionally it was explored whether $\overline{T}_b$ would be a more appropriate measure rather than T_{re} (Appendix 2). Again, it was noted that as the thermoregulatory strain increased, the difference between measures was lessened as the change in $\overline{T}_{sk}$ was less as the protocol progressed (Appendix 2). Therefore, as the study design for the first two studies was repeated measures and the difference between calculating the PSI with the lowest T_{re} or heart rate and $\overline{T}_b$ in place of T_{re} was less significant as the thermoregulatory strain increased, the results are presented as per the equation for PSI above (Moran *et al*., 1998).

3.4.2.6 Oxygen Consumption

To estimate work rate based on the rate of oxygen uptake ($\dot{V}O_2$) during the first and second studies, expired air was collected once using Douglas bags (for either one minute or two minutes depending on which work or recovery period the sample was being taken in), in the last minute or two minutes of each work and recovery period. Oxygen and carbon dioxide concentrations (Rapidox 3100, Cambridge Sensotec, UK), gas volume (Dry Gas Meter, Harvard Apparatus, UK) and gas temperature (Electronic Thermometer, UK) from expired gas samples was quantified. Daily barometric pressure was also recorded (Model F54, Fortin Barometer, Russell Scientific Instruments Ltd, UK).

3.4.2.7 Whole Body Sweating

Sweat evaporation and masses of sweat production were calculated from the difference in clothed and nude mass, fluid intake and output (such as urine, however no participant urinated during any study). Absolute whole body sweat production and evaporation as well as rates of sweat production and evaporation were calculated as follows:

$$\text{Sweat production} = (\text{nude mass pre-test} - \text{nude mass post-test}) + (\text{water intake} - \text{output})\ [\text{L}]$$

$$\text{Sweat evaporation} = (\text{clothed mass pre-test} - \text{clothed mass post-test}) + (\text{water intake} - \text{output})\ [\text{L}]$$

$$\text{Rate of sweat production} = (\text{sweat production} / t) * 60\ [\text{L.hr}^{-1}]$$

$$\text{Rate of sweat evaporation} = (\text{sweat evaporation} / t) * 60\ [\text{L.hr}^{-1}]$$

Where: t is the total time spent in the chamber [minutes]

The sweat evaporation / production ratio, which provides an indication of the efficiency of sweating was calculated as follows:

$$(\text{absolute sweat evaporation} / \text{absolute sweat production}) * 100\ [\%]$$

Absolute measures of fluid balance were calculated from the rate of whole body sweat production and the rate of fluid consumed. As participants spent varying durations in the chamber due to the stopping criteria in place, the rate of fluid consumption and sweat production was calculated in place of showing absolute values, which would be biased by the duration of time spent in the chamber.

Respiratory weight loss during exercise should also be mentioned. This would occur due to evaporative water loss during respiration as well as the difference in the mass of inspired oxygen and expired carbon dioxide.

The former (mass loss from respiratory evaporation) can be calculated using the following equation (Livingstone *et al*., 1994; Gagge & Gonzalez, 1996):

$$\text{Evaporative Mass Loss} = E_{res} \times t \times (1 / 2430) \qquad [g]$$

Where: E_{res} is the evaporative loss from respiration (W)

t is the time (s)

2430 is the latent heat of evaporation of 1 g of water ($J.g^{-1}$)

$$E_{res} = 1.27 \times 10^{-3} \times \dot{M}\ (59.34 + 0.53 \times T_a - 11.69 \times P_a) \qquad [W]$$

Where: $\dot{M}$ is the metabolic rate (W)

T_a is the air temperature (°C)

P_a is the partial pressure of water vapour in the air (kPa)

Therefore, for a light metabolic rate (180 W) in an environment set to 40.5 °C and 20 % rh, there would be an estimated evaporative mass loss from respiration of 60 g over a 170 min protocol.

The latter (metabolic mass loss) would be reflected in the calculated respiratory quotient, that being the ratio of the moles of oxygen inspired to the moles of carbon dioxide expired. Therefore, body mass loss can vary depending on the mass of carbon dioxide expired and the mass of oxygen inspired. Mitchell *et al*. (1972) proposed the following equation for calculating the rate of body mass loss ($\dot{m}$) from these differences:

$$\dot{m} = \dot{V}O_2\ (RQ \times p_{CO2} - p_{O2}) \qquad [g.min^{-1}]$$

Where: RQ is the respiratory quotient

$\dot{V}O_2$ is the rate of oxygen uptake ($L.min^{-1}$ standard temperature and pressure dry)

p_{CO2} is the density of carbon dioxide (1.96 $g.L^{-1}$ standard temperature and pressure dry)

p_{O2} is the density of oxygen (1.43 $g.L^{-1}$ standard temperature and pressure dry)

As an example, this calculation was applied *post-hoc* to data obtained from one participant during a control condition ($\dot{V}O_2$ of 1.02 $L.min^{-1}$, RQ of 0.85) and a condition where the

BAL was not worn ($\dot{V}O_2$ of 1.08 $L.min^{-1}$, *RQ* of 0.83). This elicited a difference of 0.02 $g.min^{-1}$, whereby $\dot{m}$ was 0.46 $g.min^{-1}$ in the control condition and 0.48 $g.min^{-1}$ in the condition where the BAL was not worn.

Throughout this thesis as participants exercised at the same work rate between conditions and the experimental design was repeated measures, mass loss due to respiratory and metabolic mechanisms were not calculated as it would be expected to be equal between conditions, yet it is important to mention possible mass losses through these mechanisms.

3.4.2.8 Local Sweat Rate

For the measurement of LSR during the third study, four sweat capsules (Q-Sweat^{TM}, WR Medical Electronics Co., US) were secured at the chest (right mid-clavicular line and below the heart rate monitor strap) and back (left mid-scapular line and below the heart rate monitor strap) using Polar heart rate straps, as well as at the forearm (midway as measured from the wrist to the elbow on the left side) and thigh (midway as measured from the knee to the hip on the left side) using rubber straps. De-humidifed air was passed through the sweat capsule (surface area of 0.787 cm^2) at a flow rate of 60 $mL.min^{-1}$ and the difference in water vapour content and temperature of the efflux and influx air was monitored by sensors (Honeywell International Inc., MN, US). Data were sampled every 0.25 seconds and were simultaneously viewed in real time using WR TestWorks software (Version 2.83, WR Medical Electronics Co., MN, US). For measurement of LSR during the fourth study, four custom-made sweat capsules (surface area of 3.8 cm^2) were attached to the same areas as the third study (chest, back, forearm and thigh) with adhesives and secured using surgical glue (Collodion HV, Mavidon Medical products, FL, US) and medical tape. Compressed nitrogen gas from tanks stored in the chamber passed dry air through the capsules at a flow rate of 1.0 $L.min^{-1}$ and water vapour in the effluent air from the capsules was passed through capacitance hygrometers (Model HMT333, Vaisala, FI). The difference in water vapour content between influx and efflux air was used to calculate LSR ($mg.cm^{-2}.min^{-1}$) from the flow rate, capsule area and absolute humidity ($mg.m^{-3}$) computed from rh and temperature sampled from a probe in the hygrometer. Data were sampled every 5 seconds and were simultaneously viewed in real time using Veriteq software (Spectrum 4.0, Veriteq Instruments Inc., CA).

3.4.2.9 Local Skin Blood Flow

Regional microcirculation, measured in laser Doppler units (LDU) or perfusion units (PU), was recorded using laser Doppler flowmetry (Study 3: moorVMS-LDF, Moor Instruments, UK; Study 4: Periflux System 5000, Perimed, SE). Light delivered by the laser Doppler probe was directed at the skin at a measuring depth of approximately 1 mm and collided with blood cells that undergo a Doppler shift. The disruption to the light source was detected by the receiver and displayed as LDU or PU[7]. Laser probes (Model VP1T/7, Moor Instruments, UK) were located next to each sweat capsule at the chest, back, forearm and thigh during the third study. For the third study, data were also normalized to five minutes of resting data, however as the outcome resulted in a similar conclusion to when the data were presented in absolute LDU (Appendix 3), the absolute units are presented. For the fourth study, regional SkBF, measured in PU, was recorded at the same locations as the third study, using laser Doppler probes (Model 413, Perimed, SE) and laser Doppler flowmetry (Periflux System 5000, Perimed, SE). For both the third and fourth studies, data were sampled continuously and were simultaneously viewed in real time using LabChart software (Version 7.0, ADInstruments Ltd., UK). Laser Doppler probes used during the third study (Model VP1T/7, Moor Instruments, UK) were multichannel, supplying light at a right angle to the cable and consisted of 8 collecting channels in a 2 mm diameter area, which allowed for a lower variance between repeated measures compared to single channel systems. Laser Doppler probes used during the fourth study (Model 413, Perimed, SE) consisted of one transmitting channel and two receiving channels.

3.4.2.10 Blood Pressure

During some pilot studies for the fourth study, blood pressure was monitored in real-time with a beat-to-beat blood pressure monitor (Finapres Ohmeda 2300, NL) to assess for hypotension during standing periods.

3.4.2.11 Perceptual Measures

The Borg scale (1976) was used to represent a rating of perceived exertion (RPE) (Appendix 19). During dehydration and exercise in the heat the standard relationship between RPE and heart rate (Gamberale, 1972) is compromised (Maw *et al*., 1993; Logan-Sprenger *et al*., 2012) with RPE being linked to the initial detection of the rate of heat storage (Tucker *et al*., 2006) resulting in participants reporting RPE greater than expected for a given heart rate. However, with the lack of a gold standard measure of perceived exertion for participants exercising in the heat, the Borg RPE scale was used in our experiments. Even recently, the Borg RPE scale was still being used as the primary

[7] Manual for Laser Doppler Probes for Periflux System 5000. Perimed AB, Sweden.

measure of RPE when wearing personal protective equipment during the hottest time of the day at Ebola Virus Disease Treatment Units in Sierra Leone (Maynard *et al*., 2015).

Visual analogue scales (VAS) were used to quantify perceived whole body thermal comfort, thermal sensation and skin wettedness (Appendix 20). The limitation of using a VAS is that a ceiling effect may introduce a bias into the results. The ceiling effect often limits or compresses a participant's response and does not allow for worsening ratings once the higher end of the scale has been reached, thereby concealing any variation on a perceived state (Gonzalez-Fernandez *et al*., 2014). However, VAS offers a simple technique that can be quickly executed and allows for participants to select various dimensions of a stimulus (*e.g*. just comfortable, comfortable, very comfortable) without assigning an exact descriptor (*e.g*. the participant could report feeling between comfortable and very comfortable).

3.4.3 Calibration of Equipment

3.4.3.1 Thermistors

Calibration of thermistors occurred at the expected range of temperatures for T_c (36.0 °C to 40.0 °C at every 0.5 °C interval) and T_{sk} (30.0 °C to 40.0 °C at every 1.0 °C interval). The calibration process involved thermistors being held in a water bath set at the required temperatures and compared to a calibrated, certified precision thermometer (Digitron T600i, Electron Instruments Ltd, UK). The accepted deviation for rectal and skin thermistors was 0.1 °C and 0.2 °C respectively, outside these values, thermistors were not used.

3.4.3.2 Q-Sweat™

The Q-Sweat™ does not require a day-to-day calibration but the system was switched on 30 minutes before to warm-up in accordance with the manufacturers guidelines[8]. The external desiccant was replaced when required and a validation procedure was also conducted which involved checking that measures of temperature, humidity and flow rate were within acceptable ranges. The flow rate for Channels 1 and 3 were slightly higher than Channels 2 and 4 however we were advised by WR Medical Electronics Co. that the unit was functioning correctly as the test passed the temperature and humidity measures.

[8] Q-Sweat Hardware User's Guide, Version 1.4. Quantitative Sweat Measurement System, Model 1.0. WR Medical Electronics Co. 2001-2007

3.4.3.3 Laser Doppler Probes

Calibration of the laser Doppler probes took place once a day in Pinsent chamber (40.5 °C, 20 % rh), in the morning before experiments were underway, and included suspending the probes in a Probe Flux Standard solution (Moor Instruments, UK). The polystyrene microspheres of the solution undergo motion in water based upon temperature, which provides a reference for calibration of the lasers.

3.4.3.4 Gas Analyzer

A 2-point calibration of the gas analyzer (Rapidox 3100, Cambridge Sensotec, UK) was performed 15 minutes prior to the start of each test. Firstly, the analyzer was calibrated against outside ambient air for estimation of oxygen and carbon dioxide (assumed 20.93 % and 0.04 % respectively). Secondly, the analyzer was calibrated against a calibration gas of known certified quantities of oxygen (approximately 15 %) and carbon dioxide (approximately 5 %) (BOC Industrial Gases, UK). If required, these steps were then repeated until the readings were stable and accurate.

3.4.4 Experimental End-Points

During all four studies, participants ceased exercising and recovered, seated in the chamber if any of the following criteria were reached:

a) T_{re} exceeded 39.0 °C
b) T_{sk} reached 42.0 °C or the participant reported pain
c) Heart rate exceeded 10 beats less than their age predicted maximum (*i.e.* 210 - age)
d) The participant was unable to step in a controlled manner
e) The participant requested to rest
f) On the direction of the principal investigator

During all four studies, a participant was removed from the chamber, undressed and cooled if any of the following criteria were reached:

a) The maximum experiment time
b) T_{re} exceeded 39.5 °C
c) T_{re} reached 39.0 °C and continued to rise at a rate of 2.0 °C.hr^{-1}
d) T_{sk} exceeded 42.0 °C
e) The participant requested to withdraw
f) On the direction of the principal investigator

Any data collected from participants that were removed from the chamber early due to reaching a stopping criterion was not included in the study.

3.4.5 Statistics and Data Handling

The first three studies were of a repeated measures experimental design and required that CBRN clothing and protective equipment were donned. The potential benefits of an increased sweat production as a result of heat acclimation when exercising in a hot and dry environment appear to be reduced when wearing CBRN equipment as much of the protective equipment, particularly the ancillary items, are impermeable to moisture vapour and therefore any excess sweat produced is unable to contribute to evaporative cooling (McLellan & Aoyagi, 1996). However, to eliminate any order or acclimation effects, the order of conditions was controlled using a counter-balanced (for an odd number of conditions = 5 in the first three studies) Latin square design (Appendix 1) such that Condition 1 followed Condition 2 as frequently as Condition 2 followed Condition 1.

All statistical analyses were conducted either using Prism (Version 6, GraphPad, US) or SPSS (Version 22, IBM SPSS Statistics, US). Initially data were plotted for error checking with errors subsequently handled (Appendix 9). Column statistics were conducted to check whether data passed normal distribution with the D'Agostino and Pearson normality test when the sample size was large enough, which takes into account both the skewness and kurtosis of the distribution of the data, or with the Shapiro-Wilk normality test for smaller sample sizes. Depending on the number of variables tested, normally distributed interval data were then subject to either a one-way or two-way ANOVA with significant differences located using a Tukey *post-hoc* test with multiplicity adjusted p-values. Ordinal data (RPE) were subject to a factorial ANOVA with a condition (five) by time (three) comparison and *post-hoc* pairwise analysis was performed with a Bonferroni correction for multiple comparisons. During the third study, the Bland-Altman test was used to calculate the bias in LSR between conditions N1GF *vs*. N1GF2. For all statistical analyses presented, an alpha (α) value of $\alpha < 0.05$ was considered statistically significant. Unless otherwise stated, data are presented as mean (standard error of the mean [SEM]). As SD purely quantifies the scatter of the data, the SEM was chosen to quantify the deviation of the data from the value of the true population mean taking into account the value of the SD and the sample size and was chosen as a favourable method of representing data.

CHAPTER IV: THE THERMAL BURDEN OF PROTECTIVE EQUIPMENT WITH A LOWERING THERMAL LOAD

4.1 Background

Dstl, an executive branch of the UK's Ministry of Defence (MoD), are trying to reduce the thermal burden that is associated, particularly during exercise (Rissanen, 1998; McLellan *et al*., 2013b), with wearing CBRN IPE. Manikin studies conducted at Loughborough University (Havenith *et al*., 2013) involved a "walking" and wetted manikin dressed in varying CBRN IPE ensembles. The varying ensembles involved progressively removing one MVIP CBRN item from the manikin and obtaining the improved evaporative and thermal resistance measures before removing a second item and so on. The manikin results (Tables III and IV) showed reduced evaporative and thermal resistance when MVIP items were progressively removed. The aim of this first study was to determine whether making MVIP ancillary items (respirator, BA, gloves and overboots) more MVP would reduce whole body thermoregulatory strain in humans. To simulate making the items 100 % MVP, the item was not worn and a weight, equivalent to the mass of the removed item, was secured from the area where the item had been removed, thereby completely removing the evaporative resistance but without reducing the metabolic cost of moving whilst wearing the item. Although developing material that offers an adequate degree of protection and that is also 100 % MVP is most likely unachievable, should no practically significant thermal benefit have been found during this investigation when we simulated making items 100 % MVP, then developing new materials that would be less than 100 % MVP would be of little benefit.

Dstl requested that the human studies expressed in this chapter followed a similar methodology to the manikin studies conducted at Loughborough (Havenith *et al*., 2013); particularly that ancillary items were progressively not worn during each condition, thus lowering the thermal load between conditions. Therefore the first condition would involve wearing the full CBRN ensemble, the second condition as the first but without wearing the respirator, the third condition as the second but without wearing the BAL[9] and so on (Table VI). It was recommended to Dstl that the thermal load upon the body should be

[9] Actual body armour was not worn in the current study, as when removed approximately 10 kg to 15 kg would have to be carried at the level of the torso, which would be impractical without covering a large area of the torso with load carriage equipment. Therefore soft armour liners weighing approximately 170 g made from an impermeable woven nylon (polyurethane blend with a thermoplastic polyurethane coating) were used to mimic the impermeability of body armour without matching the weight of actual body armour.

maintained throughout all conditions to more accurately quantify the individual thermal burden of each individual ancillary item. Therefore, items should be assessed in isolation to each other and then replaced for the next condition. Thus, the first condition would involve wearing the full CBRN ensemble, the second condition as the first but without wearing the respirator, the third condition as the first but without wearing the BAL and so on (Chapter 5, Table IX). However, this methodology would then not allow for direct comparison with the manikin studies which Dstl were most concerned with. Therefore, two studies were conducted, the first (Chapter 4) quantified the thermal burden of each ancillary item whilst the thermal load placed upon the participant was progressively lessened between conditions (as requested by Dstl), and the second (Chapter 5) quantified the thermal burden of each ancillary item whilst the thermal load placed upon the participant was maintained as items were not worn in isolation.

4.1.1 Preliminary Manikin Tests

Havenith *et al*. (2013) used the thermal manikin 'Newton' that has 32 independent electrically heated body segments. The manikin (suspended off the floor in an upright position) was motorized to move in a "walking" manner at 45 double steps.min^{-1}. Initially the manikin was dressed in a full CBRN protective ensemble consisting of a hooded jacket and trouser combination, MVIP respirator, BA, MVIP gloves and MVIP overboots. Measures of heat resistances, vapour resistances and vapour permeability index were calculated during a series of clothing variations which involved progressively removing one item from the manikin. The manikin's surface temperature was electronically set to 34 °C for calculation of both dry and evaporative heat measurements. The manikin's skin (absorbent, tight-fitting material) that was extended to the hands, feet and face with cotton gloves, socks and a balaclava respectively was wetted (with distilled water [dH_2O]) to simulate sweating during evaporative heat resistance calculations.

For calculation of dry heat resistance (without skin wetting), the environment was set to 20 °C, 50 % rh with a wind speed of 0.5 m.s^{-1}. By controlling the manikin's surface at 34 °C and the ambient temperature at 20 °C, an estimation of the dry heat resistance of the clothing can be calculated from the amount of heat required to maintain the T_{sk} at 34 °C using the following equation:

$$\text{Dry heat resistance} = (T_{sk} - T_{ambient}) / \text{dry heat loss } [m^2.K.W^{-1}]$$

For evaporative heat resistance the environment was set to 34 °C, 50 % rh and a 0.5 $m.s^{-1}$ wind speed. The environmental temperature was elevated compared to the dry heat resistance tests to match that of manikin surface temperature (34 °C) thereby eliminating (or minimizing as far as possible if the temperature varied slightly from 34 °C) dry heat loss and more accurately measuring only the evaporative heat loss using the following equation:

$$\text{Vapour resistance} = (P_{sk} - P_a) / \text{evaporative heat loss } [m^2.Pa.W^{-1}]$$

Where: evaporative heat loss = total measured heat loss – dry heat loss

A vapour permeability index (i_m) can be calculated in an attempt to simplify complex heat transfer equations and provides an indication of the capacity for a material to transfer water vapour (sweat). The Woodcock (1962) equation for calculating i_m is as follows:

$$i_m = h_e / (L \text{ x } h_c)$$

Where: h_e is the evaporative heat transfer coefficient ($W.m^{-2}.kPa^{-1}$)
h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$)
L is the Lewis constant (16.7 $°C.kPa^{-1}$)

This is a dimensionless value ranging from 0, indicative of an impermeable material, to 1, indicative of a completely permeable material. However, as there is no radiative component in the equation, typical values of 0.5 for a nude participant are obtained with 0.4 for normal clothing and 0.2 for MVIP type clothing (Parsons, 1993).

The radiative and convective components can be separated using the equation from ISO 9920 (Havenith *et al*., 1990):

$$R_T = I_T / (i_m \text{ x } L) \text{ therefore, } i_m = I_T / (L \text{ x } R_T) = h_e / (L \text{ x } h_{tot})$$

Where: R_T is the vapour resistance of the clothing ($m^2.kPa^{-1}.W^{-1}$)
I_T is the clothing insulation including air layers ($m^2.°C.W^{-1}$)
h_e is the evaporative heat transfer coefficient ($W.m^{-2}.kPa^{-1}$) and $h_e = 16.7 \text{ x } h_c$
L is the Lewis constant (16.7 $°C.kPa^{-1}$)
h_{tot} is the total heat transfer coefficient ($W.m^{-2}.K^{-1}$) where $h_{tot} = h_c + h_r$

Manikin data (Table III) showed that heat and vapour resistance were reduced and vapour permeability increased when the torso BA and MVIP overboots were removed and MVIP gloves were replaced with air permeable gloves compared to a full-dressed state (Havenith *et al*., 2013).

Table III: Heat resistance, vapour resistance and vapour permeability index measures from a manikin dressed in a protective suit whilst wearing progressively less moisture vapour impermeable items (Havenith *et al*., 2013).

Condition	**State of Dress**	**Heat Resistance ($m^2.K.W^{-1}$)**	**Vapour Resistance ($m^2.Pa.W^{-1}$)**	**Vapour Permeability Index (nd)**
1	**Full Dress (suit + body armour + MVIP gloves + MVIP overboots)**	0.204	46.3	0.27
2	**As Condition 1 but without body armour**	0.189	38.0	0.30
3	**As Condition 2 but with air permeable gloves (instead of MVIP gloves)**	0.191	33.6	0.34
4	**As Condition 3 but without MVIP overboots**	0.188	31.5	0.36

Note that these data were representative of the whole manikin body with the exclusion of the head (body surface area of 1.66 m^2 and are presented per m^2).

Table III shows that on the manikin, removing the torso BA resulted in the greatest reduction to whole body (excluding the head) heat resistance by 0.015 $m^2.K.W^{-1}$ (7.35 %) and vapour resistance by 8.3 $m^2.Pa.W^{-1}$ (17.93 %) compared to removal of the MVIP overboots (heat resistance: 0.003 $m^2.K.W^{-1}$ [1.57 %], vapour resistance: 2.1 $m^2.Pa.W^{-1}$ [6.25 %]) or substitution of the MVIP gloves with prototype gloves that are air permeable (gain in heat resistance: 0.002 $m^2.K.W^{-1}$ [1.06 %], reduction in vapour resistance: 4.4 $m^2.Pa.W^{-1}$ [11.58 %]). The results highlighted that when the BA was removed, there were large reductions to whole body (excluding the head) heat and vapour resistances even though the manikin was still dressed in the CBRN suit. The main explanation for this improvement could be that the surface area of the front and back torso of the manikin equated to approximately 26 % of the manikin surface area excluding the head (Havenith *et al*., 2013).

The manikin results also showed the vapour resistance imposed when the hands were covered, as when the MVIP gloves were replaced with the air permeable gloves, there was a reduced whole body (excluding the head) vapour resistance of 11.58 % and an improved vapour permeability index of 0.04 (13.33 %), even though the surface area of both hands equated to only 4.9 % of the total manikin surface area (Havenith *et al*., 2013). When the MVIP gloves were replaced with the air permeable gloves, vapour resistance was reduced by 310.3 $m^2.Pa.W^{-1}$ (93 %) at the hands, however as the surface area of the manikin hands is only 0.088 m^2, the whole body (excluding the head) reduction to vapour resistance when the MVIP gloves were replaced with the air permeable gloves was by 11.58 % (Appendix of Havenith *et al*., 2013). If removing the gloves also alleviated approximately 10 % of whole body thermoregulatory strain in the human studies, then practically this would be of interest to Dstl who could develop new gloves for warfighters most likely with a quicker turn around time than redeveloping a more permeable BA. The manikin results also showed that compared to removing the BA or substituting the MVIP gloves for the air permeable gloves, removing the MVIP overboots marginally reduced whole body (excluding the head) heat resistance by 1.57 %, reduced vapour resistance by 6.25 % and improved the vapour permeability index by 0.02 (5.88 %) compared to Condition 3 when the MVIP overboots were worn. Again the sponsor could then focus on technical development of other items such as the gloves rather than spending resources on developing the overboots that may have little whole body impact, particularly as when the overboots are not worn, combat boots and socks are still worn.

Due to Loughborough’s manikin design, separate upper torso measurements that included critical data on the impact of the hood and respirator were measured independently from the rest of the body measures. This is because the manikin had to be stationary and seated in a wheelchair (parts of which are impermeable) to obtain accurate head measures as normally the manikin was suspended from the ceiling by mounts on the head and neck thus making it impossible to wear the full CBRN IPE correctly (Havenith *et al*., 2013). These upper torso measures were then added to the rest of the measures to obtain a whole body value. Of note, the cables to collect the head data exited through the eyeglasses of the respirator, although the exit ports were taped to prevent air leakage. Furthermore, the face of the manikin was only partially covered by the skin, to allow for cable attachment, although evaporative heat loss measures were corrected by adding 25 % to the nude skin condition, which was equivalent to the amount of non-covered surface area at the face (Havenith *et al*., 2013). Whole body data, including the head, are presented in Table IV.

Table IV: Heat resistance, vapour resistance and vapour permeability index measures from a manikin data dressed in a protective suit whilst wearing progressively less moisture vapour impermeable items (Havenith *et al*., 2013).

Condition	State of Dress	Heat Resistance ($m^2.K.W^{-1}$)	Vapour Resistance ($m^2.Pa.W^{-1}$)	Vapour Permeability Index (nd)
1	**Full Dress (suit + respirator & hood + body armour + MVIP gloves + MVIP overboots)**	0.206	48.3	0.26
2	**As Condition 1 but without respirator, hood down**	0.182	40.0	0.28
3	**As Condition 2 but without body armour**	0.170	34.0	0.30
4	**As Condition 3 but with air permeable gloves (instead of MVIP gloves)**	0.171	30.7	0.34
5	**As Condition 4 but without MVIP overboots**	0.169	29.0	0.35

Note that these data were representative of the whole manikin body with the inclusion of the head (body surface area of 1.81 m^2 and are presented per m^2).

Table IV shows that when encompassing head measurements, removing the respirator and hood in combination resulted in the greatest reduction to whole body heat (0.024 $m^2.K.W^{-1}$ [11.65 %]) and vapour resistance (8.3 $m^2.Pa.W^{-1}$ [17.18 %]) measures as well as an improved vapour permeability index (0.02 [7.69 %]) compared to when the hood and respirator were worn (Condition 1). The results showed that the respirator and hood accounted for almost twice the overall heat resistance as that of BA (reduction to heat resistance of 0.012 $m^2.K.W^{-1}$ [6.6 %]) even though the manikin surface area of the torso is approximately three times the surface area of the head and face. When the BA was removed, heat resistance was reduced by 0.183 $m^2.K.W^{-1}$ (32 %) at the torso and when the respirator was removed, heat resistance was reduced down to a very low value of 0.060 $m^2.K.W^{-1}$ at the face. This is because when the hood and respirator were removed, the surface of the manikin's head was completely exposed (naked) to the environment, however when the BA was removed, the torso was still covered by the protective suit and t-shirt. These results highlight the high burden imposed by the suit itself irrespective of the ancillary items worn, which has been shown in other studies with human participants wearing chemical protective clothing (Caretti, 2002). The respective contributions from either the hood or respirator in isolation on whole body thermal indices are unknown as the items were removed in combination, although as the respirator is MVIP, this may have imposed a greater thermal burden than the hood, which possesses low air permeability. Furthermore, manikin data (Appendix of Havenith *et al*., 2013) showed the evaporative resistance at the face when the respirator and hood were worn was 2.4 times greater than the evaporative resistance at the head (which included the face). Therefore, improving the permeability of the respirator could greatly reduce thermoregulatory strain in the human.

Based upon the whole body manikin results, it can be estimated that the thermal insulation of the entire protective ensemble is 0.206 $m^2.K.W^{-1}$ equating to 1.33 Clo and when only the suit (hood down), t-shirt, undershorts, socks, combat boots and air permeable gloves are worn, the thermal insulation is improved by 18 %, that being 0.169 $m^2.K.W^{-1}$ equating to 1.09 Clo. However, the larger thermal burden imposed by this CBRN protective ensemble is associated with the vapour restrictive material, and the thermal burden imposed is therefore made apparent during exercise when the evaporation of sweat is limited by the ensemble. For example, improving the MVP of all items (respirator, hood, BA, MVIP gloves and overboots) would reduce whole body vapour resistance by 40 % (19.3 $m^2.Pa.W^{-1}$).

In summary, when the head data were excluded and the manikin was walking, removing the BA reduced whole body (excluding the head) vapour resistance to the greatest degree (17.93 %) compared to replacing the MVIP gloves with air permeable gloves (11.58 %) or removing the overboots (6.25 %). To calculate heat and vapour resistances for the head, the manikin was seated stationary as the fixation points for the manikin that enabled walking interfered with the headgear. These head data were then added to the rest of the body measures to give whole body values. Therefore, when considering the whole body, removing the respirator and hood in combination resulted in the greatest reduction to vapour resistance (17.18 %), although the contribution of the respirator alone was not calculated. Removing the BA resulted in a 15.0 % reduction to whole body vapour resistance, whilst replacing the MVIP gloves with air permeable gloves reduced whole body vapour resistance by 9.71 % and removing the overboots resulted in the least reduction to whole body vapour resistance (5.54 %). Thus, the order of improvement when the head was excluded (BA > gloves > overboots) was unchanged when the head was included (respirator > BA > gloves > overboots). Therefore, if the human tests show similar results then Dstl should consider improving the MVP of the respirator, BA or gloves primarily, rather than the overboots.

4.1.2 Manikin Versus Human Data

Obtaining data from manikin studies is a widely used method for estimation of clothing heat and vapour resistances and the data are considered reproducible, highly accurate and can be used to predict the likely effects in humans (McCullough, 2005; Havenith, 1999). Conducting human studies provides final confirmation that any advantages identified in physical tests on manikins result in human benefits with their thermoregulatory systems governed by the hypothalamus (*i.e.* they are regulated systems which are simplified in thermal manikins). Unlike manikins, the human thermoregulatory system adjusts circulatory measures (heart rate, Q, SkBF) and alters sweat output based upon afferent input (Nielsen & Nielsen, 1965; Åstrand & Rodahl, 1977). The preference of using human studies over using manikins becomes apparent when attempting to replicate human-like movement, when determining clothing insulation indices based on differing anthropomorphic measures between humans, when considering different sizes and fit between humans as opposed to a one-size manikin and when requiring perceptual data (Havenith, 1999).

Perceptual data from humans rarely correlates directly to surface area as highlighted by the somatosensory homunculus (Penfield & Boldrey, 1937; Figure 3). Furthermore, Cotter and Taylor (2005) found that the face displayed a greater thermal sensitivity compared to other areas of the body. Information on the variation in local thermal perceptions is important in a study that partitions certain areas such as the current study. Evidence from Scanlan and Roberts (2001), who conducted research on the S10 military respirator (standard, negative pressure respirator[10]), showed that the respirator inhibited evaporative cooling of the face and this resulted in a perceived heat stress (increased thermal discomfort) that was greater than the physiological response (T_{re} or heart rate) perhaps due to an increased temperature and humidity within the mask during exercise and increased facial skin wettedness (Gwosdow *et al*., 1989). Therefore, it was of additional interest in this study to determine whether any perceptual benefits of not wearing a respirator would outweigh any physiological reductions to thermoregulatory strain.

Physiologically, there are several limitations to using manikins as opposed to humans, for example: the manikin's skin was only wetted once after which the manikin was clothed, which is not indicative of the human sudomotor response which is continual and changes based upon afferent thermosensory input (Benzinger, 1959). Thus, the actual evaporative resistance might have been overestimated in the manikin tests as, once all the dH_2O was evaporated from the skin, no further evaporation took place. Furthermore, manikins also do

[10] A negative pressure respirator is tight fitting and, upon inhalation, creates a negative pressure inside the mask compared to the outside pressure.

not possess functioning sweat glands, which display regional variations in densities for example in the human, the torso exhibits intermediate densities of sweat gland distribution compared to higher densities at the hands and feet with lower densities at the legs (Taylor & Machado-Moreira, 2013). In addition, regional variations in sweat gland densities have prompted further research into intra-segmental distribution of sweat secretion such as in the torso (Machado-Moreira *et al*., 2008). Manikins also do not possess complex thermoregulatory systems that consider regional vasomotor and sudomotor sensitivity (Cotter & Taylor, 2005; Machado-Moreira *et al*., 2008; Smith & Havenith, 2011; Caldwell *et al*., 2014). Therefore, the current study was conducted to determine whether the benefits of decreased heat and vapour resistance found using manikins translated to improved human physiological and perceptual thermoregulatory strain.

4.2 Research Aims

The aims of this study were to:

4.2.1 Quantify the reduction in thermoregulatory strain for each MVIP ancillary item during exercise and recovery in a hot and dry environment, by progressively not wearing items as follows:

a. Respirator
b. BA as represented by a MVIP BAL
c. MVIP gloves with cotton liners
d. MVIP overboots

when worn with a CBRN suit over a t-shirt, undershorts, socks and combat boots.

4.2.2 Quantify the reduction in perceived thermoregulatory strain for each MVIP ancillary item when items were progressively not worn during exercise and recovery in a hot and dry environment whilst wearing a CBRN suit, t-shirt, undershorts, socks and combat boots.

4.3 Hypotheses

The general null hypothesis (H_0) was as follows:

$\boldsymbol{H_{01}}$: When exercising at a light intensity in hot and dry conditions, thermoregulatory strain would not decrease when any of the MVIP items (respirator, BAL, MVIP gloves or MVIP overboots) were not worn.

Various experimental hypotheses (H_a) were tested as stated below:

$\boldsymbol{H_{a1}}$: When exercising at a light intensity in hot and dry conditions, thermoregulatory strain would decrease when any of the MVIP items (respirator, BAL, MVIP gloves or MVIP overboots) were not worn.

$\boldsymbol{H_{a2}}$: Considering individual item removal:

a. The greatest decrease to thermoregulatory strain would occur when the MVIP torso BAL was not worn.
b. The least change in thermoregulatory strain would occur when the MVIP overboots were not worn.

$\boldsymbol{H_{a3}}$: When not wearing the respirator, the decrease in perceived thermoregulatory strain would be greater than the decrease in physiological thermoregulatory strain.

4.4 Methods

4.4.1 Research Design

Several pilot studies were conducted to develop the experimental design (Appendix 4). The aims of the pilot studies were to identify a thermal stress that would maximally differentiate between conditions by challenging participants sufficiently in one single condition but would not overwhelm them in another condition. Therefore, the ideal experimental design would have periods of exercise and resting recovery where stopping limits were reached just at the end of the most burdened condition, but would still challenge participants in the least burdened condition. Additionally, it was important that the work intensities and durations chosen were representative of actual thermal loads that are of operational relevance for the end user as well as providing an adequate driving force to elicit a response. To provide a significant thermal load with a favourable gradient for water vapour exchange to maximize evaporative cooling and thus the impact of removing the evaporative burden from items, an ambient environment of 40.5 °C and 20 % rh was selected, this also represented mean conditions between 08:00 and 21:00 for countries in the Defence Standard A2, hot and dry, category[5]. A progressively increasing workload design (Table V) was undertaken that allowed for varying rates of metabolic heating during exercise, and cooling during recovery to maximally differentiate between conditions should any differences exist. Participants completed the experimental protocol or were stopped early when reaching an end-point during Work 3 (General Methods: Section 3.4.4).

Table V: The experimental protocol to allow for calculations of rates of heating and cooling as well as to optimise the detection of differences between conditions.

Section	Time (minutes)	Percentage of time working	Workload
Baseline	0-10	0 %	Rest
Work 1	10-30	50 %	2 minutes work + 2 minutes recovery cycles
Recovery 1	30-50	0 %	20 minutes resting recovery
Work 2	50-70	75 %	3 minutes work + 1 minute recovery cycles
Recovery 2	70-90	0 %	20 minutes resting recovery
Work 3	90-150	100 %	Continuous exercise
Recovery 3	150-170	0 %	Resting recovery

The study consisted of a five-condition, repeated measures design with participants (n = 12) stepping lightly (average $\dot{V}O_2$ of approximately 13.5 $mL.kg^{-1}.min^{-1}$). Exercise was interspersed with 20-minute resting recovery periods (Table V), and took place in a hot, dry environment for a maximum of 170 minutes. The actual environmental conditions achieved were mean (SD): 40.23 (0.59) °C (dry bulb), 23.33 (0.71) °C (wet bulb) equating to approximately 26.8 % rh. There were no significant differences in environmental parameters between conditions ($p > 0.05$). Conditions varied in which MVIP items were worn (Table VI).

Table VI: The varying combinations of moisture vapour impermeable items worn.

Condition	Clothing				
	Suit + Hood	MVIP Overboots	MVIP Gloves	BAL	Respirator
SOGAR	✓	✓	✓	✓	✓
SOGA	✓	✓	✓	✓	✕
SOG	✓	✓	✓	✕	✕
SO	✓	✓	✕	✕	✕
S	✓	✕	✕	✕	✕

Note that a tick indicates the item was worn whereas a cross indicates the item was not worn.

Twelve fit and free from injury male participants volunteered from the University of Portsmouth's staff and student population. The participants' age, height, body mass, and percentage of body fat were: mean (SD) 21.7 (2.9) years, 178.9 (4.5) cm, 77.6 (13.6) kg, 15.3 (3.7) % respectively. Participants were weighed nude and clothed before and after the experiment and were instrumented with a rectal thermistor, ECG and heart rate monitor, skin thermistors at the calf, thigh, arm, chest for calculation of $\overline{T}_{sk}$ and at the finger and cheek (General Methods: Section 3.4.2). Participants rested seated for ten minutes before the commencement of exercise (Table V). During exercise periods, participants stepped to a height of 22.5 cm at a rate of 12 steps.minute^{-1} at varying work ratios interspersed with recovery periods (Table V). Perceptual measures (RPE, whole body thermal comfort, thermal sensation and skin wettedness) were taken once, toward the end of each work and recovery period and every 20 minutes during Work 3 as well as initially upon entry into the chamber to obtain baseline measures (General Methods: Section 3.4.2.11). Participants were provided with 250 mL of moderately chilled water (approximately 15 °C) every twenty minutes as water at this volume, temperature and timing results in the greatest volitional intake without greatly affecting thermoregulatory measures (Szlyk *et al*., 1989; Siegel *et al*., 2010) and was most likely to not result in dehydration as classified as a body mass loss > 4 % (Costill & Sparks, 1973). Other possible hydration strategies are presented in Appendix 6.

Due to the cumulative removal of MVIP items as conditions progressed (Table VI), to assess the thermal burden of each item individually, each condition was compared to the condition that directly preceded it (adjacent conditions). For example, to quantify the thermal burden of the gloves only, SO was compared against SOG only and not SOGA or SOGAR. The conditions were not necessarily undertaken in the order presented in Table VI but were counter-balanced to avoid any order effects (Appendix 1). The advantage of using these combinations of CBRN IPE was that it largely replicated the manikin study conducted by Havenith *et al*. (2013). This design also allowed for quantification of a cumulative removal effect *i.e*. what the thermal benefit would be if all the items were made completely MVP.

For every item that was not worn, a weight equivalent to the mass of that item was secured at the area where it was removed so that any differences found could solely be attributed to an improved MVP at the site, not merely due to a lowered metabolic heat production due to not wearing the item. For example when the overboots were not worn, weights (0.505 kg each – size L) were added to the combat boots of the participants. Other weights included: MVIP gloves (0.124 kg outer glove size 8, 0.044 kg inner cotton liner size 10) added to the wrists, BAL (0.176 kg, size M) placed in the front jacket pocket, and the respirator (0.847 kg, size 3) that was added to the torso. Adding any weights (which were MVIP) to the head presented a practical challenge by reducing the area available for efficient vapour exchange, thus the weights were placed in the front pockets of the suit at the torso region. Indeed a large load (for example 14 kg) carried on the head can induce postural muscle activation and a leverage effect, raising the metabolic energy cost by as much as 25 % compared to 14 kg carried on the torso (Soule & Goldman, 1969). However the weight of the respirator in this study was only 0.847 kg (size 3) and the design of the respirator is such that minimal leverage is induced upon the neck of the wearer, therefore the weights were added to the torso pockets.

It was imperative to balance the weight correctly at the extremities where the range of motion was greater than at the torso and therefore would impose a significant effect on energy expenditure during stepping (Soule & Goldman, 1969; Dorman & Havenith, 2005). For example, when a 4 kg weight was added to either the torso, wrists or the feet, during a task (walking and obstacle course) the metabolic rate significantly increased by ~ 6 %, ~ 10 % and ~ 10 % respectively compared to an un-weighted condition (Dorman & Havenith, 2005). Expired air was sampled to assess whether $\dot{V}O_2$ was similar between conditions (General Methods: Section 3.4.2.6) as the workload between conditions should have been equal due to the matched weight.

4.4.2 Alterations to Protective Equipment

The primary aim of this study was to assess the thermal burden that each MVIP item imposed on the body during exercise in hot, desert-like conditions. Thus, for various reasons described below, a few alterations to the military protective kit were implemented:

i. Load Carriage

Participants were not required to carry the same load as military personnel would in the field as this would require a rucksack and / or weighted webbing to be carried upon the torso of the participant. The rucksack and parts of the webbing provide a barrier to sweat evaporation, which would introduce a bias to the results particularly when measuring the thermal burden of the BAL. Furthermore, carrying the additional weight of a rucksack or loaded webbing would increase metabolic heat production. The graph below from McLellan *et al*. (2013b) illustrates that the difference in TT under varying environmental thermal loads were amplified when the metabolic rate was lower. At lower metabolic rates TT, representing the rate of metabolic heat storage, was largely influenced by the environment whereas at higher metabolic rates the rate of heat storage was mostly influenced by metabolic heat production, primarily because of the time taken for secreted sweat to be evaporated after passing through the CBRN clothing. Therefore, if the body were covered entirely with MVIP material then it is predicted that the curve as represented in Figure 6 would flatten and TT would be solely dependent upon metabolic rate (McLellan *et al*., 2013b). Thus, it was important to keep the metabolic rate in our study low enough to detect differences between conditions, but high enough to still impose a thermal challenge even in the lightest dressed condition.

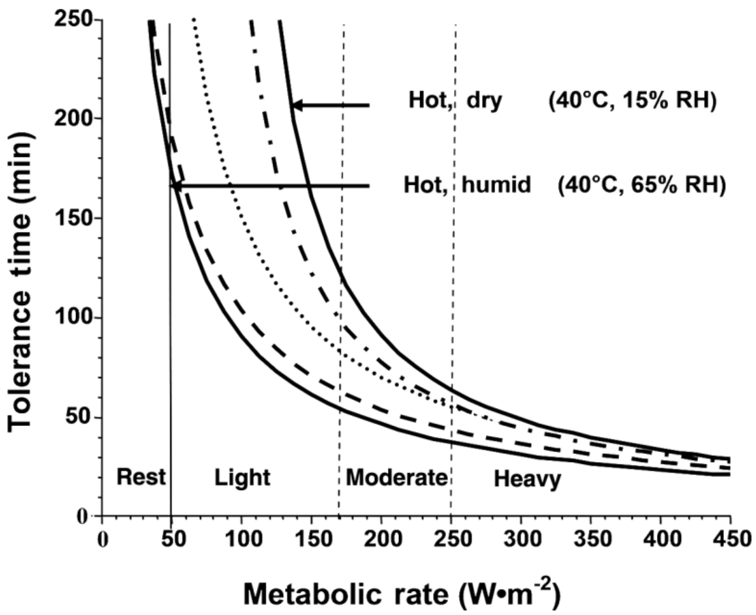

Figure 6: The relationship of metabolic rate and tolerance time under varying environmental conditions whilst wearing a Canadian nuclear, biological and chemical protective ensemble (McLellan *et al*., 2013b). Data from McLellan (1993) are represented by the solid lines, data from McLellan *et al*. (1993b), McLellan *et al*. (1992) and McLellan *et al*. (1996) are represented by the dotted lines.

ii. Body Armour

As mentioned, actual BA was not used, as when the BA was not worn in a condition, securing 10 kg to 15 kg to the torso would have been impractical without making a large area of the torso MVIP. Therefore, a lightweight (170 g) soft armour MVIP liner was used to mimic the impermeability of BA but without matching the weight and when this item was removed, a weight of only 170 g needed to be secured to the torso. Furthermore, carrying the additional weight of BA would increase the metabolic heat production only during the conditions when the BA was worn and therefore, not only would the percentage of the body covered with MVIP materials differ between conditions, but also the metabolic heat production. This would make it difficult to determine the exact benefit of improving only the MVP of the BA.

iii. Respirator

To truly assess only the thermal burden associated with wearing the respirator, the absorbent carbon contents were removed from the respirator filter canisters to minimize the inspiratory resistance normally associated with the filters.

4.4.3 Alterations to Manikin Studies

This human study involved a few differences from the manikin studies conducted by Havenith *et al*. (2013) as described below:

i. Hood

The manikin studies involved removal of the hood and respirator in combination. This study removed only the respirator and left the hood up in all conditions. This allowed for accurate quantification of the thermal burden of the respirator alone. Furthermore, when donning a respirator the hood would always be up.

ii. Removal of MVIP Gloves

When the MVIP gloves were removed from the manikin, the subsequent conditions involved wearing prototype, air permeable gloves with leather patches for protection. In the current study, when the MVIP gloves were not worn, the hands were left naked to the environment. This was to simulate the most advantageous situation possible of a theoretical 100 % MVP glove.

iii. Rigidity of the Liner

The reason for using the soft armour liner has been stated above, however during the manikin tests, actual BA was used. Although the impermeability of the torso cover was of most importance, by not using rigid armour there may have been dissimilar convective air currents within the microclimate that could have impacted on whole-body heat loss between the manikin and human studies. However, as the BA (manikin test) or BAL (human tests) was worn over the CBRN suit the effects of this are likely to be minimal.

iv. Neck Collar

A neck collar accompanied the BA when placed on the manikin. During the current study, the soft armour liner covered only the torso, leaving the neck to be covered only by the suit. This was less of a problem in that the neck collar was “open” and most likely did not prevent airflow to the face during the manikin tests, however, by wearing the neck collar an additional layer of protection was worn that may have slowed any evaporative cooling from the neck had it been worn during the human studies.

4.4.4 Experimental Protocol

All ethical considerations, environmental chamber conditions, experimental procedures prior to testing, measurements and calibrations, data calculations, experimental end-points and general statistical analyses are described in detail in Chapter 3: General Methods.

4.4.5 Data Representation

Figure 7 shows that as not all of the participants completed the final 60 minutes of stepping during Work 3, the graph produced a jagged appearance indicating where individual participants reached one of the stopping criteria (General Methods: Section 3.4.4) and had to cease stepping thus affecting the mean by causing a small step-change.

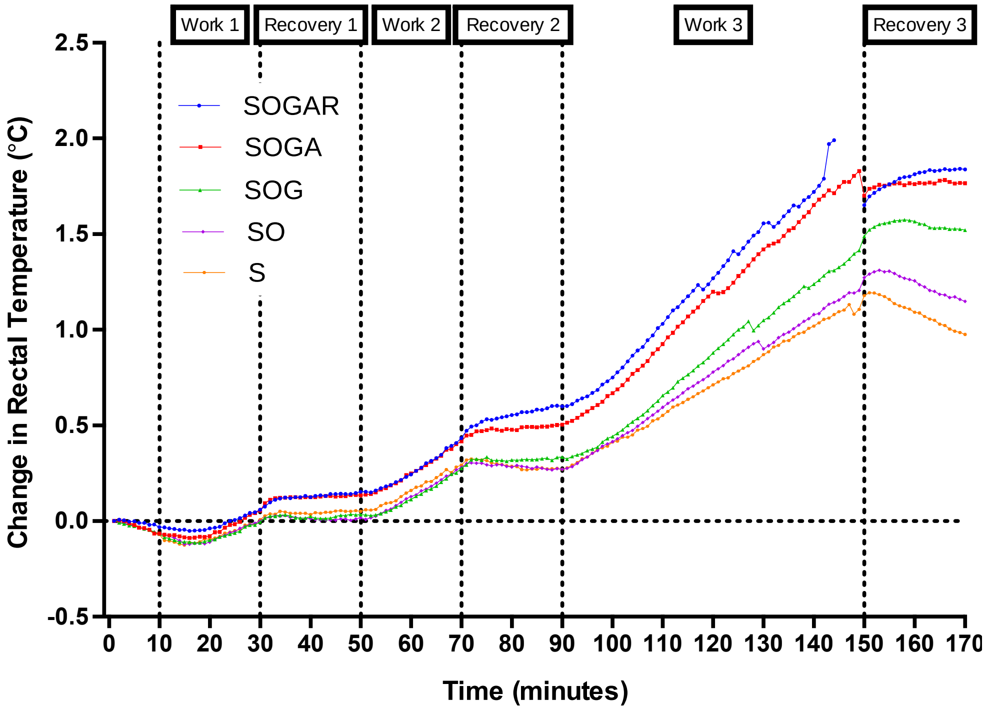

Figure 7: Mean change in rectal temperature during each condition throughout the protocol in a chamber set to 40.5 °C and 20 % rh air (n = 12).

The jagged appearance of Figure 7 does not allow for immediate and accurate estimation of mean TT trends or rates of change and therefore representing all subsequent graphs in that way might have provided an unclear and confusing representation of the data upon initial scan of the graph. Therefore, subsequent data for the first and second studies were represented until the point when the first participant ceased stepping during each condition (Figure 8) due to reaching a stopping criterion (General Methods: Section 3.4.4).

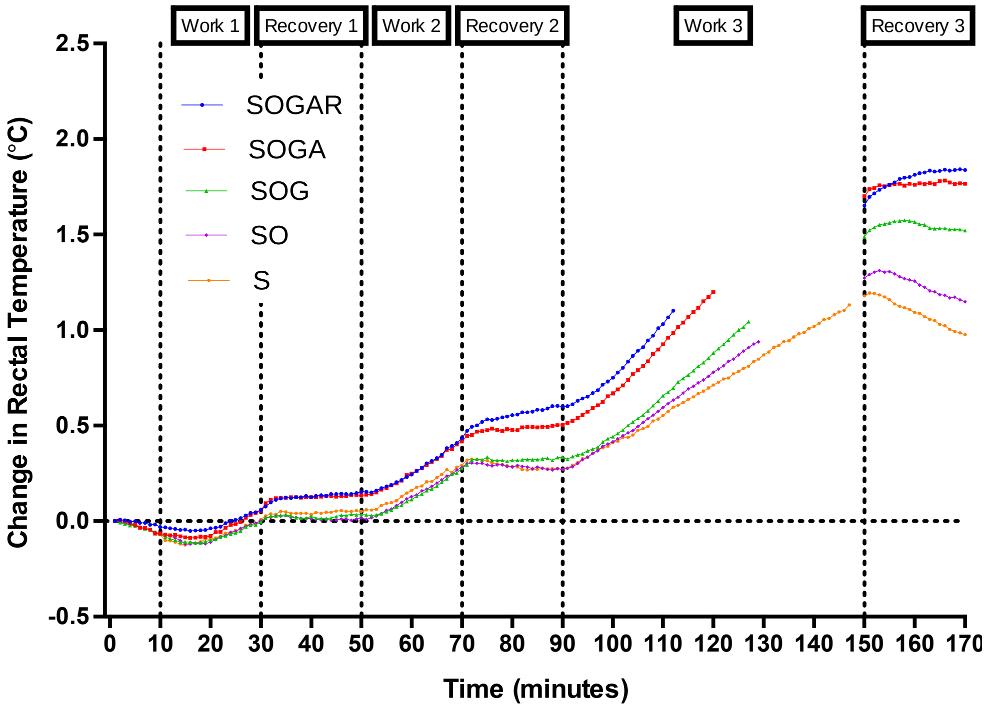

Figure 8: Mean change in rectal temperature during each condition indicating the time point during Work 3 where the first participant ceased stepping in a chamber set to 40.5 °C and 20 % rh air (n = 12).

Figure 8 illustrates the last point at which n = 12 for each condition. Presenting data in this way provides the maximum amount of descriptive information for the reader however, as ANOVA calculations require equal amounts of data points for each condition, data had to be curtailed at the time point that n = 12 in all conditions. This point occurred at 110 minutes into the protocol and data were statistically analyzed every 10 minutes from 0 minutes until 110 minutes only. All participants (n = 12) completed a final 20 minutes of recovery post-Work 3. Direct comparisons at discrete time intervals during Recovery 3 could not be made without introducing a bias into the results as participants spent varying durations in the chamber before reaching Recovery 3. For variables where data were approximately linear the hourly rates of change were calculated based upon the individual rate of rise from 10 minutes into the work period onwards or the individual rate of fall from 10 minutes into the recovery period onwards. When data were not linear during Recovery 3, the change in recovery (rΔ) data were calculated for the final 10 minutes of Recovery 3. Additionally, using the rates of change of T_{re} during Work 3, as these data were approximately linear, for those participants that stopped stepping before 150 minutes, the final T_{re} at 150 minutes could be predicted.

4.5 Results

4.5.1 Oxygen Uptake

There were no significant differences in the mean $\dot{V}O_2$ between any of the conditions except during Work 1 when the respirator was not worn (SOGA) and the mean $\dot{V}O_2$ was 1.58 $mL.kg^{-1}.min^{-1}$ greater compared to when the respirator was worn during SOGAR (mean [SEM]: 12.63 [0.45] $mL.kg^{-1}.min^{-1}$ *vs*. 11.05 [1.13] $mL.kg^{-1}.min^{-1}$, $p < 0.001$).

4.5.2 Tolerance Time

Mean predicted and actual TT and T_{re} are displayed in Table VII below. Details of participant TT and reasons for stopping early are presented in Appendix 5.

Table VII: Participant completion data with the number of participants completing the protocol, mean (SEM) work tolerance times during Work 3 for each condition, mean (SEM) predicted tolerance time to a rectal temperature of 39.5 °C and 40 °C, the mean (SEM) predicted rectal temperature if Work 3 was completed whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{****}p < 0.0001$ *vs*. adjacent condition.

Condition	**Number of Participants who Completed the Protocol (n = 12)**	**Mean (SEM) TT during Work 3 (minutes)**	**Mean (SEM) Predicted Experimental TT to a T_{re} of 39.5 °C (minutes)**	**Mean (SEM) Predicted Experimental TT to a T_{re} of 40 °C (minutes)**	**Predicted Mean (SEM) T_{re} if Work 3 was completed (°C)**
SOGAR	0	40.5 (2.9)	151.3 (2.9)	168.3 (3.1)	39.5 (0.1)
SOGA	4	48.8 (3.3)*	161.4 (4.1)	180.5 (4.4)*	39.2 (0.1)****
SOG	9	56.8 (2.0)	182.1 (5.4)**	204.7 (6.2)**	38.8 (0.1)****
SO	10	58.2 (1.7)	208.3 (9.9)	237.8 (12.0)	38.6 (0.1)****
S	11	59.8 (0.2)	236.8 (14.2)*	273.0 (18.0)*	38.4 (0.1)****

Not wearing any of the ancillary items (respirator, BAL, gloves or overboots; Condition: S) resulted in the greatest number of participants completing the protocol, whilst no participants completed the protocol when wearing the full CBRN ensemble (SOGAR). An additional five participants completed the protocol when the BAL was not worn (SOG) compared to when it was worn (SOGA) whilst only one additional participant completed the protocol when the gloves were not worn (SO) and when the overboots were not worn (S).

When comparing against adjacent conditions, mean TT during Work 3 was extended by 8.3 minutes (20.5 %) when the respirator was not worn (SOGA) compared to when the respirator was worn during SOGAR (158.8 (3.3) minutes *vs*. 150.5 (2.9) minutes, $p < 0.05$).

The predicted TT to reach a T_{re} of 39.5 °C was significantly improved when not wearing the BAL by 20.7 minutes (12.8 %, $p < 0.01$) compared to SOGA. The predicted TT to reach a T_{re} of 39.5 °C was significantly improved when not wearing the overboots by 28.5 minutes (13.7 %, $p < 0.05$) compared to SO.

The predicted TT to reach a T_{re} of 40 °C was significantly improved when not wearing any item, with the exception of the gloves. Not wearing the overboots resulted in the greatest mean extension of TT to a T_{re} of 40 °C by 35.2 minutes (14.8 %) compared to when the overboots were worn during SO (273.0 [18.0] minutes *vs*. 237.8 [12.0] minutes, $p < 0.05$).

Based upon the linear rate of rise of T_{re} during Work 3, as more items were not worn in subsequent conditions, the predicted mean T_{re} at the end of Work 3 progressively lessened such that when all items were not worn during Condition S the mean T_{re} was over 1.0 °C less than when all items were worn (SOGAR). Predicting T_{re} at the end of Work 3 when the BAL was not worn resulted in the mean T_{re} being 0.4 °C lower than when the BAL was worn during SOGA (38.8 [0.1] °C *vs*. 39.2 [0.1] °C, $p < 0.0001$), which was the greatest decrease compared to any other condition.

4.5.3 Rectal Temperature

Participants did not arrive to the laboratory with the same T_{re} everyday, although the time of day of participation was controlled. Therefore, the change in rectal temperature (ΔT_{re}) was statistically analyzed, and is presented in Figure 8, in place of absolute T_{re} to ensure no bias was introduced into the results.

Effect of not wearing the respirator

From 80 minutes (Recovery 2) until the final point analyzed during Work 3 at 110 minutes, not wearing the respirator (SOGA) resulted in a significantly lowered mean ΔT_{re} compared to when the respirator was worn during SOGAR. This was by a maximum of 0.11 °C at 110 minutes ($p < 0.001$).

Effect of not wearing the body armour liner

From as early as 40 minutes, not wearing the BAL (SOG) resulted in a significantly lowered mean ΔT_{re} (0.03 [0.06] °C) compared to the adjacent condition when the BAL was worn, SOGA (0.13 [0.04] °C, $p < 0.01$). This was by a maximum of 0.27 °C at 110 minutes ($p < 0.0001$).

For calculation of the rate of change of T_{re} (Figure 9) linear data from the final 10 minutes in each period were used. For calculation of rate of change in T_{re} during Work 3, data were obtained from 10 minutes into the work period onwards and were adjusted for individual TT.

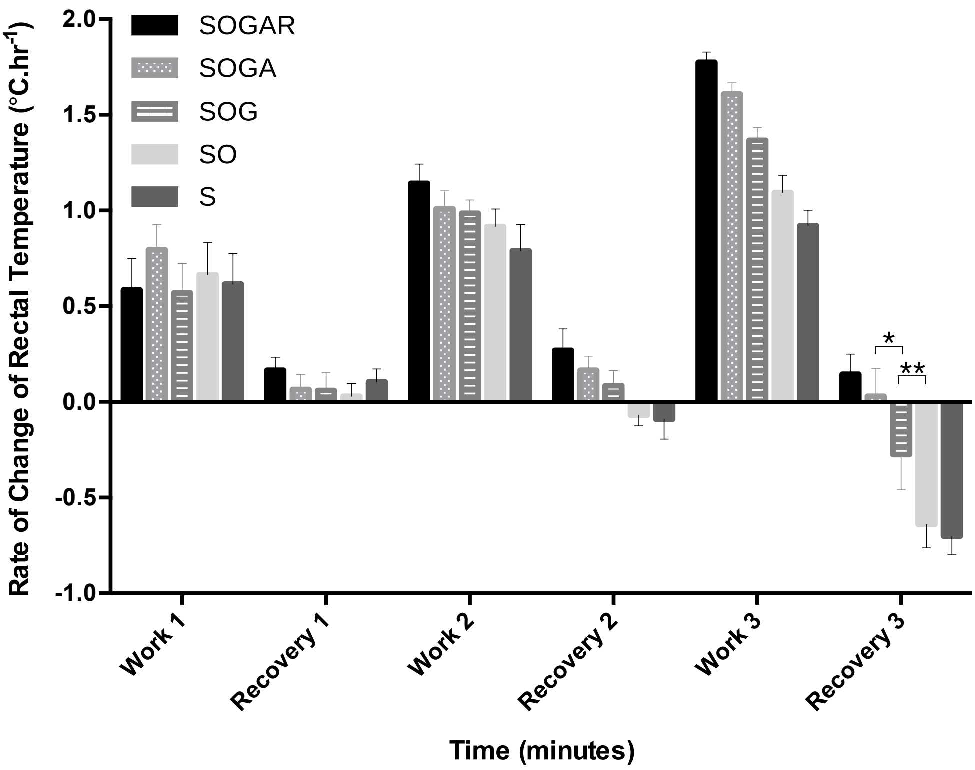

Figure 9: Mean (SEM) rate of change in rectal temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$ *vs*. adjacent condition.

Effect of not wearing the body armour liner

Only during Recovery 3 did the impact of individual items become apparent compared to the adjacent condition. Cooling was evident when the BAL was not worn (SOG) compared to when the BAL was worn during SOGA (-0.28 [0.18] $°C.hr^{-1}$ *vs*. 0.03 [0.14] $°C.hr^{-1}$, $p < 0.05$).

Effect of not wearing the gloves

During Recovery 3 cooling was greater when the gloves were not worn (SO) compared to when the gloves were worn during SOG (-0.64 [0.12] °C.hr^{-1} *vs*. -0.28 [0.18] °C.hr^{-1}, $p < 0.01$).

Assuming that there was no achievement of thermal balance, based upon the rate of rise of T_{re} during Work 3, TT from a T_{re} of 37.5 °C to 39.5 °C and 40.0 °C were calculated (Figure 10). This provides a clear, albeit extrapolated, calculation for the end user as to predicted TT when the evaporative burden of individual IPE is entirely removed whilst working at a constant intensity with no recovery periods.

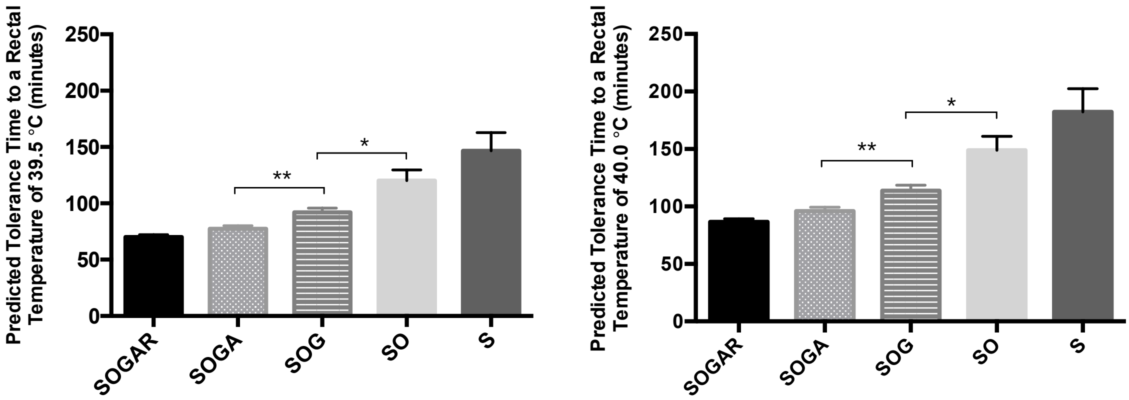

Figure 10: Mean predicted (SEM) tolerance time during each condition to a rectal temperature of 39.5 °C (left graph) and 40.0 °C (right graph) based upon the extrapolated rate of rise of rectal temperature obtained from Work 3 when working at a rate of oxygen uptake of 13.5 mL.kg^{-1}.min^{-1} in a chamber set to 40.5 °C and 20 % rh air (n = 12).

Mean predicted TT to a T_{re} of 39.5 °C was extended from 70 (2) minutes for SOGAR to 77 (3) minutes, 92 (4) minutes, 120 (10) minutes and 147 (16) minutes for SOGA, SOG, SO and S respectively. Significant improvements were only found when the BAL was not worn and mean TT was significantly improved from SOGA by 18.7 % (14.5 minutes, $p < 0.01$) as well as when the gloves were not worn and mean TT was significantly improved from SOG by 30.5 % (28.08 minutes, $p < 0.05$).

Mean predicted TT to a T_{re} of 40.0 °C was extended from 87 (3) minutes for SOGAR to 96 (4) minutes, 114 (5) minutes, 149 (12) minutes and 182 (20) minutes for SOGA, SOG, SO and S respectively. Significant improvements were only found when the BAL was not worn and mean TT was significantly improved from SOGA by 18.4 % (17.68 minutes, p <

0.01) as well as when the gloves were not worn and mean TT was significantly improved from SOG by 31.1 % (35.30 minutes, $p < 0.05$).

4.5.4 Mean Skin Temperature

The $\overline{T}_{sk}$ during each condition is illustrated in Figure 11.

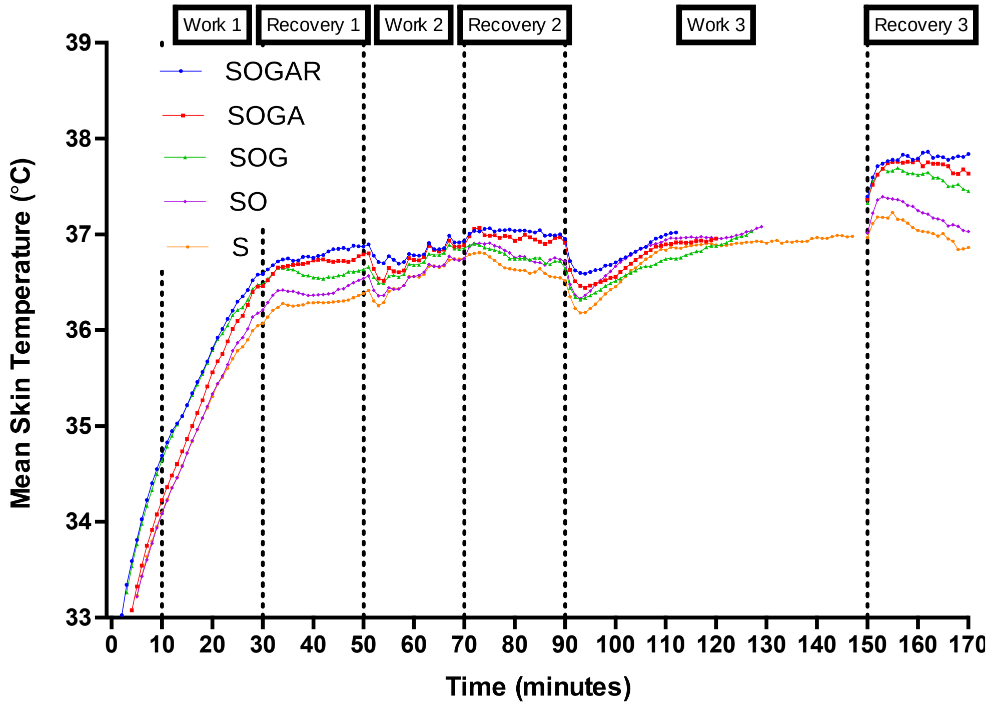

Figure 11: Average mean skin temperature whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

Note that due to thermistor detachment, T_{sk} data were not available and were subsequently predicted (Appendix 9) for the following:

P2 T_{arm} from 90 minutes during SO

P4 T_{calf} from 112 minutes during SOGA

P7 T_{calf} from 101 minutes during S

P9 T_{arm} from 86 minutes during S

Effect of not wearing the respirator

Only at 10 minutes into the protocol did not wearing the respirator (SOGA) significantly lower $\overline{T}_{sk}$ compared to SOGAR (34.23 [0.19] °C *vs*. 34.72 [0.24] °C, $p < 0.0001$).

Effect of not wearing the body armour liner

Compared to when the BAL was worn (SOGA), not wearing the BAL (SOG) resulted in a significantly higher $\overline{T}_{sk}$ at 10 minutes into the protocol (34.23 [0.19] °C *vs*. 34.64 [0.22] °C, $p < 0.001$).

Effect of not wearing the gloves

Not wearing the gloves (SO) compared to when the gloves were worn (SOG) resulted in a significantly lowered $\overline{T}_{sk}$ at 10 minutes (34.01 [0.24] °C *vs*. 34.64 [0.22] °C, $p < 0.0001$) and 20 minutes (35.34 [0.21] °C *vs*. 35.79 [0.17] °C, $p < 0.001$).

4.5.5 Mean Body Temperature

The mean $\Delta\overline{T}_b$ for all conditions with comparisons made every 10 minutes from 0 minutes to 110 minutes is illustrated in Figure 12. As participants were in the chamber for varying durations during Work 3 (Table VII) and the $\overline{T}_{sk}$ (a component of the $\overline{T}_b$ equation) was not linear (Figure 11), comparisons of the mean $\Delta\overline{T}_b$ for the final 10 minutes of Recovery 3 ($r\Delta\overline{T}_b$) were made in place of calculating the hourly rate of change.

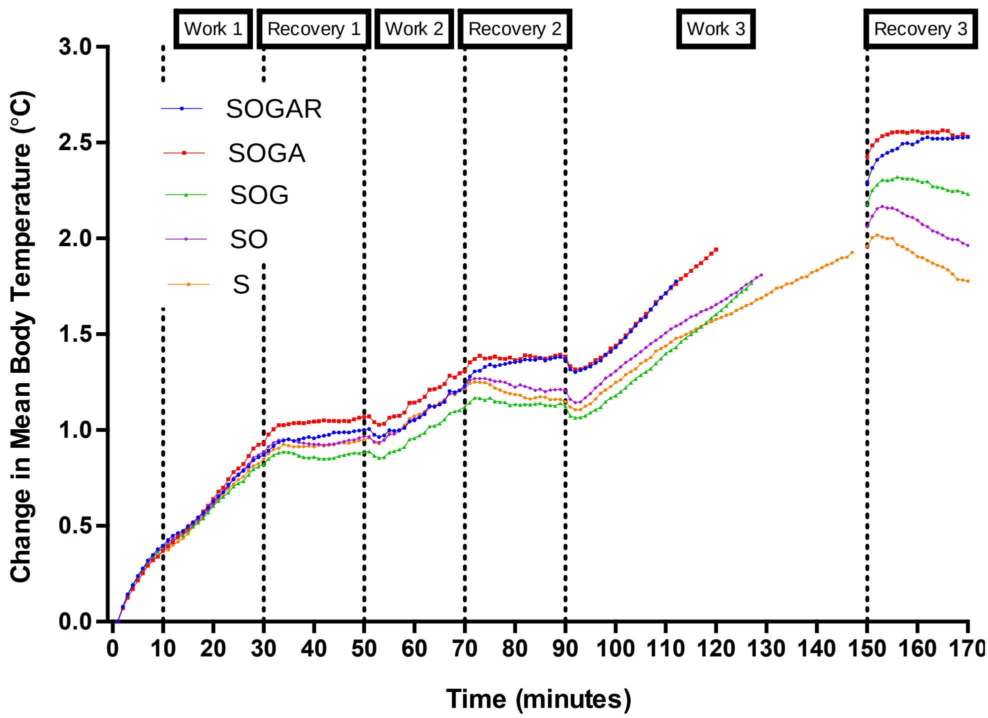

Figure 12: Mean change in mean body temperature whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

Effect of not wearing the respirator

When the respirator was not worn (SOGA), mean $\Delta\overline{T}_b$ was greater at 40 minutes and 60 minutes into the protocol compared to when the respirator was worn during SOGAR, this was by a maximum of 0.09 °C at 60 minutes ($p < 0.05$).

Effect of not wearing the body armour liner

By the end of the first work period (30 minutes into the protocol) until the last point measured during Work 3 (110 minutes), the mean $\Delta\overline{T}_b$ was less when the BAL was not worn (SOG) compared to when the BAL was worn during SOGA. This was by a maximum of 0.31 °C at 110 minutes ($p < 0.0001$).

Effect of not wearing the gloves

By the end of the first recovery period (50 minutes into the protocol) until the last point measured during Work 3 (110 minutes), the mean $\Delta\overline{T}_b$ was greater when the gloves were not worn (SO) compared to when the gloves were worn during SOG. This was by a maximum of 0.13 °C at 100 minutes ($p < 0.001$).

4.5.6 Local Skin Temperatures

4.5.6.1 Finger Temperature

Mean T_{finger} is shown in Figure 13. Comparisons were made between all conditions from 0 minutes until 110 minutes and the mean $r\Delta T_{finger}$ was calculated during Recovery 3.

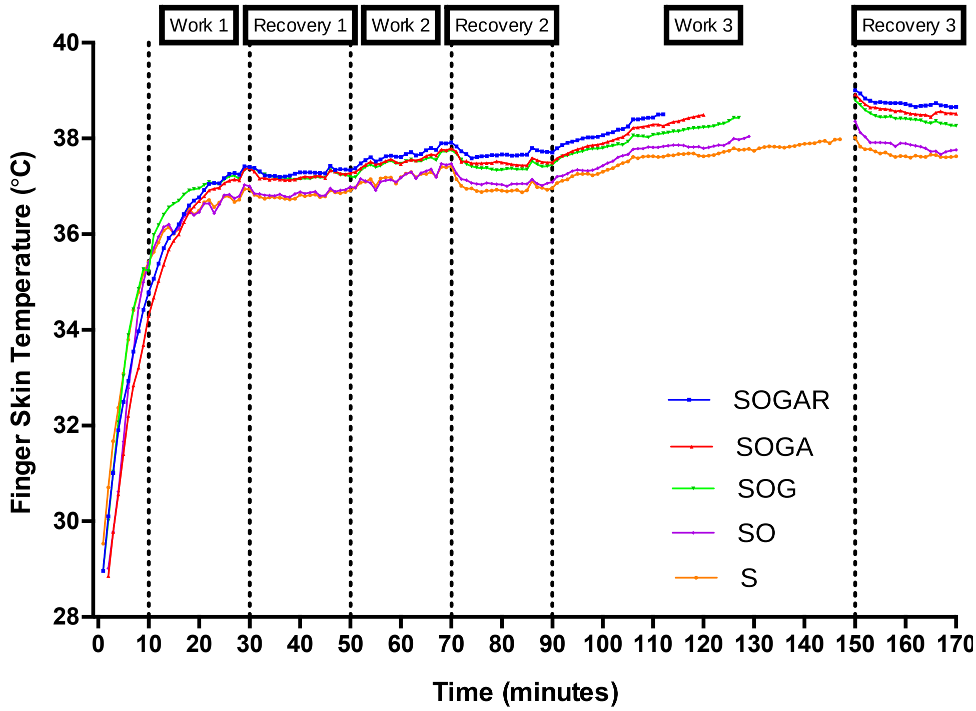

Figure 13: Mean finger skin temperature whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

There were no significant differences in mean T_{finger} between any adjacent conditions from 0 to 110 minutes into the protocol ($p > 0.05$). There was no difference to the mean $r\Delta T_{finger}$ during Recovery 3 between any adjacent conditions.

4.5.6.2 Cheek Temperature

Mean T_{cheek} is shown in Figure 14. Comparisons were made between all conditions from 0 minutes until 110 minutes and the mean $r\Delta T_{cheek}$ was calculated during Recovery 3.

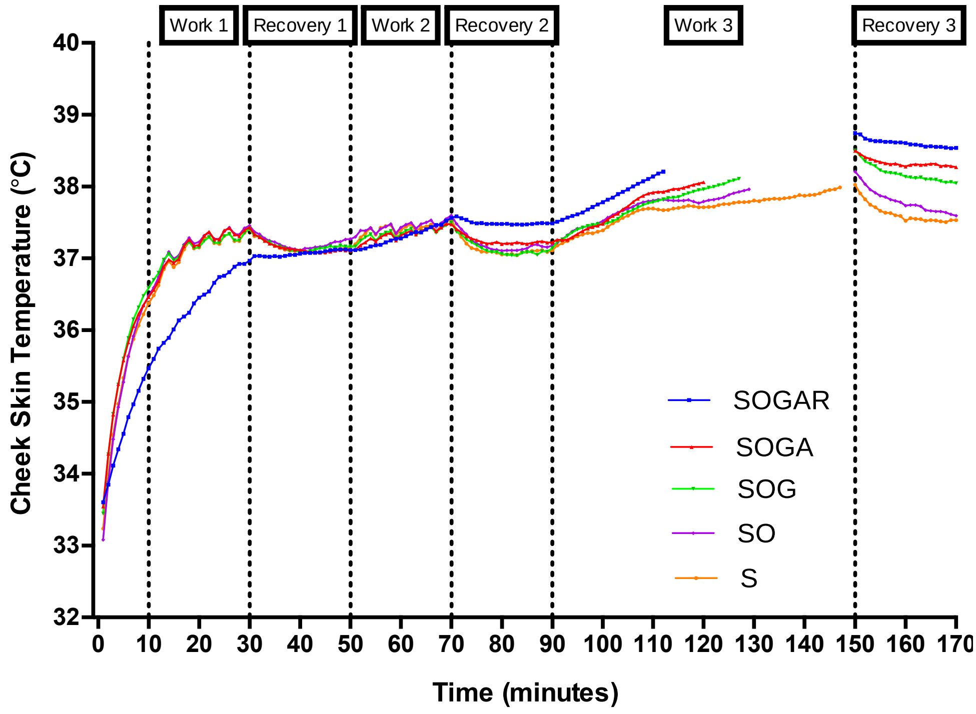

Figure 14: Mean cheek skin temperature whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

Effect of not wearing the respirator

From the start of the protocol until 30 minutes into the protocol, not wearing the respirator (SOGA) resulted in a greater mean T_{cheek} compared to when the respirator was worn during SOGAR. This was by a maximum of 1.0 °C at 10 minutes ($p < 0.0001$). This trend was observed in all other conditions as the respirator was only ever worn during SOGAR. Between 40 minutes to 70 minutes there appeared to be a “crossover” period where there were no significant differences to mean T_{cheek} between SOGAR and when the respirator was not worn (SOGA) as well as between SOGAR and any other condition. By 80 minutes the crossover ended and SOGA (along with all other conditions where the respirator was not worn) resulted in a reduced mean T_{cheek} until 110 minutes compared to SOGAR. This was by a maximum of 0.3 °C at 100 minutes ($p < 0.01$).

4.5.6.3 Chest Temperature

Mean T_{chest} is shown in Figure 15. Comparisons were made between all conditions from 0 minutes until 110 minutes and the mean $r\Delta T_{chest}$ was calculated during Recovery 3.

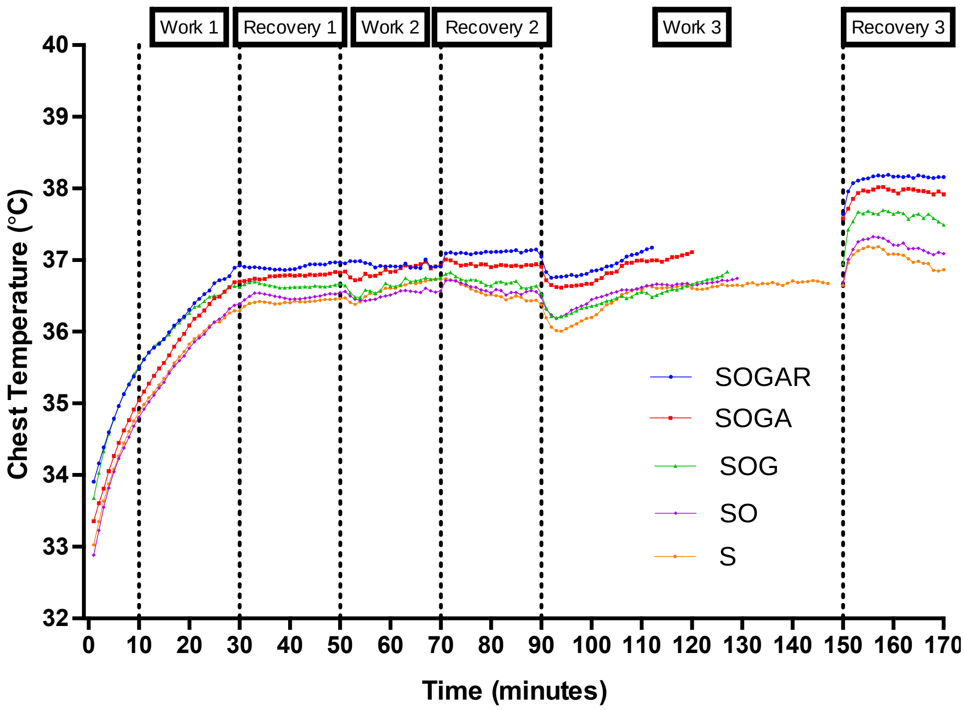

Figure 15: Mean chest temperature whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

Effect of not wearing the body armour liner

Not wearing the BAL resulted in a significantly greater mean T_{chest} at 10 minutes into the protocol compared to when the BAL was worn during SOGA (35.51 [0.20] °C *vs*. 35.05 [0.22] °C, $p < 0.01$). However, by 90 minutes until 110 minutes, not wearing the BAL resulted in a significantly lower mean T_{chest} compared to SOGA by a maximum of 0.44 °C at 110 minutes ($p < 0.01$).

Effect of not wearing the gloves

Not wearing the gloves resulted in a significantly lower mean T_{chest} at 10 minutes and 20 minutes into the protocol compared to when the gloves were worn during SOG. This was by a maximum of 0.70 °C at 10 minutes ($p < 0.0001$).

4.5.7 Whole Body Sweat Production and Evaporation

Figure 16 illustrates the mean whole body rate of sweat production, rate of sweat evaporation and the sweat evaporation / production ratio.

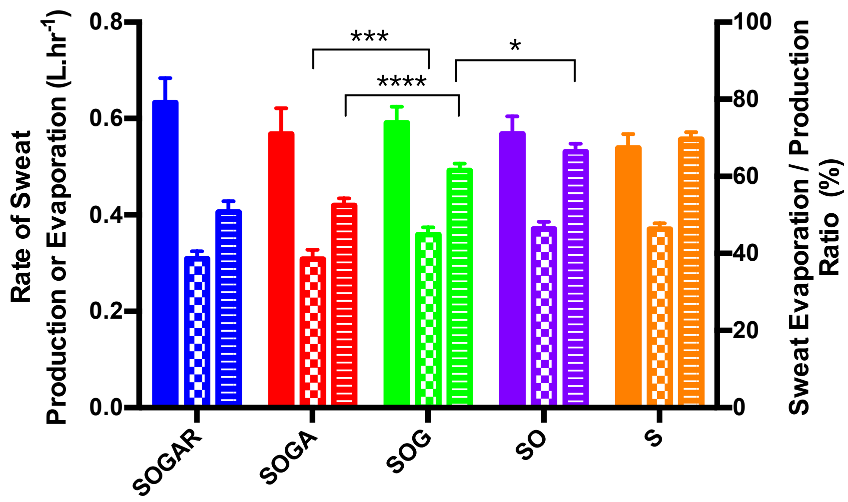

Figure 16: Mean (SEM) whole body rate of sweat production (solid) and evaporation (checked) and the sweat evaporation / production ratio (stripes) whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). $^{*}p < 0.05$, $^{***}p < 0.001$, $^{****}p < 0.0001$ *vs*. adjacent condition.

Effect of not wearing the body armour liner

Not wearing the BAL significantly improved the mean rate of sweat evaporation by 16.1 % (SOG: 0.36 [0.02] $L.hr^{-1}$ *vs*. SOGA: 0.31 (0.02) $L.hr^{-1}$, $p < 0.001$). Not wearing the BAL also improved the mean sweat evaporation / production ratio by 17.3 % compared to SOGA (61.52 [1.76] % *vs*. 52.45 [1.87] %, $p < 0.0001$).

Effect of not wearing the gloves

Figure 16 also illustrates the 7.9 % improvement to the mean sweat evaporation / production ratio when the gloves were not worn compared to when the gloves were worn during SOG (66.40 [2.08] % *vs*. 61.52 [1.76] %, $p < 0.05$).

4.5.8 Heart Rate

Figure 17 displays the mean heart rate over time for all conditions.

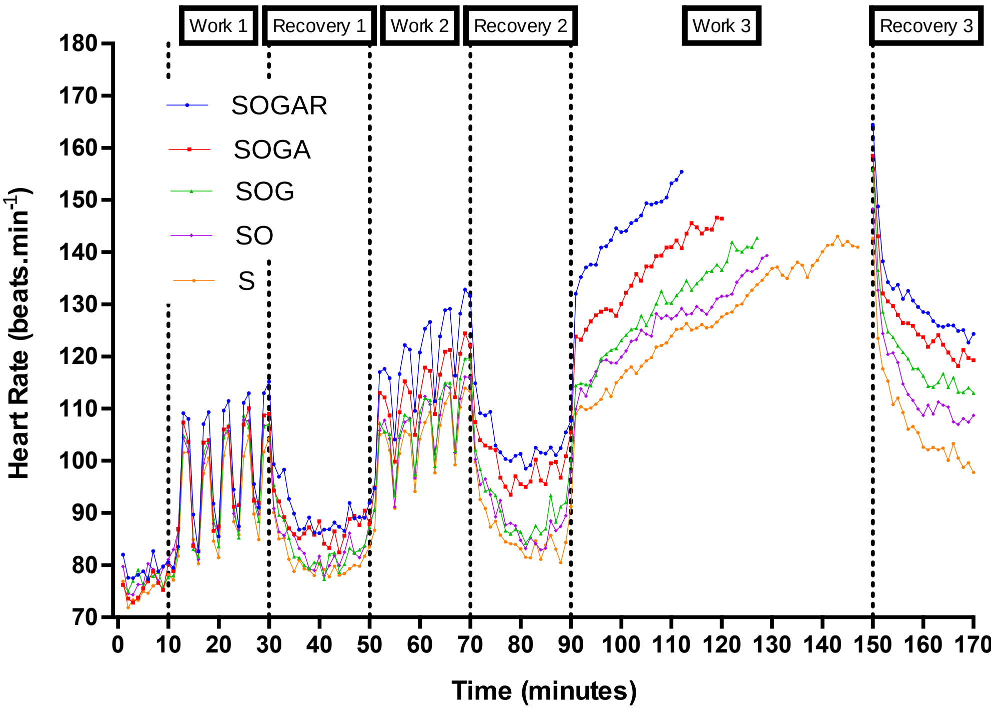

Figure 17: Mean heart rate whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). Data were truncated at the last point where n = 12 for each condition.

Effect of not wearing the respirator

Compared to SOGAR, not wearing the respirator (SOGA) resulted in a lowered mean heart rate at the end of Work 1 (30 minutes), during Work 2 (60 minutes and 70 minutes) and during Work 3 (100 minutes and 110 minutes). This was by a maximum of 14 beats.min^{-1} at 100 minutes ($p < 0.0001$).

Effect of not wearing the body armour liner

Compared to SOGA, not wearing the BAL (SOG) resulted in a lowered mean heart rate during Recovery 1 (40 minutes), during Recovery 2 (80 minutes) and during Work 3 (100 minutes and 110 minutes). This was by a maximum of 11 beats.min^{-1} at 110 minutes ($p < 0.0001$).

4.5.9 Physiological Strain Index

The effects of not wearing MVIP items on the mean PSI are shown in Figure 18.

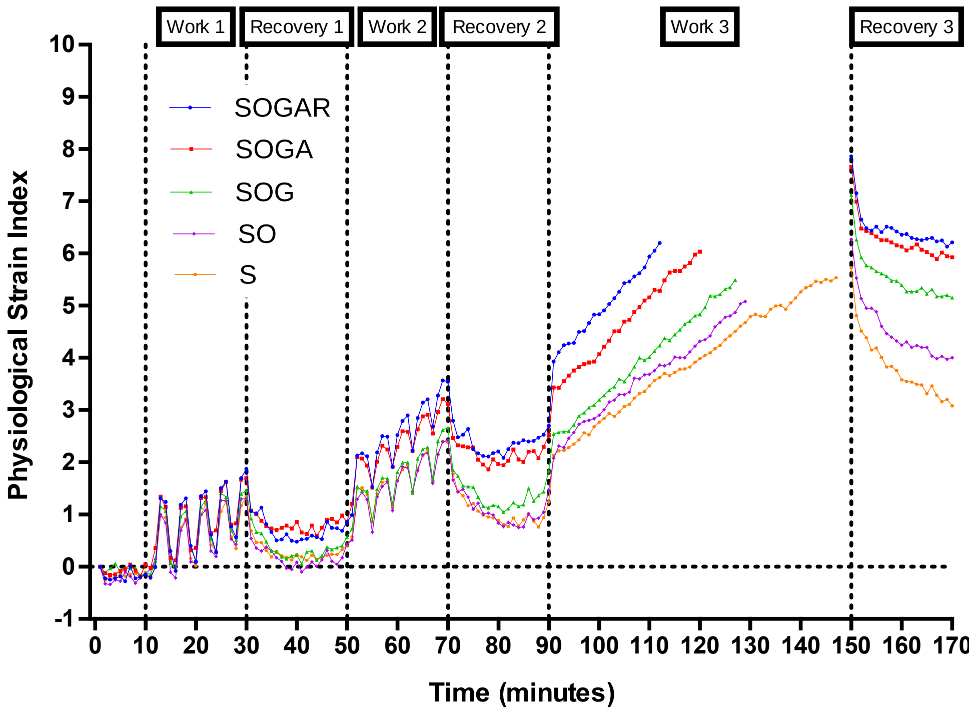

Figure 18: Mean physiological strain index whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the respirator

Compared to SOGAR, not wearing the respirator (SOGA) resulted in a lowered mean PSI at the end of Work 2 (70 minutes) and during Work 3 only (100 minutes and 110 minutes). This was by a maximum of 0.78 (13.1 %) at 110 minutes ($p < 0.0001$).

Effect of not wearing the body armour liner

Compared to SOGA, not wearing the BAL (SOG) resulted in a lowered mean PSI during Recovery 1 (40 minutes) and from Work 2 (60 minutes) until 110 minutes. This was by a maximum of 1.14 (22.1 %) at 110 minutes ($p < 0.0001$).

4.5.10 Perceptual Measures

As the first perceptual measure during Work 3 was taken at 110 minutes into the protocol, all participants (n = 12) were still stepping, however by the second perceptual measure time point (130 minutes), participants had begun to drop out. Therefore only the first perceptual measure was presented during Work 3 and the data from Recovery 3 should be taken with caution as at this point participants had been in the chamber for varying durations. As participants on average spent a longer duration in the chamber as more items were not worn (Table VII), it is likely that any improvements to the perceptual response were underestimated. Mean perceptual measures of thermal sensation and thermal comfort are illustrated below. There were no significant differences to the mean RPE or perceived skin wettedness.

4.5.10.1 Thermal Sensation

Figure 19 illustrates mean thermal sensation between conditions throughout the protocol.

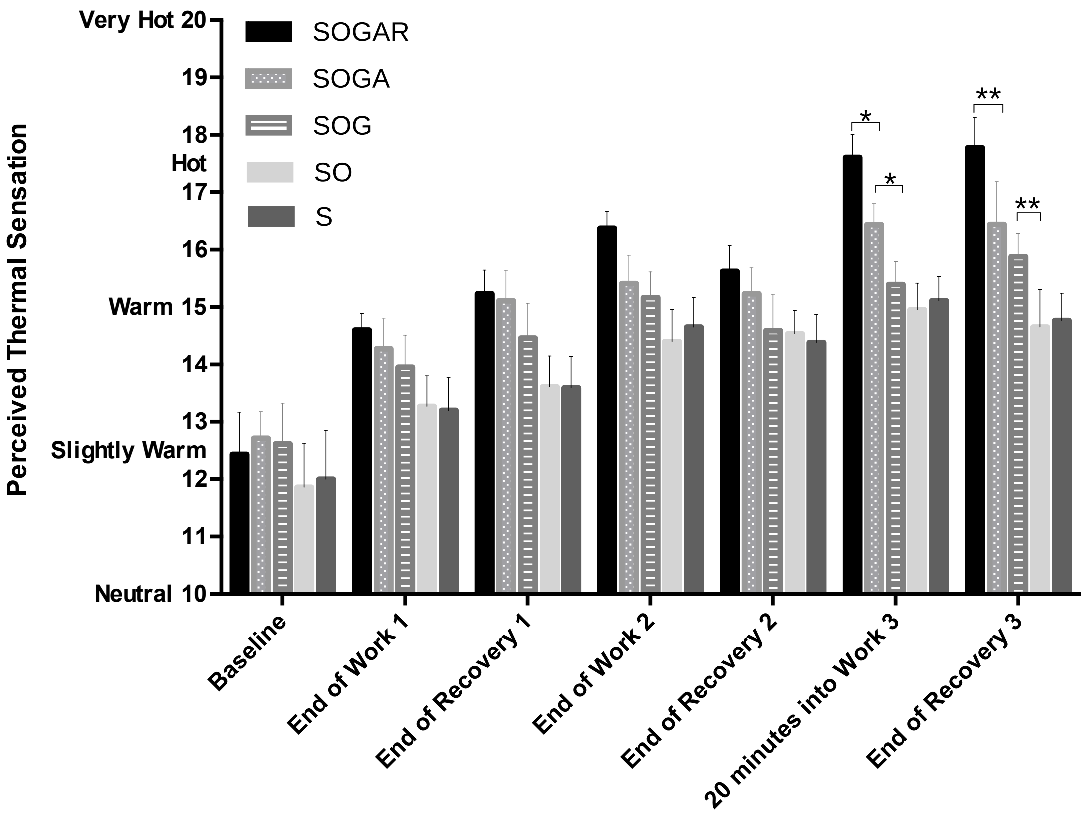

Figure 19: Mean (SEM) perceived thermal sensation whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$ *vs*. adjacent condition.

Effect of not wearing the respirator

Regarding whole body thermal sensation, not wearing the respirator was perceived as less hot at 20 minutes into Work 3 (16.43 [0.37] *vs*. 17.61 [0.40], $p < 0.05$) and at the end of Recovery 3 (16.44 [0.75] *vs*. 17.78 [0.53], $p < 0.01$) compared to SOGAR.

Effect of not wearing the body armour liner

Not wearing the BAL was perceived to be less hot only 20 minutes into Work 3 compared to SOGA (15.39 [0.41] *vs*. 16.43 [0.37], $p < 0.05$).

Effect of not wearing the gloves

Not wearing the gloves was perceived as less hot than SOG at the end of Recovery 3 (14.65 [0.66] *vs*. 15.88 [0.04], $p < 0.01$).

4.5.10.2 Thermal Comfort

Figure 20 illustrates mean thermal comfort between conditions throughout the protocol.

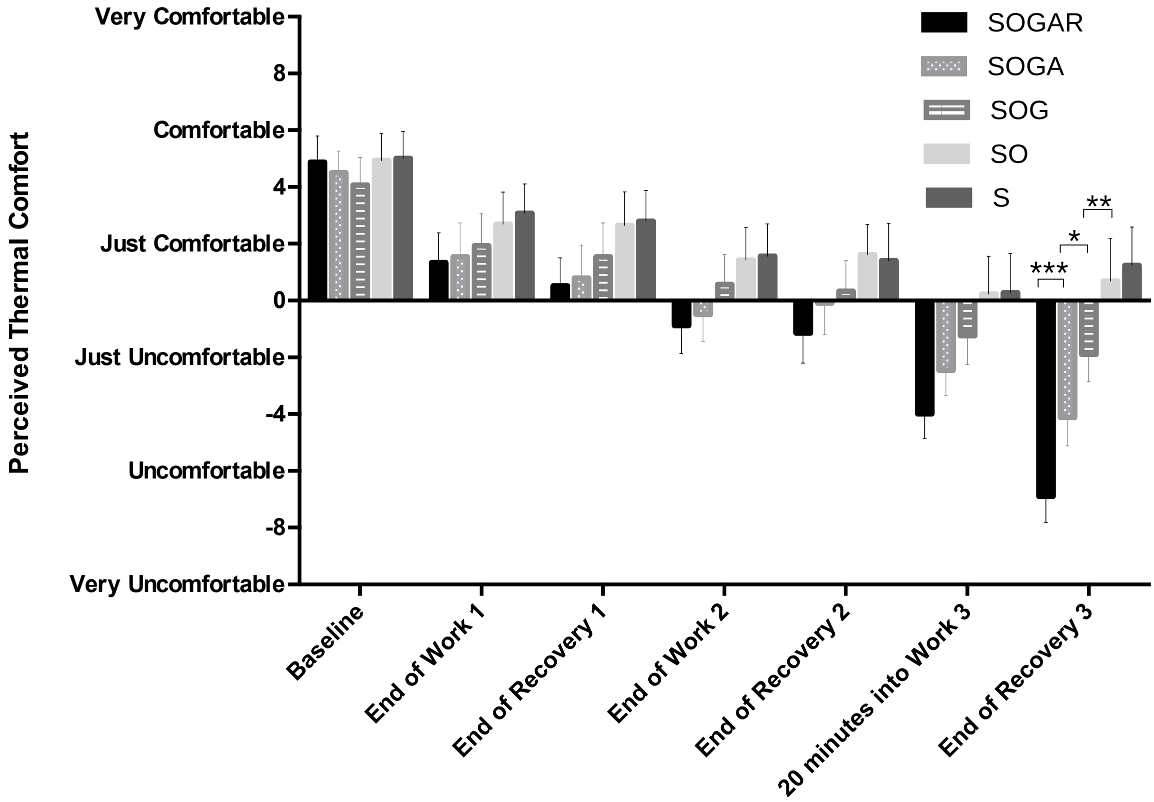

Figure 20: Mean (SEM) perceived thermal comfort whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ *vs*. adjacent condition.

Effect of not wearing the respirator

At the end of Recovery 3, not wearing the respirator (SOGA) was perceived to be "just uncomfortable" compared to when the respirator was worn during SOGAR and participants rated as feeling "uncomfortable" (-4.11 [1.01] *vs*. -6.90 [0.91], $p < 0.001$).

Effect of not wearing the body armour liner

At the end of Recovery 3, not wearing the BAL (SOG) was perceived to be less uncomfortable compared to when the BAL was worn during SOGA (-1.89 [0.97] *vs*. -4.11 [1.01], $p < 0.05$).

Effect of not wearing the gloves

At the end of Recovery 3, not wearing the gloves (SO) was perceived to be "just comfortable" compared to when the gloves were worn during SOG and participants rated as feeling "just uncomfortable" (0.69 [1.50] *vs*. -1.89 [0.97], $p < 0.01$).

4.5.11 Summary of Results

Table VIII below shows a summary of the results discussed above.

Table VIII: Summary of results indicating where thermoregulatory strain has been reduced (green arrow) or increased (red arrow) whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 12).

Whole Body Measure of Thermoregulatory Strain	**SOGA**	**SOG**	**SO**	**S**
Tolerance Time (Work 3)	↑			
Predicted Experimental TT to a T_{re} of 39.5 °C		↑		↑
Predicted Experimental TT to a T_{re} of 40 °C	↑	↑		↑
Predicted T_{re} if all 60 minutes of Work 3 were completed	↓	↓	↓	↓
Predicted TT from a T_{re} of 37.5 °C to 39.5 °C		↑	↑	
Predicted TT from a T_{re} of 37.5 °C to 40 °C		↑	↑	
Rate of Sweat Evaporation		↑		
Sweat Evaporation / Production Ratio		↑	↑	
Measure of Thermoregulatory Strain 20 minutes into Work 3	**SOGA**	**SOG**	**SO**	**S**
ΔT_{re}	↓	↓		
$\Delta \bar{T}_b$		↓	↑ (red)	
ΔT_{cheek}	↓			
ΔT_{chest}		↓		
Heart Rate	↓	↓		
PSI	↓	↓		
Perceived Thermal Sensation	↓	↓		
Measure of Thermoregulatory Strain at the end of Recovery 3	**SOGA**	**SOG**	**SO**	**S**
Rate ΔT_{re}		↑	↑	
Perceived Thermal Sensation	↓		↓	
Perceived Thermal Comfort	↑	↑	↑	

Note that a green arrow indicates that the measure of thermoregulatory strain was improved; with a red arrow indicating the measure was worsened. A blank cell indicates that the measure was unchanged.

4.6 Discussion

The results presented show that wearing fully encapsulating military CBRN protective equipment places a physiological and perceptual thermoregulatory strain on the wearer. Elimination of the evaporative burden of ancillary items reduced the thermoregulatory strain but the reductions were not equal between items.

In this study it was imperative that the mass of the ensemble worn was matched between conditions to ensure that the metabolic heat production was equal between conditions. $\dot{V}O_2$ is a direct measure of work and therefore is an indirect, but proportional measure of metabolic heat production (Cathcart & Boyd-Orr, 1919; Weir, 1949). $\dot{V}O_2$ was not significantly different between conditions in all work and recovery periods except a small difference between when the respirator was worn (SOGAR) and when it was not worn (SOGA) during Work 1. Given that the clothing mass was constant between conditions and the stepping rate the same, this small difference was surprising. A possible explanation for this is that the method requires that the Douglas bag valve be opened or closed mid-inspiration (to allow for the measurement of a full expiration), but this was not always achievable given the tube attachment to the respirator (custom made) obstructing visual confirmation of inspiration. Additionally, the technique requires that samples be taken usually after 3 minutes of exercise to ensure $\dot{V}O_2$ was sampled during steady state; however, during the current study the measurement was only taken at the second minute period during Work 1 for 1 minute. This was because the participant only stepped for 2 minutes at a time; therefore it could be that the participant had not yet reached a steady state of exercise, which might have introduced a bias into the results. Moreover, the direction of error ($\dot{V}O_2$ for SOGA was greater than SOGAR for Work 1) would in this case underestimate the impact of not wearing the respirator. For example if when the respirator was not worn, $\dot{V}O_2$ was less compared to SOGAR, then any benefits seen during SOGA would be attributable to both the improved MVP at the face, as well as a lowered external work load. Similar $\dot{V}O_2$ values between conditions at all other time points confirmed that the weight was matched in all dress configurations, allowing further quantitative comparisons between conditions.

4.6.1 Thermal Burden of Protective Equipment

The first null hypothesis stated that when exercising at a light intensity in hot and dry conditions, thermoregulatory strain would not decrease when any of the MVIP ancillary items were not worn. Whilst wearing fully encapsulating protective clothing imposed a considerable thermal burden upon the wearer during exercise in hot, dry conditions, as measured by T_{re}, $\overline{T}_b$, whole-body sweat measures, heart rate, PSI and perceptual measures, a simulation of making ancillary items completely MVP in isolation or cumulatively resulted in improved thermoregulatory measures. For example by the end of the final work period, T_{re} was 38.90 (0.03) °C during SOGAR and 38.36 (0.10) °C during S even when participants had spent an extra 19.3 minutes exercising in the chamber. When considering TT to a T_{re} of 39.0 °C (a stopping criterion, General Methods: Section 3.4.4), a bias was introduced into the results due to the maximum TT being capped at 170 minutes as in some conditions, the TT to 39.0 °C for some participants exceeded the 60-minute work period *i.e*. after 60 minutes in Work 3 their T_{re} was below 39.0 °C. Therefore, it was of interest to predict TT to a T_{re} greater than 39.0 °C.

The upper limit of T_{re} for young, fit and healthy participants unimpeded by protective clothing could be beyond 40.6 °C as this temperature has been recorded for individuals without suffering heat illness after physical exertion (Richards *et al*., 1979). However, when wearing CBRN protective clothing the upper limit for T_{re} tolerance is reduced most likely because $\overline{T}_{sk}$ is higher than when wearing much less restrictive clothing and thus, $\overline{T}_b$ would be higher for a given T_{re}. Therefore, the T_{re} limit when wearing protective clothing is most likely less than 40.6 °C, but would probably lie somewhere between 39.0 °C and 40.6 °C, and this is likely to vary across individuals. Therefore, it is plausible to predict TT to a T_{re} of both 39.5 °C and 40.0 °C. However, tolerance is not only due to a T_{re} limit but can also be due to volitional stopping and heat exhaustion both which may be linked to maximum heart rate. Therefore, a prediction of when each participant would reach his age-predicted maximum heart rate was also made. This was achieved by calculating the rate of rise of heart rate from 10 minutes into Work 3 (to account for a linear rate of rise and cardiovascular drift [Ekelund, 1967] during exercise in the heat) from a hypothetical initial working heart rate of 110 beats.min^{-1}. This heart rate (110 beats.min^{-1}) is the approximate value during the first work period and seems suitable to use as a representative starting heart rate for continuous light exercise. It was found that when predicting TT to a T_{re} of 39.5 °C, 0 % (SOGAR), 8 % (SOGA), 0 % (SOG), 0 % (SO) and 17 % (S) of participants would have reached their age-predicted maximum heart rate before predicted T_{re} reached 39.5 °C. When T_{re} was predicted to 40.0 °C, 0 % (SOGAR), 12 % (SOGA), 33 % (SOG), 50 % (SO) and 50 % (S) of participants would have reached their age-predicted maximum heart rate before predicted T_{re} reached 40.0 °C. Furthermore, it is likely that those participants not reaching a predicted T_{re} based on reaching a maximum heart rate first, may have stopped volitionally (although in combat, individuals might continue to maximum) as the maximum heart rate was being approached, or may have become heat casualties. Although when the gloves or overboots were not worn, 50 % of people would have reached a maximum heart rate before reaching a critical T_{re} of 40.0 °C, in some cases, such as when the respirator was not worn, 88 % of participants would not yet have reached a maximum heart rate before reaching a T_{re} of 40.0 °C. Unlike in civilian work practices, military planners and military personnel do expect work rates that are severely stressful. Of course, 50 % or more heat casualties in planning is likely to be considered unacceptable, but for some conditions where the percentage of heat casualties was lower, it is still valid to report these predictions.

When wearing the fully encapsulating protective ensemble (SOGAR) predicted TT to a T_{re} of 40 °C was 168.3 (3.1) minutes, and if all ancillary items could be made of 100 % MVP materials (condition: S), then predicted TT to a T_{re} of 40 °C would theoretically be increased by 104.7 minutes to 273.0 minutes. However, this prediction includes set recovery periods and working for varying durations, which might not represent a realistic situation in a contaminated war zone. Therefore, based upon the rate of rise of T_{re} during Work 3, mean TT from a T_{re} of 37.5 °C to 39.5 °C and 40.0 °C were calculated. When predicting TT from the rate of rise of T_{re} during Work 3, the calculation assumed that the rate would remain constant and there would be no achievement of thermal balance, which in reality might not be the case. This is because early in the protocol T_{re} rises due to metabolic heat production as well as gaining heat from the ambient environment. Later in the protocol, as T_{re} and T_{sk} rises, the temperature gradient between T_{re}, T_{sk} and the ambient environment reduces and the rate of increase of T_{re} might lessen. Therefore, when considering the predicted TT it must be remembered that these data were extrapolated and should be taken with caution. Nonetheless, this calculation rudimentarily estimated TT and predicted TT to a T_{re} of 39.5 °C and 40.0 °C were extended by 77 minutes (with approximately 17 % of participants not reaching this T_{re} due to reaching a maximum heart rate before reaching the predicted T_{re} of 39.5 °C) and 95 minutes (with approximately 50 % of participants not reaching this based on heart rate) respectively in a fully encapsulated ensemble when the evaporative resistance of all ancillary items was removed (Condition: S). If a warfighter walked at a speed of 1.1 $m.s^{-1}$ at a 0 % gradient (McLellan *et al.*, 1992) then an improved TT of 77 minutes to a T_{re} of 39.5 °C or 95 minutes to a T_{re} of 40.0 °C equates to a further 5.08 km (with 17 % not reaching this based on heart rate) or 6.27 km (with 50 % not reaching this based on heart rate) walked before there is an increased risk of heat stroke causing serious systemic dysfunction (Knochel & Reed, 1994).

Therefore, the null hypothesis was rejected and the experimental hypothesis accepted that, when exercising at light intensity in hot and dry conditions, thermoregulatory strain would decrease when any of the MVIP ancillary items were not worn. Thus, if these items could be made from MVP materials in future, there would be benefits of a reduced thermal burden. However, as future items are unlikely to be 100 % MVP, it is not clear how effective this would actually be, it would depend on the relative level of MVP.

4.6.2 Improved Evaporation from the Torso Greatly Reduces Thermoregulatory Strain

The second hypothesis stated that the greatest decrease to thermoregulatory strain would occur when the MVIP torso BAL was not worn. The results showed that when the BAL was not worn the greatest reduction to thermoregulatory strain at the earliest time point in the protocol was observed in most measures. Removing all evaporative and thermal resistance from the BAL improved whole body sweat evaporation by 16.1 %, which concurred well with the manikin results whereby removal of the BA reduced the whole body (excluding the head) vapour resistance by 17.9 % (Table III). The torso is an important area for dissipation of heat, particularly in a hot and dry environment as the torso accounts for approximately 39.5 % of total body surface area (Weiner, 1945) and has a high rate of sweat production (Smith & Havenith, 2011) that could theoretically account for 33 % of the total contribution of whole body evaporative cooling if maximum evaporation was permitted (Taylor & Machado-Moreira, 2013; Table II). The improved evaporation at the torso resulted in a significantly lower T_{chest} between 90 minutes until 110 minutes, and lowered $\overline{T}_b$ from as early as 30 minutes into the protocol and by a maximum of 0.31 °C at 110 minutes, at which point participants also felt less hot. The rate of cooling during Recovery 3 was increased by 0.31 $°C.hr^{-1}$ and participants felt less thermally uncomfortable at the end of Recovery 3. Not wearing the BAL also resulted in a lowered heart rate during Recovery 1 and 2 as well as during Work 3.

The torso is minimally represented on the somatosensory homunculus compared to the face for example (Penfield & Boldrey, 1937) and the torso was never naked to the environment when the BAL was not worn, as the face and hands were when the gloves or respirator were not worn, due to the participant still wearing the protective suit; yet the perceptual benefits associated with not wearing the BAL were considerable. Reasons for this might be due to the large surface area of the torso (Weiner, 1945) or that the perceptual benefits reflected the degree of decreased thermoregulatory strain. Due to the significant improvements to the physiological and perceptual thermal state of the participants when the BAL was not worn, the null hypothesis was rejected, and the experimental hypothesis that the greatest decrease to thermoregulatory strain would occur when the MVIP torso BAL was not worn, was accepted.

Whilst not wearing the BAL resulted in the greatest improvement to thermoregulatory strain, this study found that exposing the face (SOGA) or hands (SO) were also effective at dissipating heat. For example, although the greatest improvement to the number of participants completing the protocol was found when the BAL was not worn (5 participants), the only condition to significantly extend TT during Work 3 (by 8.3 minutes) was when the respirator was not worn (SOGA). Also, compared to when the gloves were worn (SOG), exposing the hands, which have a surface area approximately 8 times less than the torso (Weiner, 1945; Yu *et al*., 2008), caused a further 7.9 % increase to the sweat evaporation / production ratio, which is half that of the improved sweat evaporation / production ratio at the torso (17.3 %) when the BAL was not worn. Furthermore, the condition in which there was the greatest improvement to cooling during Recovery 3 was SO when the gloves were not worn (an additional 0.36 $°C.hr^{-1}$), which might have been due to the complete exposure of the hands.

During the final recovery period, participants cooled at a rate of 0.28 $°C.hr^{-1}$ when both the respirator and BAL were not worn. It can then be calculated that for the T_{re} of the average participant to cool by 0.5 °C it would take approximately 108 minutes. If the evaporative and thermal resistance of the gloves was completely removed in addition to both the evaporative and thermal resistance of the respirator and BAL then, as the rate of cooling of T_{re} during SO was 0.64 $°C.hr^{-1}$, it would take the average participant only 47 minutes to cool by 0.5 °C. This is less than half the amount of time it would take to cool by 0.5 °C when both the BAL and respirator were not worn whilst only uncovering an extra 4.6 % of total body surface area and highlights the importance of the hands. Practically, as ballistic protection surrounding the torso is unlikely to be made any more MVP and as the torso is often the site chosen for load carriage (Knapik & Reynolds, 2012), improving the MVP of the gloves would therefore represent a worthwhile avenue for future design research.

4.6.3 The Minimal Thermal Burden Imposed by the Overboots

The second hypothesis stated that the least decrease to thermoregulatory strain would occur when the MVIP overboots were not worn. Data from the manikin tests showed that removing the overboots did reduce measures of whole body (excluding the head) heat (by 1.57 %) and vapour (by 6.25 %) resistance and improve the permeability index (by 5.88 %) (Table III). Therefore, with such marginal changes seen in the manikin, it was expected that not wearing the overboots would not greatly reduce whole body thermoregulatory strain. It was only the predicted TT to a T_{re} of 39.5 °C or 40 °C that was increased by 28.5 minutes or 35.2 minutes respectively when the overboots were not worn. This prediction might have been overestimated due to a bias being introduced at later conditions (S and SO) when a relatively small difference in the rate of change of T_{re} would have a minimal influence over a short duration, but a greater influence over an extended duration. For example, the rate of rise of T_{re} was improved by 0.17 $°C.hr^{-1}$ between SOGAR and SOGA which equated to a 9.4 % improvement, whilst the rate of rise of T_{re} was also improved by the same absolute amount (0.17 $°C.hr^{-1}$) between SO and S but which equated to a 15.8 % improvement. If the duration of the experiment was 200 minutes then an improvement of 9.4 % would be equivalent to 18.8 minutes whereas an improvement of 15.8 % would equate to 31.6 minutes even though the absolute improvement to the rate of rise of T_{re} was the same (0.17 $°C.hr^{-1}$). If the duration of the experiment were only 30 minutes then the improved TT would be 2.8 minutes at a 9.4 % improvement and 4.7 minutes at a 15.8 % improvement. The discrepancy in the percentage improvement even for the same absolute improvement happens because as the conditions progressed, the thermal load placed on the participant was lessened, as more MVIP materials were not worn. Therefore, future studies should focus on quantifying the thermal burden of each MVIP item when the thermal load is maintained between conditions.

The lack of whole body influence when the evaporative and thermal resistance of the overboots was removed does not mean that the feet are poor channels of heat dissipation. Recent research has identified the feet as “excellent radiators, insulators and evaporators” (Taylor *et al*., 2014a). When the overboots were not worn, the feet and ankles were not made 100 % MVP, as the combat boots that are largely MVIP (predominantly leather with small sections of permeable material) were still worn. Therefore, any potential thermoregulatory gains by improving the MVP of the overboots were masked in this study by the combat boots and possibly the socks also. Future prototype development should consider improving the permeability of the combat boots, and then research could more effectively highlight the benefits of making the overboots more MVP. Improving the permeability of the overboots alone however was found to provide minimal thermal benefit other than extending the predicted TT to a T_{re} of 39.5 °C or 40 °C, and therefore the null hypothesis was rejected and the experimental hypothesis was accepted, that not wearing the MVIP overboots would result in the least improvement to thermoregulatory strain.

4.6.4 Exposing the Face: Perceptual Versus Physiological Benefits

The final hypothesis stated that when the respirator was not worn, the decrease in perceived thermal strain would be greater than the decrease in physiological thermoregulatory strain. The face is an area of the body, which possesses a high sensitivity for warmth, alliesthesia and sudomotor control (Penfield & Boldrey, 1937; Kissen *et al*., 1971, Cotter & Taylor, 2005) and is often the site that dictates whole body thermal comfort and sensation in a warm environment (Zhang, 2003). In this study, when the respirator was not worn both physiological and perceptual thermoregulatory improvements were evident. While the forehead in particular has previously been shown to possess a high density of sweat glands (Szabo, 1962; Knip, 1969), a high rate of sweat production (Smith & Havenith, 2011) and a high volume of sweat secretion during exercise in warm environments (Cotter *et al*., 1995a), this was not reflected when assessing whole body sweat responses in the current study. The most likely reason is that the face has only a small surface area (approximately 2.7 % of total body surface area [manikin Newton, Thermetrics, US]). However, even with the small surface area, eliminating the evaporative and thermal resistance of materials covering the face by not wearing the respirator was still detected perceptually (improved thermal comfort at the end of Recovery 3, improved thermal sensation 20 minutes into Work 3 and at the end of Recovery 3) and did result in an improved TT during Work 3 by 20.5 % compared to SOGAR, a lowered ΔT_{re} by a maximum of 0.11 °C and a lowered heart rate by a maximum of 14 beats.min^{-1}.

As evaporation of sweat results in T_{sk} cooling at the site of evaporation (McAdams, 1942), T_{cheek} data could provide a rudimentary indication as to the extent of evaporation at the face specifically (as sweat evaporation measures were only obtained for the whole body not regional sites in the current study). Early into the protocol (0 minutes to 30 minutes) the temperature of the cheek was lower when the respirator was worn (Figure 14); when it was not worn, and the face was exposed to the environment, the cheek skin was gaining heat from the environment. It should be noted that the respirator, and indeed all other CBRN equipment, were not pre-conditioned to the chamber temperature before being placed upon the participant and might have acted as a heat sink initially. However, wearing the respirator (SOGAR) during the first 30 minutes might also have provided a protective shield against convective and radiative heat gain, a protection that was not seen in T_{finger} when the gloves were worn (Figure 13). From 40 minutes to 70 minutes there were no differences in T_{cheek} between any of the conditions and the shielding respirator had reached its maximum capacity for protection against heat gain and the evaporative burden of the respirator became increasingly apparent. From 80 minutes, there was a crossover point where the benefits of evaporative cooling, in all non-respirator conditions, began to slow the rise of T_{cheek}. Additionally, as T_{cheek} increased, the gradient between T_{cheek} and the ambient environment lessened which would also have slowed heat gain at the cheek. Perceptually, from 20 minutes into Work 3 and at the end of Recovery 3 participants rated thermal sensation as being more tolerable although $\overline{T}_b$ remained unchanged compared to SOGAR, suggesting that the perceptual benefits of not wearing the respirator may have arisen despite no great whole body physiological benefit. Furthermore, it is interesting to note that when exposing the face that has a surface area of approximately 2.7 % of total body surface area (manikin Newton, Thermetrics, US) participants felt between warm and hot by the end of Recovery 3, yet when the BAL, that covers majority of the torso, and respirator were not worn (SOG) in combination, participants also felt between warm and hot. Thus highlighting the perceptual benefits of not wearing the respirator.

When the respirator was not worn, it was only at the end of Recovery 3 that any differences to perceived thermal comfort were noted even though participants were in the chamber for 8.3 minutes longer compared to SOGAR. Previously it has been identified that whole body thermal comfort can be improved by active facial cooling in a warm environment (33 °C and 27 % rh) when participants were lightly dressed and exercising (Mündel *et al*., 2007). The current study has shown that both perceived whole body thermal sensation and thermal comfort can be improved when only evaporative cooling is permitted at the face in the absence of active cooling. Improved whole body thermal sensation was detected sooner (20 minutes into Work 3) than improved whole body thermal comfort (end of Recovery 3). This alludes to potentially a lower threshold for the detection of an improved thermal sensation as opposed to thermal comfort or exclusive variable(s) affecting each measure of perceived thermal status.

During exercise in the heat, heart rate is elevated beyond the demands of the physical activity in an attempt to dissipate heat from the skin (Rowell *et al*., 1970). Not wearing the respirator lowered heart rate to the greatest degree compared to not wearing any other ancillary item yet $\overline{T}_b$ was largely unaffected and was actually higher at 40 minutes and 60 minutes into the protocol. In addition, the benefits of not wearing the respirator on the PSI (calculated using both heart rate and T_{re}) were less compared to the improvements to heart rate. These data suggest that the lowered heart rate observed when the respirator was not worn, might not solely have been a result of a lowered physiological thermal burden. Studies have found that active facial cooling reduces heart rate while T_{re} remains unchanged (Mündel *et al*., 2007). Bradycardia during facial cooling might, as observed in the diving response, be due to trigeminal nerve stimulation and subsequent changes to vagal tone (Heistad *et al*., 1968). Additionally an improved venous return and SV due to vasoconstriction of facial blood vessels during cooling would cause bradycardia (Booth *et al*., 1997). However, as T_{cheek} was approximately 4.0 °C above initial T_{cheek} when the face was exposed, vasoconstriction was most likely not occurring. Air-conditioned cooling during rest in very hot conditions (66 °C air temperature) reduced heart rate, SV and Q (and sweat rate) to a greater degree when applied to the head and neck compared to the trunk or legs (Kissen *et al*., 1971). However, active cooling was not used in this study and therefore only cooling by evaporation was shown to reduce cardiovascular strain. Furthermore it must be considered that the lowered heart rate might have been indicative of a lowered level of arousal or anxiety (although not measured in this study) when not wearing the respirator, as these measures (arousal and anxiety) have been associated with wearing a full-face mask (Morgan, 1983).

When the head data were included from the manikin tests, the greatest improvements were noted when the respirator and hood were not worn (Table IV). To truly assess only the impact of removing the thermal resistance of the respirator in the human studies, the respirator was tested in isolation to the hood *i.e.* the hood was always worn up in the study, and therefore the results were expected to be lower than the manikin data. Nonetheless with the hood and respirator removed in the manikin tests whole body vapour resistance was reduced by 17.2 %. During the human tests, the largest physiological improvement was a lowered ΔT_{re} of 10.4 %. In this study improvements were noted both perceptually and physiologically when the respirator was not worn and therefore the hypothesis that when the respirator was not worn, the decrease in perceived thermoregulatory strain would be greater than the decrease in physiological thermoregulatory strain during exercise was rejected. This conflicts with the work of Scanlan and Roberts (2001) who found that the perceived thermal burden of wearing a respirator was not matched physiologically. Scanlan and Roberts (2001) used only four volunteers who wore the respirator for a total of 45 minutes of which only 30 minutes was exercise. The results obtained in the current study were from 12 volunteers who either wore or did not wear the respirator for 170 minutes of which 95 minutes was exercise. Additionally, the environment was set to 30 °C during the Scanlan and Roberts (2001) study which was approximately 10 °C cooler than the current study which might have been responsible for the varied results as in the current study the face would also initially be gaining heat from the hotter environment when the respirator was not worn (Figure 14).

4.7 Conclusions

Undertaking light exercise whilst wearing fully encapsulating CBRN IPE resulted in increased hyperthermia in a hot and dry environment. Not wearing any of the MVIP ancillary items attenuated the rise in thermoregulatory strain and / or reduced the perception of thermoregulatory strain, and therefore the null hypothesis was rejected. Thus, the experimental hypothesis was accepted that when exercising at light intensity in hot and dry conditions, thermoregulatory strain would be decreased when not wearing any of the MVIP ancillary items. Regarding the cumulative effect of improving the MVP of all ancillary items, large thermoregulatory benefits would be observed if the evaporative and thermal resistance of all items could be eliminated.

Not wearing the BAL resulted in the greatest decrease to thermoregulatory strain compared to not wearing the respirator, gloves or overboots and therefore the second experimental hypothesis was accepted. Minimal thermoregulatory benefits were observed when the overboots were not worn and therefore the third experimental hypothesis was accepted. Furthermore, improving the permeability of the overboots would have little benefit if combat boots remain largely MVIP. Exposing the face significantly improved both physiological and perceptual measures and therefore the null hypothesis was not rejected. Improving the MVP of the gloves would also improve whole body physiological and perceptual thermoregulatory measures.

Human studies can provide final confirmation that the possible advantages identified in physical tests on manikins are present in humans with their complex thermoregulatory systems which affect heat transfer (*e.g.* manikins do not vasoconstrict or vasodilate nor do manikins possess functioning sweat glands). The results of this study gave new insights into the thermal burden of protective equipment compared to manikin data and also provided essential human perceptual measures. During the manikin tests the conditions were ranked as follows (based on the best to worst reduction to whole body vapour resistance): removing the respirator and hood (17.2 %), removing the BA (15.0 %), replacing the MVIP gloves with air permeable gloves (9.7 %), removing the overboots (5.5 %) (Table IV). During the human tests the conditions were ranked as follows (based on the best to worst overall reduction to whole body thermoregulatory strain): not wearing the BAL, not wearing the gloves, not wearing the respirator, not wearing the overboots. Therefore, the human results concurred well with the manikin results, albeit a slightly greater thermal burden of the respirator and overboots were quantified during the manikin tests. Possible reasons for the difference in human and manikin results include the following:

i. Removing the respirator and hood in combination (manikin tests) compared to not wearing only the respirator whilst the hood remained up (human test).
ii. Controlling the entire manikin surface temperature at 34 °C at each zone (32 segments), which is not representative of the varying T_{sk} found in humans at different body areas (Nadel *et al*., 1971a; Nakamura *et al*., 2008).
iii. Equal wetting of the cotton skin of the manikin at all zones, which is not representative of the human sweat response of which the rate and volume of sweat production can vary at different parts of the body (Cotter *et al*., 1995a; Smith & Havenith, 2011; Taylor & Machado-Moreira, 2013).

Caution should be taken when directly comparing the human and manikin results as several methodological alterations were made such as: removing the evaporative and thermal resistance of the respirator in isolation to the hood; completely removing the evaporative and thermal resistance of the gloves and not replacing them with air permeable gloves; wearing a less rigid BAL not actual BA; and finally not wearing the neck collar (Section 4.4.3).

4.8 Impact of Findings and Future Research

- Improving the MVP of the respirator, BA, gloves and overboots in combination could theoretically allow for a further 5.08 km (to a T_{re} of 39.5 °C, with 17 % of people not reaching this based on reaching a maximum heart rate) or 6.27 km (to a T_{re} of 40.0 °C, with 50 % of people not reaching this based on reaching a maximum heart rate) of patrolling before there is an increased risk of heat stroke to the warfighter in hot (40.5 °C) and dry (20 %) conditions carrying no loads.
- Improving only the permeability of the BAL would allow for an improved rate of sweat evaporation and early improvements to the thermal status of the warfighter.
- Improving the MVP of the gloves by the maximum theoretical amount (100 % MVP) would half the cooling time required to drop T_{re} by 0.5 °C when recovering in a hyperthermic state in a hot (40.5 °C) and dry (20 %) environment. Although developing a material that is essentially moisture vapour "invisible" is unlikely, this is the maximum possible improvement that could be achieved if such a material existed and any material that is less than 100 % MVP would most likely result in a smaller improvement as demonstrated in Appendix 10.

- Making the respirator MVP by the maximum theoretical amount would improve TT during continuous exercise by 20.5 % and result in warfighters feeling less hot and uncomfortable. Again, this would be the maximum possible improvement to TT if a material was 100 % MVP.
- It is recommended that although the BAL imposed the greatest thermoregulatory strain on participants, this item would be difficult to make more MVP whilst still maintaining ballistic protection and furthermore, loads are often carried on the torso, which may mask any benefits to evaporative cooling from a more MVP BA. Thus, it is recommended to reduce the evaporative and thermal resistance of the respirator or gloves primarily and finally the overboots and combat boots in combination to promote evaporative cooling and lower the overall, whole-body physiological and perceptual thermoregulatory strain.
- Further research to accurately quantify the thermal burden imposed by each item (not in combination with other CBRN items), should assess each item during a maintained thermal load between conditions, *i.e.* not wearing an item in isolation during a condition and replacing it for subsequent conditions. This recommendation was carried out in the next experiment (Chapter 5).

4.9 Limitations

A limitation of this study was that when the MVIP items were not worn at the torso and feet those areas did not become 100 % MVP, unlike the hands and face when the gloves and respirator were not worn, as those areas were still covered by the suit or the combat boots and socks respectively. However, as the aim of the study was to quantify the thermoregulatory strain imposed by each MVIP ancillary item during exercise in a hot and dry environment, the results presented directly address this aim in a manner appropriate to the ultimate end user.

CHAPTER V: THE THERMAL BURDEN OF PROTECTIVE EQUIPMENT WITH A MAINTAINED THERMAL LOAD

5.1 Rationale for the Second Study

A second investigation was carried out, that was supplementary to the first study, to determine the thermoregulatory strain imposed by each MVIP ancillary item in isolation to other items; that is when the thermal load was maintained across conditions. The thermal load during the first study was progressively lessened as fewer items were worn (at the start of Recovery 3 the ΔT_{re} was 1.65 °C and 1.18 °C in SOGAR and S respectively even though during S, the participants had been in the chamber for 36 minutes longer) and this might have resulted in the thermal burden of some items, particularly those not worn last (gloves and overboots) being underestimated. For example, given that the hands possess a high density of sweat glands and capillaries as well as having large arteriovenous anastomoses (Hales, 1985; Taylor & Machado-Moreira, 2013; Caldwell *et al*., 2014), it might be expected that exposing the hands in a hot and dry environment would reduce whole body thermoregulatory strain a considerable amount. Therefore, the improvements to thermoregulatory strain when the gloves were not worn during the first study (when the thermal load was lowered between conditions) might actually be greater, and better represented, when the thermal load is higher and maintained between conditions. As the feet were still covered by the socks and combat boots, even altering the thermal load might not result in large improvements to whole body thermoregulatory strain when the overboots are removed. An attempt was made in the first study to continually impose a thermal challenge by progressively increasing the levels of metabolic heat production throughout the protocol through increasing the duration of work from intermittent to continuous stepping as the protocol progressed (Table V). Additionally, conditions were only compared against adjacent conditions for quantification of the reduction to thermoregulatory strain when an item was not worn.

The design of the first study was under the direction of Dstl who required that the human studies compare well with previous studies conducted on manikins (Havenith *et al*., 2013). Additionally the design also allowed for quantification of the potential benefits of making a combination of items MVP. Constructing a second experimental design that allowed for a maintained thermal load on the body was important for human studies where a lowered thermal load provided less of a driver for thermoregulatory responses.

5.1.1 Thermal Loading

McLellan *et al*. (1992) quantified improvements to thermoregulatory strain when a new Canadian NBC clothing ensemble, which did not require CC to be worn underneath, was compared to previous generations of NBC kit where CC was required to be worn underneath. The tests were conducted with participants treadmill walking either continuously at a high workload (3 % gradient at a speed of 4.8 $km.hr^{-1}$) or intermittently (15 minutes of walking and 15 minutes of recovery) at a lower workload (0 % gradient at a speed of 4.0 $km.hr^{-1}$) in an environmental chamber set to hot (40 °C) and dry (25 % rh) conditions. Work TT was defined by participants reaching a T_{re} of 39.3 °C, 95 % of HR_{max}, dizziness or nausea. Work TT was improved by 14 minutes (30.4 %) under a high workload when CC was not worn (60 [21] min) compared to when CC was worn (46 [15] min) underneath the CB suit, yet no significant differences to work TT were identified between clothing ensembles under a lowered workload (113 [12] min *vs*. 139 [18] min) (McLellan *et al*., 1992). The study highlighted that differences between conditions were amplified when the body was placed under a higher thermal load compared a lowered thermal load. E_{req} was most likely lower during the lighter workload and the clothing conditions would have allowed for adequate vapour transport through the clothing that was probably below E_{req}. However, during a heavier workload, E_{req} was higher and either closer to or (for at least one condition) above the maximal vapour transport limit for the clothing such that differences between clothing ensembles would then be identified.

Other studies have also investigated the thermoregulatory strain of wearing CBRN equipment under different military protective postures which either imposed a high or low thermal burden on the wearer (McLellan, 1993; Montain *et al*., 1994; Amos & Hansen, 1997). However, not many studies have attempted to quantify the thermoregulatory strain imposed by each individual CBRN ancillary item, with the exception of the respirator (Scanlan & Roberts, 2001; Caretti, 2002; Roberge *et al*., 2012). In a pilot study Scanlan and Roberts (2001) assessed the thermal burden of the S10 respirator when wearing a CBRN suit in either a masked or unmasked condition during exercise (treadmill walking at 5.0 $km.hr^{-1}$ with a 0 % gradient) and rest in 30 °C and 60 % rh, thus when a maintained thermal load was placed upon the body. The authors found that physiologically, there were no significant differences in mean T_{re} or heart rate between masked and unmasked conditions, however during the masked condition participants reported greater whole body thermal discomfort. As mentioned in the previous chapter, only four volunteers were used in the Scanlan and Roberts (2001) study who wore the respirator for a total of 45 minutes of which only 30 minutes was exercise. Therefore, although the study was a repeated measures design, the results should be interpreted with caution.

Caretti (2002) investigated the thermal load imposed by the United States M40A1 respirator (this respirator is similar to the S10 respirator) on four male volunteers during treadmill exercise (40 % to 45 % of $\dot{V}O_{2max}$) and recovery in an environmental chamber set to 35 °C. The study consisted of four conditions; two conditions involved participants wearing a cotton coveralls with a protective overgarment (high thermal load) in either a masked or unmasked state, and two conditions involved wearing only cotton coveralls (lower thermal load) in either a masked or unmasked state. At a low thermal load there were no significant differences in T_{gi} (gastrointestinal temperature estimated by ingesting a telemetric temperature pill), sweat rate, $\overline{T}_{sk}$ or heart rate between masked and unmasked conditions. However at a high thermal load heart rate was significantly lower during unmasked compared to the masked condition at 110 minutes into the 120-minute protocol, which the authors commented might have been related to the lowered T_{gi} during the unmasked condition. This provided evidence that under a lower thermal load, differences between conditions were less distinct compared to a higher thermal load. However, this study also had a small sample size (n = 4) and the results should be interpreted with caution. The second study design described in this chapter incorporated periods of exercise and recovery however, unlike Caretti's (2002) study where the recovery periods were only 10 minutes long, this study allowed the participant to recover for 20 minutes. This methodological difference allowed for a greater distinction between conditions through calculations of linear rates of change of T_{re} over each time period.

5.2 Research Aims

The aims of this study were to:

4.11.1 Independently quantify the thermal burden imposed by each MVIP ancillary item during exercise and recovery in a hot and dry environment, whilst the thermal load between conditions was maintained.

4.11.2 Assess whether the quantification of the thermal burden of each item in the first study, when the thermal load was progressively lowered, would be matched in this study when a high thermal load was maintained between conditions.

5.3 Hypotheses

The general null hypothesis (H_0) was as follows:

H_{01}: Not wearing MVIP ancillary items would not decrease thermoregulatory strain when exercising at a light intensity in hot and dry conditions.

Various experimental hypotheses (H_a) were tested as stated below:

H_{a1}: Not wearing MVIP ancillary items would decrease thermoregulatory strain when exercising at a light intensity in hot and dry conditions.

H_{a2}: When exercising at a light intensity in hot and dry conditions the greatest decrease to thermoregulatory strain would occur when the gloves were not worn.

H_{a3}: When exercising at a light intensity in hot and dry conditions the least decrease to thermoregulatory strain would occur when the overboots were not worn.

5.4 Methods

5.4.1 Research Design

The research design, experimental protocol and procedures were identical to the first study (Chapter 4: Section 4.4.1) except that during each condition, only one MVIP was not worn: N_R (no respirator), N_{BAL} (no BAL), N_G (no gloves) and N_{OB} (no overboots) (Table IX). Environmental conditions were set to 40.5 °C and 20 % rh with the actual conditions achieved being mean (SD): 40.25 (0.77) °C (dry bulb) and 23.46 (0.79) °C (wet bulb) equating to approximately 27.1 % rh. There were no significant differences in environmental parameters between conditions ($p > 0.05$). Based upon the power analysis conducted (General Methods: Section 3.3), 13 fit and free from injury male participants volunteered from the University of Portsmouth's staff and student population. The participants' age, height, body mass and percentage of body fat were: mean (SD) 21.5 (2.4) years, 178.3 (5.0) cm, 75.7 (9.7) kg, 14.4 (4.1) % respectively. The statistical analysis conducted was identical to the analysis of the first study and is described in detail in General Methods: Section 3.4.5.

Table IX: The varying combinations of moisture vapour impermeable items worn.

Condition	Clothing				
	Suit + Hood	MVIP Overboots	MVIP Gloves	BAL	Respirator
CON	✓	✓	✓	✓	✓
N_{R}	✓	✓	✓	✓	✕
N_{BAL}	✓	✓	✓	✕	✓
N_{G}	✓	✓	✕	✓	✓
N_{OB}	✓	✕	✓	✓	✓

Note that a tick indicates the item was worn whereas a cross indicates the item was not worn.

Figure 21: Four participants exercising in the environmental chamber. Participants' conditions (from far left) are as follows: N_{BAL}, CON, N_{G} and N_{BAL}.

Figure 22: Two participants recovering in the environmental chamber. The participant on the left shows the quantification of the thermal burden of the gloves when the body was placed under a lowered thermal load (first study). The participant on the right shows the quantification of the thermal burden of the gloves when the thermal load on the body was maintained between conditions (current study).

For both the first and second studies, participants wore the same CBRN suit throughout all conditions. Although some suits had a woodland disruptive pattern material (DPM) and others had a desert DPM, the suits were identical in heat and vapour resistance measures. As no radiation light source was purposefully applied to the environment that could affect the amount of heat absorbed by the material (Lotens, 1995); participants wearing different DPM was not expected to significantly affect the results.

5.5 Results

5.5.1 Oxygen Uptake

Not wearing the gloves resulted in a marginally (0.84 $mL.kg^{-1}.min^{-1}$) greater mean $\dot{V}O_2$ during Work 2 compared to CON ($p < 0.01$). The mean $\dot{V}O_2$ during Work 1 when the overboots were not worn was again, marginally (0.81 $mL.kg^{-1}.min^{-1}$) greater compared to CON ($p < 0.05$).

5.5.2 Tolerance Time

Mean actual and predicted TT data are displayed in Table X. Details of participant TT and reasons for stopping early are presented in Appendix 7.

Table X: Participant completion data with the number of participants completing the protocol, mean (SEM) work tolerance times during Work 3 for each condition, mean (SEM) predicted tolerance time to a rectal temperature of 39.5 °C and 40 °C, the mean (SEM) predicted rectal temperature if Work 3 was completed whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{****}p < 0.0001$ *vs*. CON; $^{§}p < 0.05$ *vs*. N_G; $^{\#}p < 0.05$, $^{\#\#\#}p < 0.001$ *vs*. N_{OB}.

Condition	Number of Participants who Completed the Protocol (n = 13)	Mean (SEM) TT during Work 3 (minutes)	Mean (SEM) Predicted Experimental TT to a T_{re} of 39.5 °C (minutes)	Mean (SEM) Predicted Experimental TT to a T_{re} of 40 °C (minutes)	Predicted Mean (SEM) T_{re} if all 60 minutes of Work 3 were completed (°C)
CON	1	43.2 (2.5)	153.2 (3.3)	169.9 (3.7)	39.44 (0.11)
N_R	5	50.5 (3.2)	163.4 (3.2)§	182.2 (3.5)§	39.17 (0.08)$^{**** \#\#\#}$
N_{BAL}	5	51.4 (2.9)	161.1 (3.5)	179.2 (3.8)§	39.22 (0.09)$^{**** \#}$
N_G	7	52.4 (3.0)*	171.6 (3.8)**	192.5 (4.5)**	39.02 (0.07)$^{**** \#\#\#}$
N_{OB}	2	45.8 (2.6)	157.4 (3.7)	175.0 (4.1)§	39.34 (0.10)

Effect of not wearing the gloves

The condition with the greatest number of participants completing the full 60 minutes of stepping during Work 3 was N_G (7 out of 13), with a significantly extended mean TT during Work 3 of 9.2 minutes (21.3 %) compared to CON ($p < 0.05$) and an extended predicted mean TT to a T_{re} of 40 °C by 22.6 minutes (13.3 %, $p < 0.01$) compared to CON, by 10.3 minutes (5.7 %, $p < 0.05$) compared to N_R, by 13.3 minutes (7.4 %, $p < 0.05$) compared to N_{BAL} and by 17.5 minutes (10.0 %, $p < 0.05$) compared to N_{OB}. Predicted TT to a T_{re} of 39.5 °C was also significantly extended by 18.4 minutes (12.0 %, $p < 0.01$) compared to CON and by 8.2 minutes (5.0 %, $p < 0.05$) compared to N_R.

Effect of not wearing the overboots

The predicted mean T_{re} if all the 60 minutes of Work 3 were completed was significantly extended in all groups (N_R [0.17 °C, $p < 0.001$], N_{BAL} [0.12 °C, $p < 0.05$] and N_G [0.32 °C, $p < 0.001$]) except CON ($p > 0.05$) compared to N_{OB}.

5.5.3 Rectal Temperature

Figure 23 illustrates the ΔT_{re}, as presenting the absolute T_{re} for all conditions during the 170-minute protocol would introduce a slight bias, as participants did not begin each trial at the exact same T_{re} each day, although the time of day for participation was controlled.

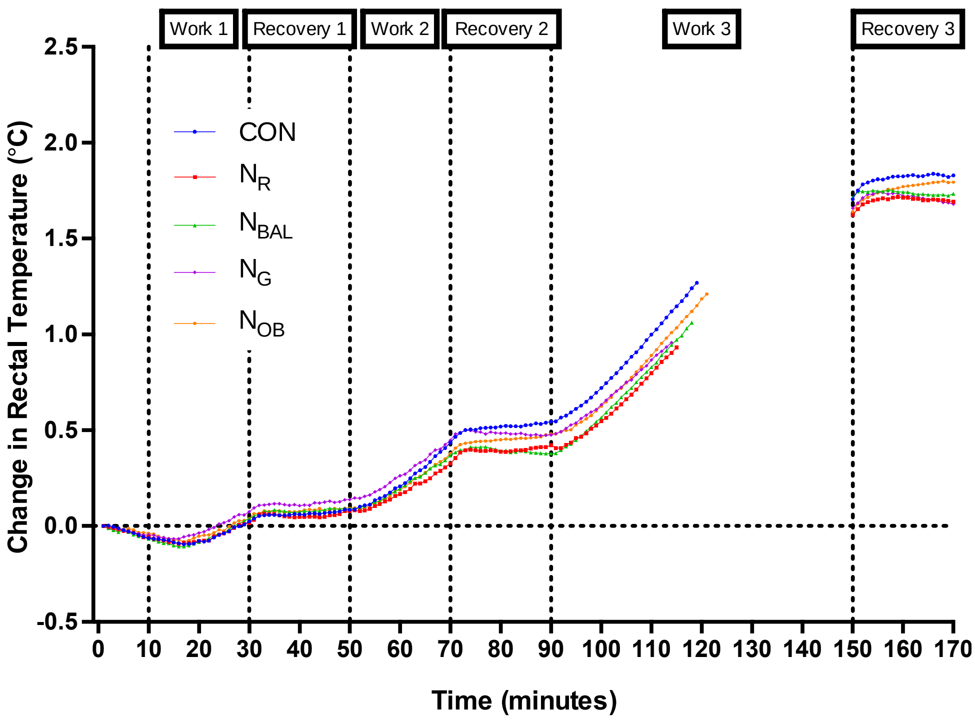

Figure 23: Mean change in rectal temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the respirator

Not wearing the respirator resulted in an attenuated rise of mean T_{re} compared to CON from 70 minutes (0.33 [0.05] °C *vs*. 0.44 [0.05] °C, $p < 0.05$) until 110 minutes (0.80 [0.06] °C *vs*. 1.00 [0.05] °C, $p < 0.0001$). This was by a maximum of 0.20 °C (20.1 %) at 110 minutes ($p < 0.0001$).

Effect of not wearing the body armour liner

Not wearing the BAL attenuated the rise of mean T_{re} from 80 minutes until the final measured point of Work 3 (110 minutes). This was by a maximum of 0.17 °C (16.9 %) at 110 minutes ($p < 0.001$).

Effect of not wearing the gloves

The rise of mean T_{re} was significantly attenuated when the gloves were not worn compared to CON at 110 minutes (0.87 [0.07] °C *vs*. 1.00 [0.05] °C, $p < 0.01$). This equated to a difference of 0.13 °C (13.3 %) at 110 minutes.

Effect of not wearing the overboots

Only at 110 minutes did not wearing the overboots significantly attenuate the rise of mean T_{re} compared to CON (0.89 [0.10] °C *vs*. 1.00 [0.05] °C, $p < 0.05$). This equated to a difference of 0.11 °C (10.9 %) at 110 minutes.

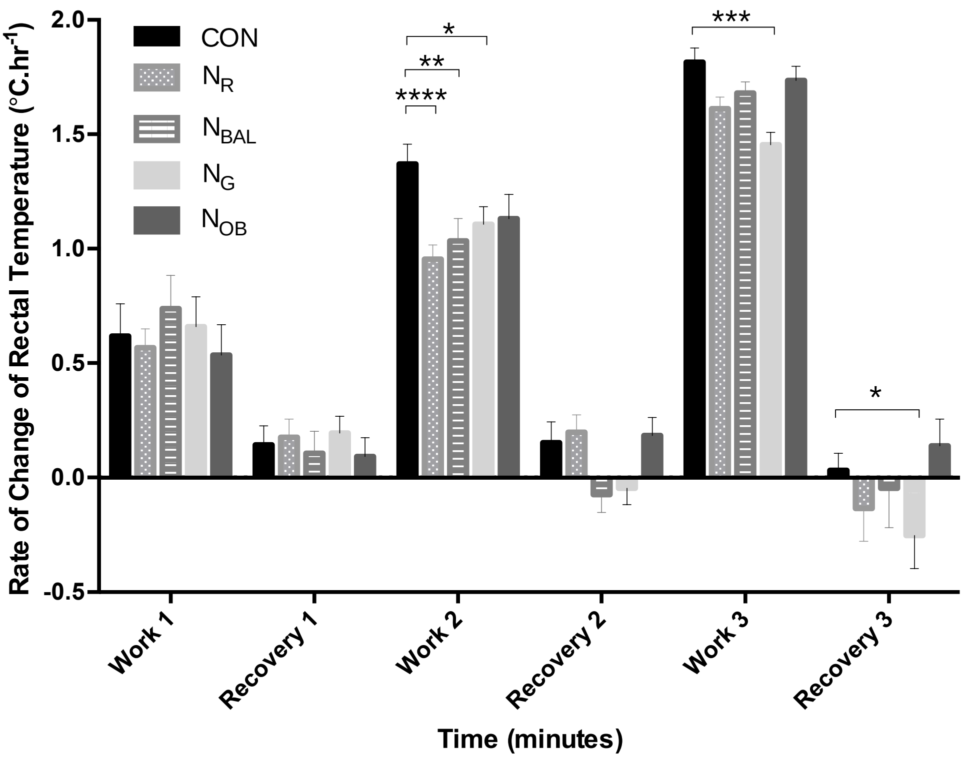

Figure 24: Mean (SEM) rate of change in rectal temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001 *vs*. CON.

Effect of not wearing the respirator

The mean rate of increase of T_{re} was significantly attenuated only during Work 2 when the respirator was not worn by 29.9 % (0.96 [0.06] °C.hr^{-1} *vs*. 1.37 [0.09] °C.hr^{-1}, $p < 0.0001$).

Effect of not wearing the body armour liner

Again, it was only during Work 2 that the mean rate of increase in T_{re} was significantly attenuated by 24.8 % when the BAL was not worn (1.03 [0.10] °C.hr^{-1} *vs*. 1.37 [0.09] °C.hr^{-1}, $p < 0.01$).

Effect of not wearing the gloves

Not wearing the gloves largely impacted on the mean rate of change of T_{re} as evidenced by a significant attenuation by 19.0 % during Work 2 (1.11 [0.08] °C.hr^{-1} *vs*. 1.37 [0.09] °C.hr^{-1}, $p < 0.05$), by 20.3 % during Work 3 (1.45 [0.05] °C.hr^{-1} *vs*. 1.82 [0.06] °C.hr^{-1}, $p < 0.001$) and cooling evident during Recovery 3 (-0.25 [0.14] °C.hr^{-1} *vs*. 0.03 [0.07] °C.hr^{-1}, $p < 0.05$).

Based upon the rate of rise in T_{re} during Work 3, mean TT from a T_{re} of 37.5 °C to 39.5 °C and 40.0 °C could be predicted (Figure 25).

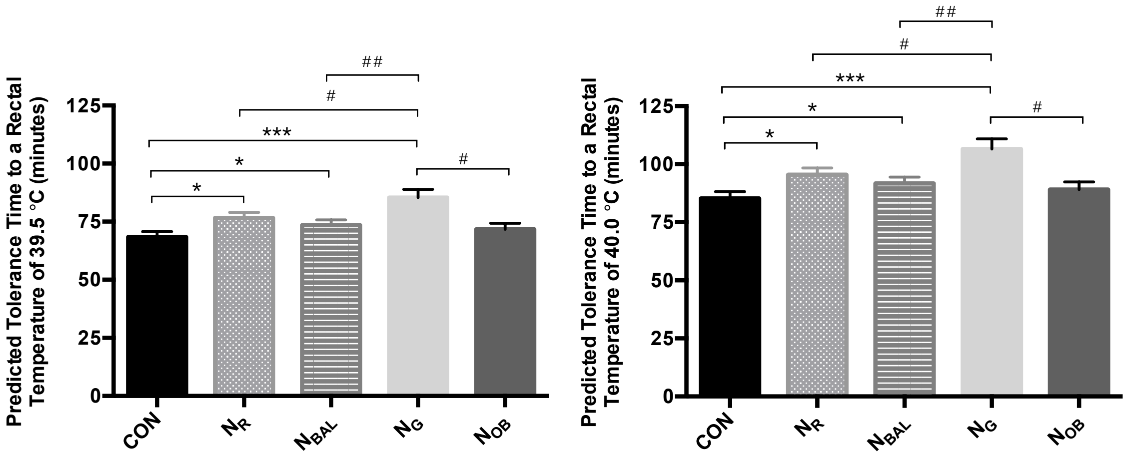

Figure 25: Mean predicted (SEM) tolerance time during each condition to a rectal temperature of 39.5 °C (left graph) and 40.0 °C (right graph) based upon the extrapolated rate of rise of rectal temperature obtained from Work 3 when working at a rate of oxygen uptake of 13.6 $mL.kg^{-1}.min^{-1}$ in a chamber set to 40.5 °C and 20 % rh air (n = 13). $^{*}p < 0.05$, $^{***}p < 0.001$ *vs*. CON; $^{\#}p < 0.05$, $^{\#\#}p < 0.01$ *vs*. N_G.

Effect of not wearing the respirator

Predicted mean TT to a T_{re} of 39.5 °C from 37.5 °C was extended by 8.2 minutes (12.1 %) when the respirator was not worn compared to CON ($p < 0.05$). Predicted mean TT to a T_{re} of 40.0 °C from 37.5 °C was extended by 10.2 minutes (12.0 %) when the respirator was not worn compared to CON ($p < 0.05$).

Effect of not wearing the body armour liner

Predicted mean TT to a T_{re} of 39.5 °C from 37.5 °C was extended by 5.2 minutes (7.5 %) when the BAL was not worn compared to CON ($p < 0.05$). Predicted mean TT to a T_{re} of 40.0 °C from 37.5 °C was extended by 6.5 minutes (7.6 %) when the BAL was not worn compared to CON ($p < 0.05$).

Effect of not wearing the gloves

Predicted mean TT to a T_{re} of 39.5 °C from 37.5 °C was extended by 17.0 minutes (24.9 %) when the gloves were not worn compared to CON ($p < 0.001$). Predicted mean TT to a T_{re} of 40.0 °C from 37.5 °C was extended by 21.3 minutes (25.0 %) when the gloves were not worn compared to CON ($p < 0.001$). Predicted mean TT to a T_{re} of 39.5 °C from 37.5 °C was extended by 8.8 minutes when the gloves was not worn compared to N_R, by 11.9 minutes when the gloves were not worn compared to N_{BAL} ($p < 0.01$) and by 13.6 minutes when the gloves were not worn compared to N_{OB} ($p < 0.05$). Predicted mean TT to a T_{re} of 40.0 °C from 37.5 °C was extended by 11.0 minutes when the gloves were not worn compared to N_R ($p < 0.05$), by 14.8 minutes when the gloves were not worn compared to N_{BAL} ($p < 0.01$) and by 17.3 minutes when the gloves were not worn compared to N_{OB} ($p < 0.05$).

5.5.4 Mean Skin Temperature

Mean $\overline{T}_{sk}$ during each condition is illustrated in Figure 26. Comparisons were made between all conditions from 0 minutes until 110 minutes (where n = 13 for all conditions). As $\overline{T}_{sk}$ was not linear, comparisons of $r\Delta\overline{T}_{sk}$ were calculated.

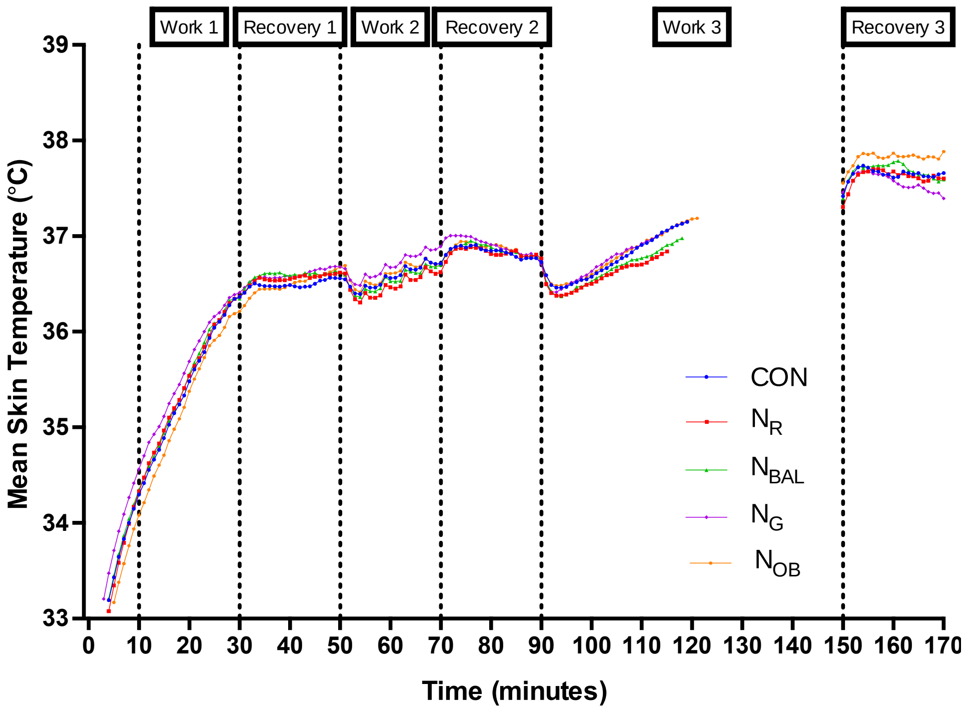

Figure 26: Average mean skin temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Note that due to thermistor detachment, T_{sk} data were not available and were subsequently predicted (Appendix 9) for the following:

P1 T_{calf} from 92 minutes during N_R

P4 T_{calf} from 136 minutes during N_{OB}

P8 T_{calf} from 93 minutes and 116 minutes during N_{OB} and N_{BAL}

Effect of not wearing the body armour liner

Compared to when the BAL was worn during CON, not wearing the BAL (N_{BAL}) resulted in a significantly greater mean $r\Delta\overline{T}_{sk}$ by 0.23 (0.02) °C ($p < 0.05$).

5.5.5 Mean Body Temperature

Figure 27 illustrates the mean $\Delta\overline{T}_b$ for all conditions with comparisons made every 10 minutes from 0 minutes to 110 minutes. During Recovery 3 $r\Delta\overline{T}_b$ was calculated.

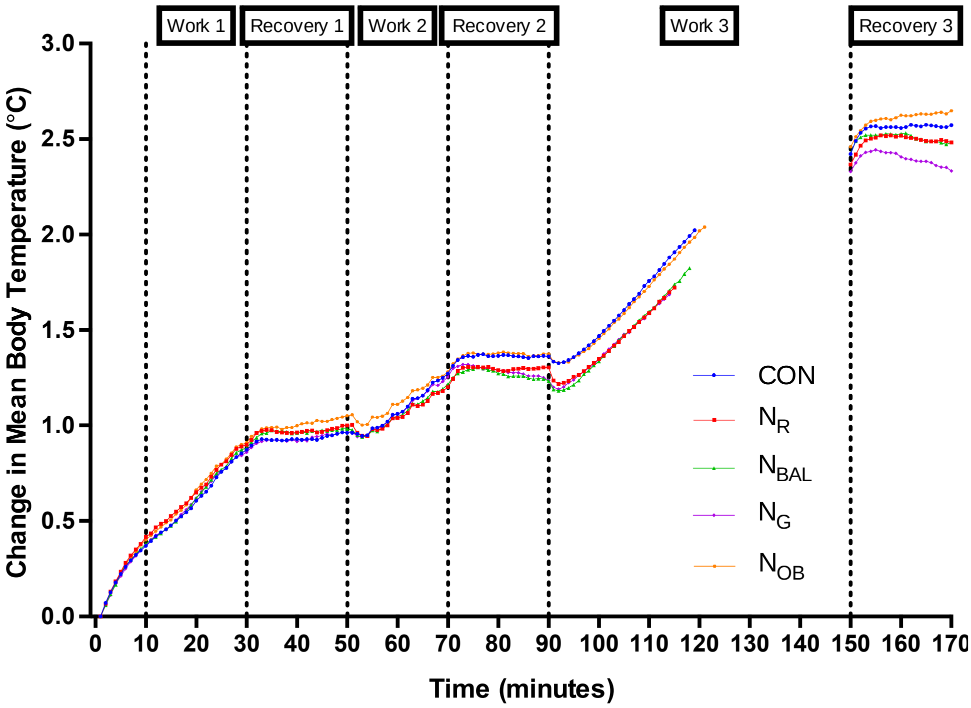

Figure 27: Mean change in mean body temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the respirator

Not wearing the respirator significantly attenuated the rise of $\overline{T}_b$ during Work 3 at 100 minutes (1.35 [0.09] °C *vs.* 1.47 [0.08] °C, $p < 0.05$) and 110 minutes (1.59 [0.09] °C *vs.* 1.76 [0.08] °C, $p < 0.001$) compared to CON. This was by a maximum of 0.17 °C (9.7 %).

Effect of not wearing the body armour liner

Not wearing the BAL significantly attenuated the rise of $\overline{T}_b$ compared to CON at 90 minutes (1.23 [0.11] °C *vs.* 1.36 [0.08] °C, $p < 0.05$) to 110 minutes (1.60 [0.11] °C *vs.* 1.76 [0.08] °C, $p < 0.01$). This was by a maximum of 0.16 °C (9.1 %). The mean $r\Delta\overline{T}_b$ during Recovery 3 when the BAL was not worn was also significantly improved by 0.06 (0.02) °C compared to CON ($p < 0.01$).

Effect of not wearing the gloves

When the gloves were not worn, the rise of $\overline{T}_b$ was significantly attenuated compared to CON at 90 minutes (1.24 [0.10] °C *vs.* 1.36 [0.08] °C, $p < 0.05$) to 110 minutes (1.59

[0.09] °C *vs*. 1.76 [0.08] °C, $p < 0.001$). This was by a maximum of 0.17 °C (9.7 %). The mean $r\Delta\overline{T}_b$ during Recovery 3 when the gloves were not worn was also significantly improved by 0.09 (0.03) °C compared to CON ($p < 0.05$).

5.5.6 Local Skin Temperatures

5.5.6.1 Cheek Temperature

Mean T_{cheek} during each condition is shown in Figure 28.

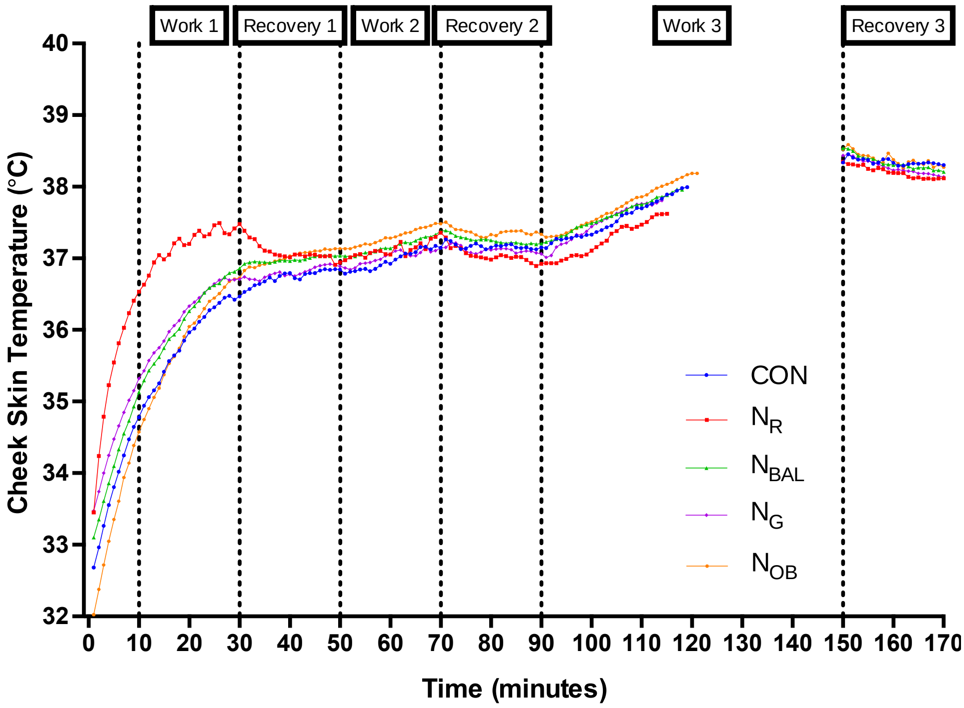

Figure 28: Mean cheek temperature whilst stepping and recovering in 40.5 °C and 20 % rh air ($n = 13$). Data were truncated at the last point where $n = 13$ for each condition.

Effect of not wearing the respirator

During the first 30 minutes into the protocol, not wearing the respirator resulted in a significantly greater mean T_{cheek} compared to CON and all other conditions (at 10 minutes: 36.54 [0.12] °C *vs*. CON: 34.78 [0.31] °C, $p < 0.0001$; at 20 minutes: 37.20 [0.10] °C *vs*. CON: 35.97 [0.21] °C, $p < 0.0001$; at 30 minutes: 37.48 [0.14] °C *vs*. CON: 36.47 [0.20] °C, $p < 0.0001$). When the respirator was not worn, the mean T_{cheek} was 1.76 °C hotter than during CON after 10 minutes rest in the chamber and remained hotter throughout Work 1, until 10 minutes into Recovery 1.

Effect of not wearing the gloves

During the first 10 minutes, not wearing the gloves also increased mean T_{cheek} compared to CON (35.32 [0.27] °C *vs*. 34.78 [0.31], $p < 0.01$).

5.5.6.2 Finger Temperature

Mean T_{finger} during each condition is shown in Figure 29.

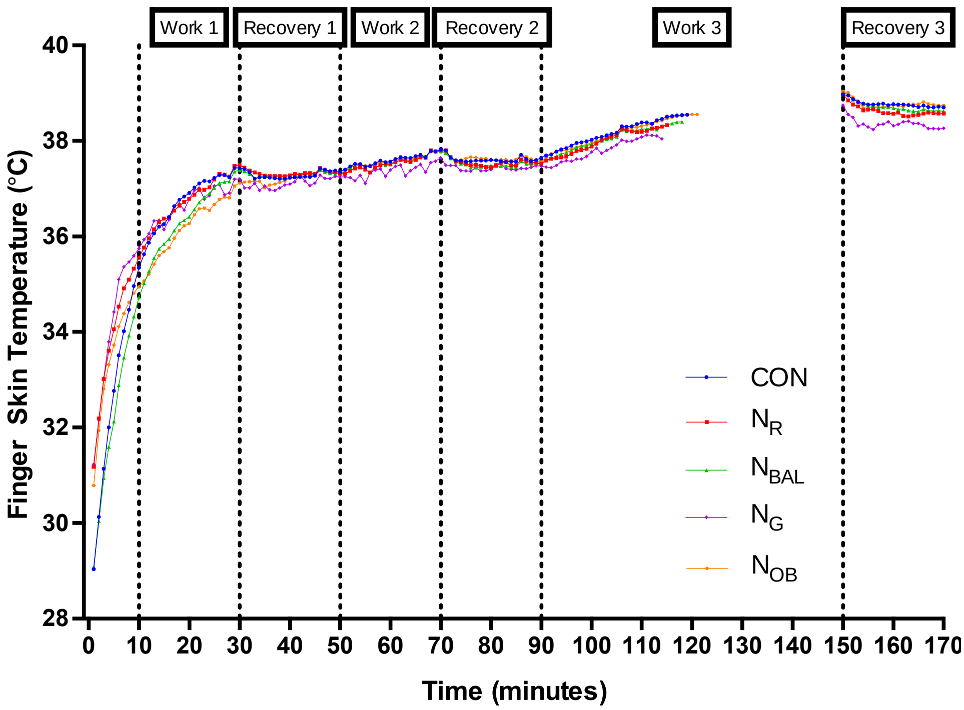

Figure 29: Mean finger temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the body armour liner

Not wearing the BAL resulted in a significantly lowered mean T_{finger} at 10 minutes compared to CON (34.72 [0.89] °C *vs*. 35.35 [0.73] °C, $p < 0.05$).

Effect of not wearing the overboots

Not wearing the overboots resulted in a significantly lowered mean T_{finger} at 20 minutes compared to CON (36.27 [0.64] °C *vs*. 36.91 [0.15] °C, $p < 0.05$).

5.5.6.3 Chest Temperature

Mean T_{chest} during each condition is shown in Figure 30.

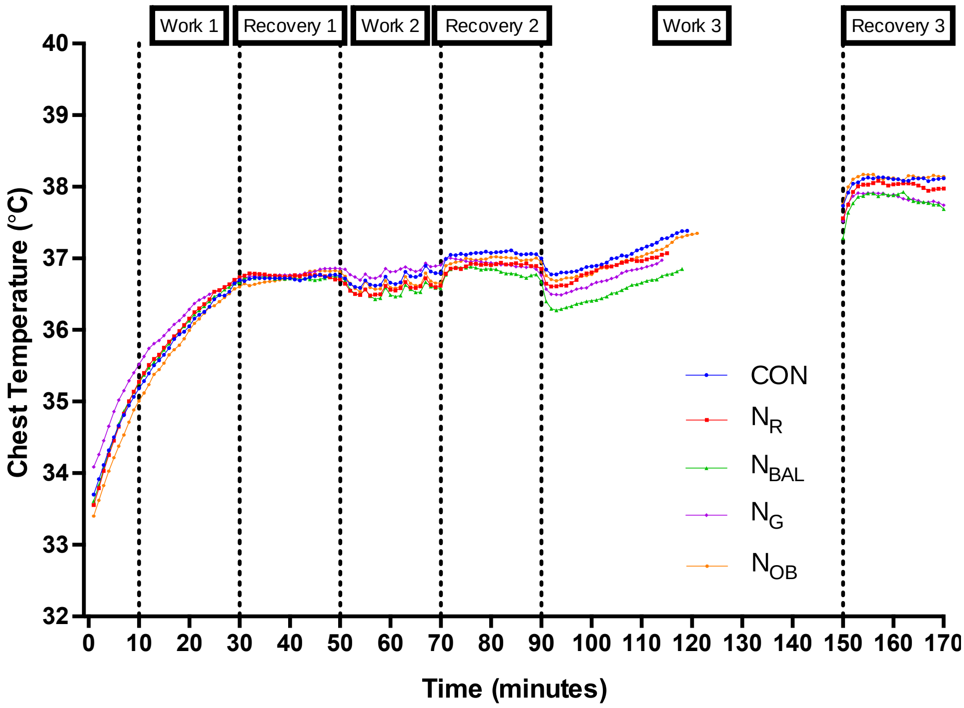

Figure 30: Mean chest temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the body armour liner

Mean T_{chest} when the BAL was not worn was significantly lowered compared to CON at 100 minutes (36.41 [0.23] °C *vs*. 36.89 [0.10] °C, $p < 0.01$) and 110 minutes (36.66 [0.23] °C *vs*. 37.13 [0.11] °C, $p < 0.01$).

5.5.7 Whole Body Sweat Production and Evaporation

The mean whole body rate of sweat production, rate of sweat evaporation and the sweat evaporation / production ratio are illustrated in Figure 31.

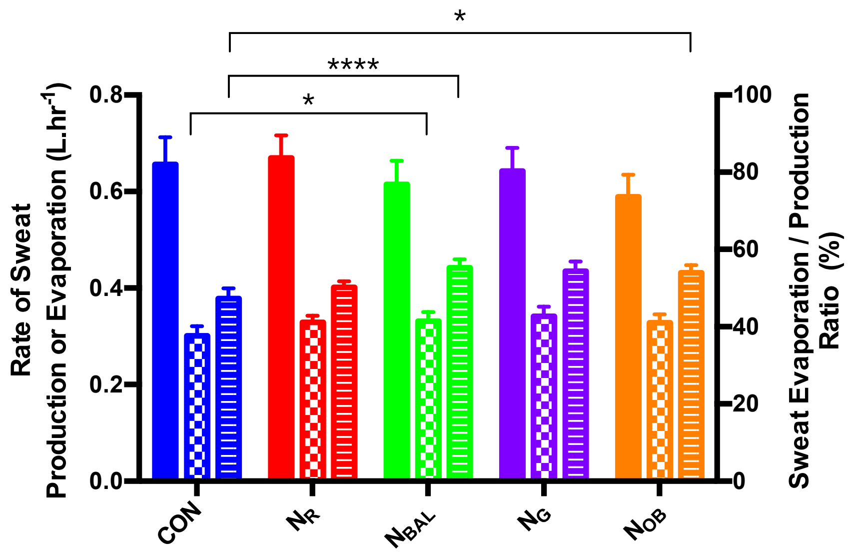

Figure 31: Mean (SEM) whole body rate of sweat production (solid) and evaporation (checked) and the sweat evaporation / production ratio (stripes) whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 13). $^{*}p < 0.05$, $^{****}p < 0.0001$ *vs*. CON.

Effect of not wearing the body armour liner

When adjusted for individual TT the mean rate of sweat evaporation when the BAL was not worn was increased by 10 % compared to CON (0.33 [0.02] $L.hr^{-1}$ *vs*. 0.30 [0.02] $L.hr^{-1}$, $p < 0.05$). The mean sweat evaporation / production ratio was also improved by 17.1 % when the BAL was not worn compared to CON (55.32 [2.11] % *vs*. 47.25 [2.68] %, $p < 0.01$).

Effect of not wearing the overboots

Not wearing the overboots significantly improved the mean whole body sweat evaporation / production ratio by 14.2 % compared to CON (53.98 [2.01] % *vs*. 47.25 [2.68] %, $p < 0.05$).

5.5.8 Heart Rate

The mean heart rate during each condition is shown in Figure 32.

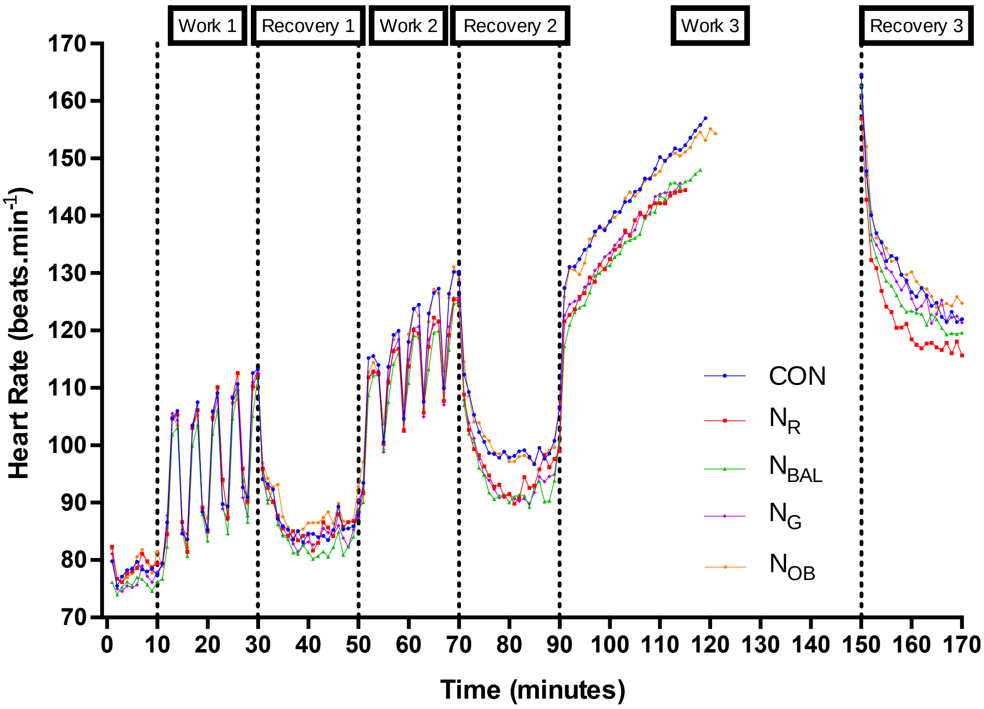

Figure 32: Mean heart rate whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the respirator

Not wearing the respirator significantly lowered the mean heart rate compared to CON at 90 minutes (99 [4] beats.min^{-1} *vs*. 107 [4] beats.min^{-1}, $p < 0.05$) and 110 minutes (142 [4] beats.min^{-1} *vs*. 150 [4] beats.min^{-1}, $p < 0.01$) and this was by a maximum of 8 beats.min^{-1}.

Effect of not wearing the body armour liner

Compared to CON, the mean heart rate when the BAL was not worn was significantly lowered during Work 2 at 60 minutes (111 [4] beats.min^{-1} *vs*. 118 [4] beats.min^{-1}, $p < 0.05$), Work 3 at 100 minutes (131 [3] beats.min^{-1} *vs*. 139 [4] beats.min^{-1}, $p < 0.05$) and 110 minutes (144 [4] beats.min^{-1} *vs*. 150 [4] beats.min^{-1}, $p < 0.05$) with an enhanced reduction in mean heart rate during Recovery 2 at 80 minutes (90 [5] beats.min^{-1} *vs*. 98 [4] beats.min^{-1}, $p < 0.05$). This was by a maximum of 8 beats.min^{-1}.

5.5.9 Physiological Strain Index

The mean PSI during each condition is shown in Figure 33.

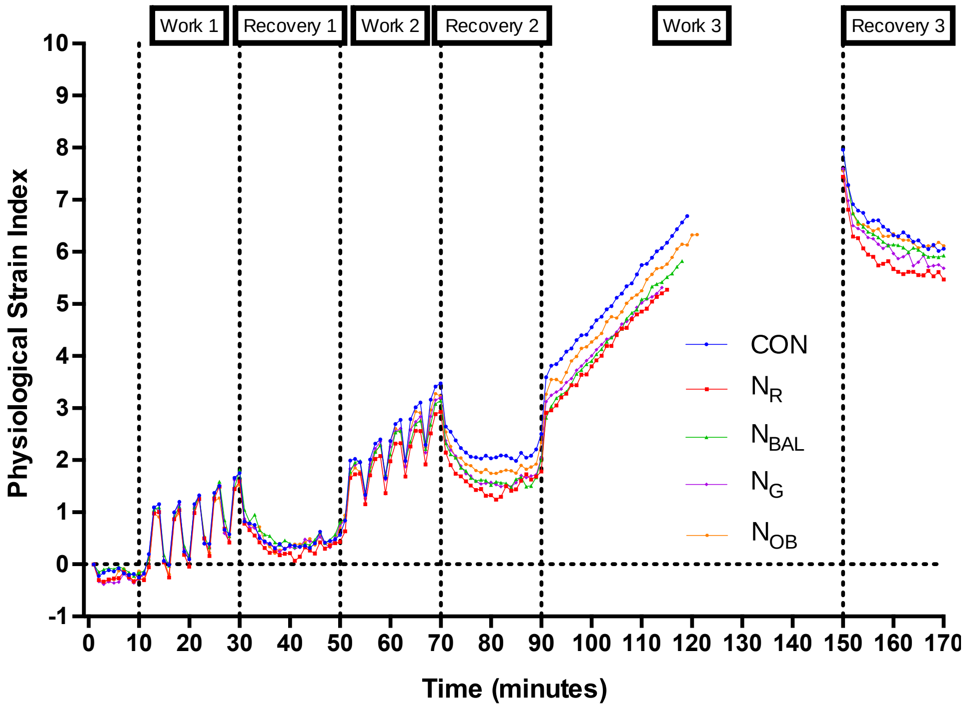

Figure 33: Mean physiological strain index whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). Data were truncated at the last point where n = 13 for each condition.

Effect of not wearing the respirator

The mean PSI when the respirator was not worn was significantly lowered throughout the protocol compared to CON from 70 minutes (2.93 [0.19] *vs*. 3.48 [0.20], $p < 0.05$) until 110 minutes (5.76 [0.28] *vs*. 4.86 [0.23], $p < 0.0001$) and was reduced by a maximum of 0.89 (15.5 %) during Work 3.

Effect of not wearing the body armour liner

The mean PSI was lowered when the BAL was not worn from 80 minutes (1.53 [0.27] *vs*. 2.03 [0.18], $p < 0.05$) until 110 minutes (5.09 [0.29] *vs*. 5.75 [0.28], $p < 0.01$) compared to CON and was lowered by a maximum of 0.66 (11.4 %).

Effect of not wearing the gloves

Not wearing the gloves significantly lowered the mean PSI at 100 minutes (4.00 [0.28] *vs*. 4.55 [0.23], $p < 0.05$) and 110 minutes (5.02 [0.30] *vs*. 5.75 [0.28], $p < 0.001$) compared to CON. The mean PSI was lowered by a maximum of 0.73 (12.6 %).

Effect of not wearing the overboots

The only time during the entire protocol whereby not wearing the overboots lowered the mean PSI was at 110 minutes compared to CON (5.25 [0.04] *vs*. 5.75 [0.28], $p < 0.05$), with an attenuation of 8.6 %.

5.5.10 Perceptual Measures

Mean perceptual measures of thermal comfort, thermal sensation and skin wettedness are presented in the figures below. There were no significant differences to the mean RPE.

5.5.10.1 Thermal Comfort

Figure 34 illustrates the mean perceived thermal comfort during each condition.

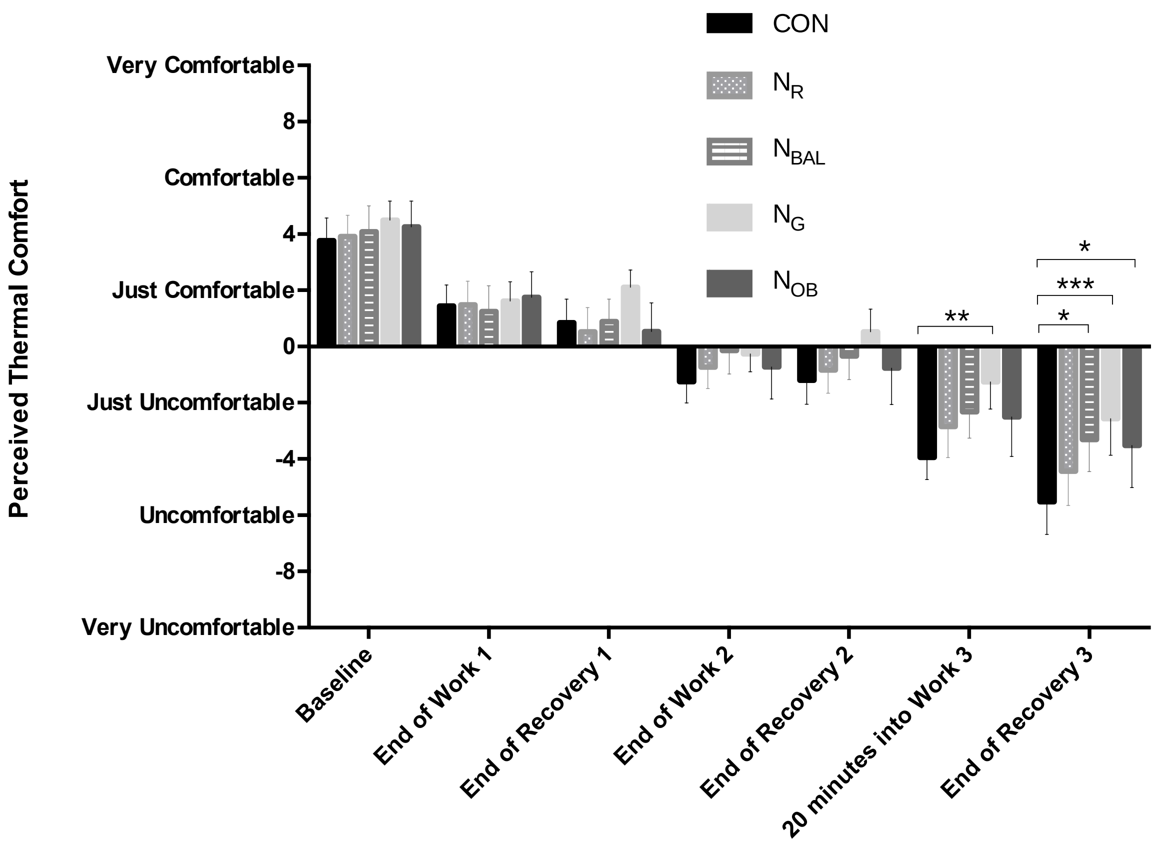

Figure 34: Mean (SEM) perceived thermal comfort whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ *vs*. CON.

Effect of not wearing the body armour liner

It was only at the end of the final recovery period that participants rated N_{BAL} less uncomfortable than CON (-3.31 [1.14] *vs*. -5.52 [1.17], $p < 0.05$).

Effect of not wearing the gloves

Participants reported feeling significantly less uncomfortable when the gloves were not worn compared to CON 20 minutes into Work 3 (-1.26 [0.96] *vs*. -3.94 [0.79], $p < 0.01$) and at the end of Recovery 3 (-2.57 [1.30] *vs*. -5.52 [1.17], $p < 0.001$). At the end of Recovery 3, participants' reported feeling "just uncomfortable" during N_G compared to "uncomfortable" during CON.

Effect of not wearing the overboots

It was only at the end of the final recovery period that participants reported feeling less uncomfortable when the overboots were not worn compared to CON (-3.52 [1.50] *vs*. -5.52 [1.17], $p < 0.05$).

5.5.10.2 Thermal Sensation

Figure 35 illustrates the mean perceived thermal comfort during each condition.

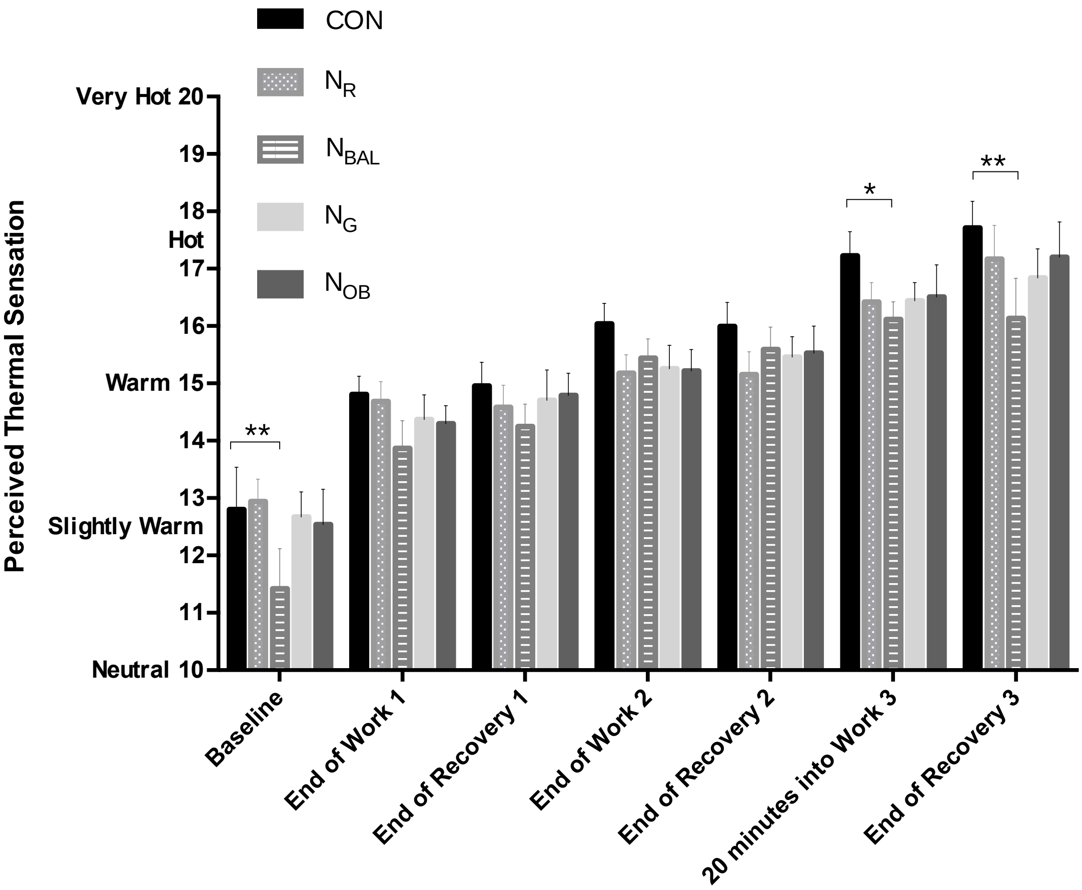

Figure 35: Mean (SEM) perceived thermal sensation whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). $^{*}p < 0.05$, $^{**}p < 0.01$ *vs*. CON.

Effect of not wearing the body armour liner

Significant differences to the mean perceived thermal sensation were only noted during N_{BAL}. Initially at baseline, participants reported feeling less warm when the BAL was not worn compared to when the BAL was worn during CON (11.42 [0.70] *vs*. 12.80 [0.74], $p < 0.01$). Not wearing the BAL also significantly improved mean reporting's of thermal sensation compared to CON 20 minutes into Work 3 (16.12 [0.31] *vs*. 17.22 [0.42], $p < 0.05$) and at the end of Recovery 3 (16.13 [0.70] *vs*. 17.71 [0.47], $p < 0.01$).

5.5.10.3 Skin Wettedness

Mean perceived skin wettedness is illustrated in Figure 36. Participants felt progressively wetter as the protocol progressed.

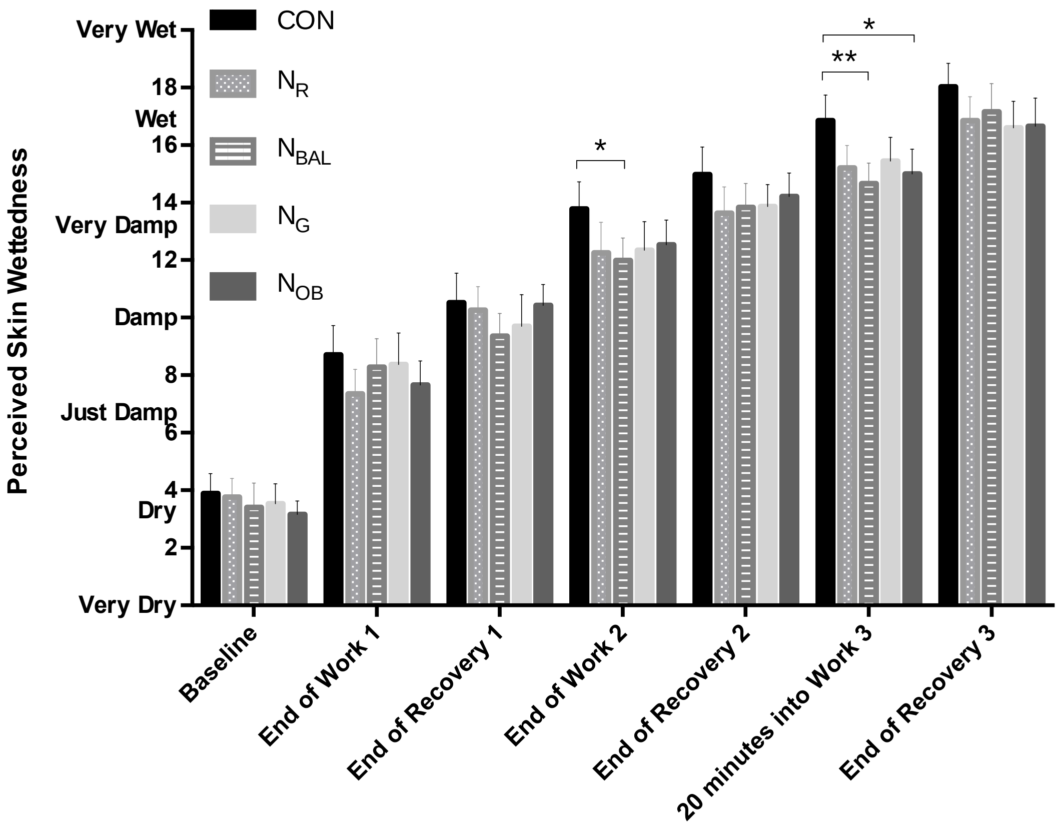

Figure 36: Mean (SEM) perceived skin wettedness whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 13). $^{*}p < 0.05$, $^{**}p < 0.01$ *vs*. CON.

Effect of not wearing the body armour liner

Not wearing the BAL was reported as feeling less wet compared to CON at the end of Work 2 (11.99 [0.79] *vs*. 13.78 [0.94], $p < 0.05$) and 20 minutes into Work 3 (14.65 [0.72] *vs*. 16.85 [0.88], $p < 0.01$). The maximum difference between conditions resulted in participants reporting feeling "very damp" compared to "wet".

Effect of not wearing the overboots

Not wearing the overboots was reported as feeling less wet compared to CON 20 minutes into Work 3 only (15.00 [0.86] *vs*. 16.85 [0.88], $p < 0.05$).

5.5.11 Summary of Results

Table XI below shows a summary of the results discussed above.

Table XI: Summary of results indicating where thermoregulatory strain has been reduced (green arrow) or increased (red arrow) whilst stepping and recovering in 40.5 °C and 20 % rh air when wearing varying combinations of MVIP ancillary items (n = 13).

Whole Body Measure of Thermoregulatory Strain	**N_R**	**N_{BAL}**	**N_G**	**N_{OB}**
Tolerance Time (Work 3)			↑	
Predicted Experimental TT to a T_{re} of 39.5 °C			↑	
Predicted Experimental TT to a T_{re} of 40 °C			↑	
Predicted T_{re} if all 60 minutes of Work 3 were completed	↓	↓	↓	
Predicted TT from a T_{re} of 37.5 °C to 39.5 °C	↓	↓	↓	
Predicted TT from a T_{re} of 37.5 °C to 40 °C	↓	↓	↓	
Rate of Sweat Evaporation		↑		
Sweat Evaporation / Production Ratio		↑		↑
Measure of Thermoregulatory Strain 20 minutes into Work 3	**N_R**	**N_{BAL}**	**N_G**	**N_{OB}**
ΔT_{re}	↓	↓	↓	↓
Rate ΔT_{re}			↓	
$\Delta\overline{T}_b$	↓	↓	↓	
ΔT_{chest}		↓		
Heart Rate	↓	↓		
PSI	↓	↓	↓	↓
Perceived Thermal Comfort			↑	
Perceived Thermal Sensation		↓		
Perceived Skin Wettedness		↓		↓
Measure of Thermoregulatory Strain at the end of Recovery 3	**N_R**	**N_{BAL}**	**N_G**	**N_{OB}**
Rate ΔT_{re}			↑	
$\Delta\overline{T}_{sk}$		↑ (red)		
$\Delta\overline{T}_b$		↓	↓	
Perceived Thermal Sensation		↓		
Perceived Thermal Comfort		↑	↑	↑

Note that a green arrow indicates that the measure of thermoregulatory strain was improved; with a red arrow indicating the measure was worsened. A blank cell indicates that the measure was unchanged.

5.6 Discussion

The first aim of this study was to quantify the thermal burden imposed by each MVIP item independently, whilst the overall thermal load placed on the body was maintained at a high level. Overall, the results indicated that each MVIP item imposed a thermal burden but that the thermal burden was not equal between items, with the gloves imposing the largest burden and the overboots the least as quantified by the reduction to thermoregulatory strain when the items were not worn. This was different to the results of the first study whereby the BAL imposed the greatest thermal burden on the wearer, although the overboots were also the least burdensome item in the first study. Therefore as discussed in detail below, altering the thermal load placed upon the body (progressively lowering the thermal load in the first study *vs*. maintaining the thermal load in the current study) impacted on the quantification of the thermal burden imposed by any single MVIP item.

5.6.1 The Thermal Burden of Protective Equipment

The first hypothesis stated that not wearing MVIP ancillary items would decrease thermoregulatory strain when exercising at a light intensity in hot and dry conditions. In line with previous research (McLellan *et al*., 1992; McLellan *et al*., 1993; Amos & Hansen, 1997; Chapter 4), this study highlighted that the fully encapsulating CBRN protective ensemble imposed a thermal burden on the wearer as removing the thermal resistance of any one of the ancillary items reduced thermoregulatory strain. For example, when the gloves were not worn, TT was significantly extended and there were improved ratings of thermal comfort, whilst not wearing the respirator attenuated the rise of $\overline{T}_b$ and heart rate. Not wearing the BAL increased the rate of sweat evaporation, which most likely was the reason participants felt drier and less hot. Finally, not wearing the overboots increased the whole body sweat evaporation / production ratio and resulted in participants feeling less wet. Therefore the null hypothesis was rejected and the experimental hypothesis accepted that not wearing MVIP ancillary items decreased thermoregulatory strain when exercising at a light intensity in hot and dry conditions.

5.6.2 The Significant Thermal Burden of the Gloves

The second hypothesis stated that the greatest decrease to thermoregulatory strain would occur when the gloves were not worn. N_G was the only condition that significantly attenuated the rate of rise of T_{re} during Work 3 compared to CON by 20.3 % and this resulted in the greatest number of participants completing the full 60 minutes of stepping (7 out of 13), with TT significantly extended by 21.3 % during Work 3. Additionally, when analyzing the predicted TT to a T_{re} of 39.5 °C or 40.0 °C from a T_{re} of 37.5 °C, the TT when the gloves were not worn (N_G) was significantly extended compared to all conditions (CON, N_R, N_{BAL} and N_{OB}). As mentioned in the first study discussion, it is appropriate to predict TT to a T_{re} of 39.5 °C and 40.0 °C. It was found that when predicting TT to a T_{re} of 39.5 °C, 8 % (CON), 0 % (N_R), 8 % (N_{BAL}), 8 % (N_G) and 8 % (N_{OB}) of participants would have reached their age-predicted maximum heart rate before predicted T_{re} reached 39.5 °C. When T_{re} was predicted to 40.0 °C, 8 % (CON), 8 % (N_R), 15 % (N_{BAL}), 31 % (N_G) and 8 % (N_{OB}) of participants would have reached their age-predicted maximum heart rate prior to predicted T_{re} reaching 40.0 °C.

Although the hands only have a surface area of 4.6 % of total body surface area (Yu *et al*., 2008), the hands possess a high density of sweat glands (Taylor & Machado-Moreira, 2013) and allow for a large increase in SkBF due to high densities of capillaries and large arteriovenous anastomoses (Grant & Bland, 1931; Hales, 1985; Caldwell *et al*., 2014) and therefore exposing the hands in a hot and dry environment during exercise was expected to reduce thermoregulatory strain. Furthermore, due to the nature of the exercise prescribed (stepping) and the subsequent hand swinging motion that accompanies stepping, the range of motion at the extremities, which is greater than the range of motion centrally (Graves *et al*., 1988; Dorman & Havenith, 2005; Wang *et al*., 2012) should allow for a greater degree of forced evaporative cooling at the hands, although direct evaporative cooling at the hands was not measured in this study.

The study protocol required that participants stepped at a rate of 12 steps.min^{-1} with pre-defined recovery periods and therefore any extension to TT would be specific to this work rate and intensity. Therefore, assuming a linear rate of increase of T_{re} without achieving thermal balance, predicting TT from a T_{re} of 37.5 °C to 39.5 °C or 40.0 °C significantly extended TT by 17.0 minutes or 21.3 minutes respectively. This would equate to the warfighter theoretically patrolling for an extra 1.12 km (T_{re} to 39.5 °C, 8 % not reaching this based on reaching a maximum heart rate) or 1.41 km (T_{re} to 40.0 °C, 31 % not reaching this based on heart rate) (McLellan *et al*., 1992). Additionally, the patrolling warfighter would, where possible, stop exercising and recover when the thermal burden became overwhelming, rather than only recovering at pre-defined time points. Thus, the rate of decline of T_{re} during recovery was of importance and there was a significant degree of cooling by 0.28 °C.hr^{-1} during Recovery 3 in N_G compared to CON, where T_{re} continued to rise overall by 0.03 °C.hr^{-1}. Therefore improving the MVP of materials covering the hands could result in large thermoregulatory gains that are of operational significance.

The rate of sweat evaporation from the hands was not reflected in the whole body measure, which does not mean that there was not a significant amount of evaporative cooling at the hands, but rather that the local evaporation was not sufficient to impact on the whole body response. We acknowledge that the thermistor was attached to the finger pad using a Tegaderm™ tape which itself is waterproof[11] (therefore largely MVIP) and could have restricted evaporative cooling directly at that specific finger pad site (whilst all other fingers and parts of the hand remained entirely exposed) and therefore T_{finger} may have been overestimated in this, and the previous, study and may not have been truly representative of the entire exposed hand temperature. To address this concern, an experiment was conducted whereby two skin thermistors were attached to the cheek of a participant using either Tegaderm™ tape or a more permeable Transpore™ tape, whilst the T_{sk} of the entire face was monitored with a thermal imaging camera (Appendix 8). Each method of measuring T_{sk} was found to possess a limitation; a surface skin thermistor is mounted onto a highly thermally conductive stainless steel disc that either gains or loses heat from the skin or the environment and therefore may not represent exact T_{sk}, whilst the thermal imaging camera estimates the T_{sk} taking into account the emissivity of the object that can change with a change in skin wettedness. Additionally, while attaching the skin thermistor was more secure with the Tegadem™ tape and protected the thermistor from the direct influence of sweat beads unlike the Transpore™ tape, the Tegaderm™ tape may have created an insulative microclimate around the thermistor. Therefore, it was concluded that securing a surface skin thermistor with a Tegaderm™ tape, while acknowledging its limitations in restricting evaporative cooling and possibly fostering an insulative microclimate, was favorable to other methods available to our laboratory (Appendix 8).

A recent review by Taylor *et al*. (2014a) dedicated to explaining why the hands (and feet) in particular are of great thermoregulatory importance, stated that not only is the surface area to mass ratio of the hands favourable for heat dissipation (male hand: 0.098 $m^2.kg^{-1}$ *vs*. male foot: 0.069 $m^2.kg^{-1}$) but maximal blood flow to the hands can increase 4.5 times compared to basal blood flow. Although exact increases to the entire hand SkBF during heating have not been determined, finger SkBF increases from basal levels by approximately 3 times during local heating (Freccero *et al*., 2003). Additionally, blood flow greatly increases upon dilatation of the arteriovenous anastomotic vessels that are prolific throughout the glabrous skin of the hands and feet (Metzler-Wilson *et al*., 2012;

[11] http://solutions.3m.com Wound care product information. 3M™ Tegaderm™ HP Transparent Film Dressing Frame

Taylor *et al*., 2014a). Although local SkBF at the hands was not measured directly in this study we can speculate that blood flow to the hands most likely reached near to maximal values based upon the work of Caldwell *et al*. (2014) who assert that maximal blood flow to the hands is only accomplished in the presence of some level of hyperthermia (T_{oe}: 38.5 °C, hand T_{sk}: 40.0 °C), which was the case in the current study, particularly during Work 3 and Recovery 3 (at the start of Recovery 3 mean T_{re}: 38.8 °C, mean T_{finger}: 38.8 °C).

The significant physiological improvements to thermoregulatory strain when the gloves were not worn were also detected perceptually. Indeed under conditions of a continuous stimulus, possible adaptation of skin thermoreceptors could diminish any perceptions of improved thermal comfort (de Dear & Brager, 2001; Barwood *et al*., 2009; Davey *et al*., 2013) and therefore the findings in the current study are noteworthy. Furthermore, perceptual improvements were found at the end of Recovery 3 compared to CON even though participants had, by that time, spent a longer duration in the chamber during N_G (Table X). Although not wearing the gloves did not impact on participants' perceived thermal sensation throughout the protocol, N_G did result in participants feeling less uncomfortable. It was unexpected that improving evaporation at a small surface area such as the hands (~ 4.6 % of total body surface area [Yu *et al*., 2008]) would dominate one perceptual thermal response (comfort) over another (sensation) (Hensel, 1981; Zhang, 2003). To clarify, during N_{BAL} at 110 minutes, T_{chest} was 0.47 °C cooler than T_{chest} during CON, and there was an improved thermal sensation but not thermal comfort. This suggests the threshold for improved thermal sensation at the torso is lower than for improved thermal comfort as was found in Chapter 4 when the improved thermal sensation was detected sooner than improved thermal comfort when the BAL was not worn. Whereas during N_G at 110 minutes, T_{finger} was 0.30 °C cooler than T_{finger} during CON, and there was an improved thermal comfort but not thermal sensation. This suggests that the threshold for improving thermal comfort at the finger / hand is lower than the threshold for improving thermal sensation. Therefore for a lesser decrease in T_{finger} (0.30 °C) compared to T_{chest} (0.47 °C) whole body thermal comfort was improved. This suggests that the extremities might possess a lowered threshold for detection of thermal discomfort *i.e.* a higher sensitivity to thermal discomfort, compared to the torso. This was mentioned in the Review of Literature (Chapter 2: Section 2.4.1) and builds on the work of Fukazawa and Havenith (2009).

It is well known that isolated body areas possess varying limits of local thermal comfort, and that particularly the periphery possesses a higher sensitivity to thermal discomfort compared to the torso (Fukawaza & Havenith, 2009), as was in the present study. However, it was expected that the thermal comfort threshold would be closely linked to perceptions of skin wettedness (Fukawaza & Havenith, 2009), which was not the case in the current study (at 110 minutes perceived skin wettedness during CON was 16.85 [0.88] and during N_G was 15.44 [0.83]; $p = 0.131$). To accurately detect skin wettedness under a warm stimulus in the absence of visual detection (as is the case when wearing CBRN protective equipment), it is the experience of coldness that determines the perception of skin wettedness (Filingeri *et al*., 2014). As sweat produced by the body under the thermal burden of wearing CBRN protective equipment is not cold, but rather is close to T_{sk}, the perception of skin wettedness in a CBRN microclimate might have been distorted. Furthermore, this study assessed whole body, rather than site-specific, perceived skin wettedness thereby making our measure of skin wettedness less sensitive to detect local changes. Interestingly though, participants could distinguish local changes to thermal comfort using a whole body measure suggesting there may be an additional driver for thermal comfort in addition to local skin wettedness. Ueda *et al*. (2006) found that the perceptual response of thermal comfort outweighed physiological responses when regional areas were subject to improved air permeability during exercise (30 % and 45 % $\dot{V}O_{2max}$) in moderate conditions (25 °C, 50 % rh, air velocity of 0.3 $m.s^{-1}$). Thus, as moisture vapour transport was greater at the extremities than centrally during walking, or indeed stepping, due to increased limb speed (Wang *et al*., 2012) this might have accounted for the improved perceived thermal comfort when the gloves were not worn.

Overall not wearing the gloves resulted in: the greatest number of participants completing the protocol (7 out of 13); was the only condition that significantly attenuated the rate of rise of T_{re} during Work 3 and increased cooling during Recovery 3; reduced the change of $\overline{T}_b$ by 0.17 °C; and extended TT by 21.3 % during Work 3; as well as improved thermal comfort. Therefore, the null hypothesis was rejected and the experimental hypothesis that when exercising at a light intensity in hot and dry conditions the greatest decrease to thermoregulatory strain would occur when the gloves were not worn was accepted.

5.6.3 The Minimal Thermal Burden of the Overboots

The third hypothesis stated that the least decrease to thermoregulatory strain would occur when the overboots were not worn. Due to their large surface area to volume ratio, as well as a high density of active sweat glands, the feet are an effective avenue of heat loss (Taylor & Machado-Moreira, 2013; Caldwell *et al*., 2014; Taylor *et al*., 2014a). Additionally, during exercise (including exercise with a load carriage component), venous return from the foot is enhanced due to the pumping action induced by muscle contraction and compression (Pegum & Fegan, 1967). Therefore if evaporative cooling was permitted at the feet then the cooled blood returning from the feet would be circulated around the body thus reducing thermoregulatory strain. Not wearing the overboots improved the mean whole body sweat evaporation / production ratio by 14.2 %, lowered PSI and T_{re} at 110 minutes by 8.6 % and 10.9 % respectively, and resulted in improved mean ratings of skin wettedness and thermal comfort. There were no significant reductions to other markers of thermoregulatory strain such as the rate of change of T_{re}, $\overline{T}_b$ or heart rate. This was most likely because 100 % evaporation from the feet was not permitted in this study due to the feet still being covered by socks and combat boots. Therefore any benefits to whole body cooling from foot exposure would not have been apparent in this study, although the practical benefits of improving the permeability of the overboots in isolation to any alterations of other materials covering the feet (socks and combat boots) was highlighted. Considering the research aim was to identify which CBRN ancillary item should be improved due to the high thermal burden it imposed, again, as in the first study, it was not recommended that the overboots be improved before the gloves, respirator or BAL. Considering the predicted T_{re} if all of the 60 minutes of Work 3 were completed (Table X), the T_{re} of all conditions except N_{OB} were significantly reduced compared to CON. Additionally, N_R ($p < 0.001$), N_{BAL} ($p < 0.05$) and N_G ($p < 0.001$) all displayed a significantly reduced T_{re} compared to N_{OB}. Thus, the null hypothesis was rejected and the experimental hypothesis was accepted that when exercising at a light intensity in hot and dry conditions the least decrease to thermoregulatory strain would occur when the overboots were not worn.

5.6.4 The Thermal Burden of the Body Armour Liner

Although the gloves have been shown to impose the greatest thermal burden upon the wearer with the overboots imposing the least, it is important to discuss the thermal burden imposed by the BAL and respirator. The torso accounts for approximately 39.5 % of total body surface area (Weiner, 1945) and during the first study was the item that imposed the greatest thermal burden and therefore it was expected that when the BAL was not worn there would be significant improvements to thermoregulatory strain. When adjusted for individual TT, the rate of sweat evaporation during N_{BAL} was increased by 10.0 % and the sweat evaporation / production ratio was also improved by 17.1 %. A significantly lowered T_{chest} expressed the enhanced evaporative cooling as chest sweat evaporated. The thermoregulatory improvements to sweat evaporation were insufficient to extend TT during Work 3, although a trend was evident ($p = 0.059$). However, when predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C or 40.0 °C was calculated from the rate of rise of T_{re} during Work 3 in N_{BAL} (1.68 $°C.hr^{-1}$), there was a significantly extended TT of 5.2 minutes (7.5 %) or 6.5 minutes (7.6 %) respectively compared to CON.

Although $\overline{T}_{sk}$ was only lowered during the last 10 minutes of Recovery 3, not wearing the BAL attenuated the rise of $\overline{T}_b$ by a maximum of 0.16 °C at 110 minutes. The lowered thermal burden lowered heart rate throughout Work 2 and Work 3, with an enhanced reduction in heart rate throughout Recovery 2. The reduction in PSI was significant during Recovery 2 and Work 3 by a maximum of 0.66 (11.4 %), which was 0.07 less than the maximum reduction to PSI during N_G even though the surface area of the hands is approximately 8 times smaller than the torso (Weiner, 1945; Yu *et al*., 2008). Furthermore, when considering that the rate of cooling during Recovery 3 was 0.05 (0.17) $°C.hr^{-1}$ when the BAL was not worn compared to 0.25 (0.14) $°C.hr^{-1}$ when the gloves were not worn, it can be predicted that for T_{re} to cool by 0.5 °C it would take approximately 2 hours if the gloves were not worn compared to approximately 10 hours if the BAL was not worn. Importantly, however, it must be remembered that when the BAL was not worn, materials covering the torso were not made 100 % MVP as the torso was still covered by the suit, unlike when the gloves were not worn and the hands were completely exposed and evaporation was unhindered.

Not wearing the BAL was the only condition that resulted in improved ratings of thermal sensation and skin wettedness (apart from N_{OB} 20 minutes into Work 3). These perceptual results from improving the MVP of materials covering the torso were not expected as the somatosensory homunculus, highlighted that the hands and face provide a large amount of sensory feedback to the brain in comparison to the trunk (Penfield & Boldrey, 1937). Furthermore, thermoreceptors are not homogenously distributed across the skin surface (Nadel *et al*., 1973; Cotter *et al*. 1996) and the face in particular displays a greater thermal sensitivity compared to other areas of the body (Cotter & Taylor, 2005). Upon further analysis of the local T_{sk} at 110 minutes when thermal sensation was lowest during N_{BAL} only, when the BAL was not worn, T_{chest} was 0.47 °C cooler than T_{chest} during CON, when the gloves were not worn, T_{finger} was 0.30 °C cooler than T_{finger} during CON and when the respirator was not worn T_{cheek} was 0.23 °C cooler than T_{cheek} during CON. The greatest reduction to local T_{sk} (T_{chest}) during N_{BAL} was most likely responsible for the lowest perceived thermal sensation reported. This suggests that a local T_{sk} threshold exists for individual's to feel less hot, particularly as $\overline{T}_{sk}$ was not significantly lowered during N_{BAL} at 110 minutes compared to CON although participants felt less hot. Gueritee *et al*. (2015)

found that the magnitude of change from the normal T_{sk} distribution in thermoneutral air affects perceptual measures of thermal comfort and the results found in the current study might extend their work to thermal sensation. Furthermore, the dominance of removing a MVIP layer from the torso on improved thermal sensation responses in this study could also be explained by the large surface area of the torso in comparison to other body areas (face, hands and feet) as well as the torso possessing a high sensitivity to warmth for initiation of the sweating response (Cotter & Taylor, 2005). Additionally, it may be that the somatosensory homunculus could be altered with increased thermoregulatory strain and /or when wearing moisture-vapour restrictive clothing.

5.6.5 The Thermal Burden of the Respirator

While not wearing the respirator and exposing the face to the hot and dry environment did not significantly impact whole body sweat production or evaporation, the PSI during N_R was lowered throughout the protocol from 70 minutes until 110 minutes and was attenuated by a maximum of 0.89 (15.5 %) during Work 3 which was the greatest attenuation to PSI compared to not wearing any other item. Calculation of the PSI involves both T_{re} and heart rate as previously mentioned, and not wearing the respirator resulted in the earliest attenuation to the rise of T_{re} with the maximum reduction by 0.20 °C, which again was the greatest reduction compared to not wearing any other item. More importantly however, unlike N_G, the rate of change of T_{re} was not attenuated during Work 3. Therefore, N_R did not result in any significant extension to TT, although predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C or 40.0 °C was extended by 8.2 minutes (12.1 %) and 10.2 minutes (12 %) respectively. It was also calculated that if participants were to have completed the full one-hour of stepping during Work 3, then compared to when the respirator was worn (CON), by 150 minutes into the protocol participants would have been 0.34 °C cooler during N_R. Not wearing the respirator also resulted in a significantly lowered rise of $\overline{T}_b$ during Work 3 by a maximum of 0.17 °C. It was not surprising that exposing the face improved the thermal status of participants as the large cooling potential of the forehead has been noted due to a high rate of sweat output and a large sudomotor sensitivity (Taylor *et al*., 2008; Smith & Havenith, 2011).

Not wearing the respirator also lowered heart rate compared to CON and heart rate during N_G was not significantly different compared to CON throughout the entire protocol although a trend was present ($p = 0.058$). Early work investigating the physiological responses when wearing a respirator, found that during two hours of exercise, heart rate was elevated when a respirator was worn even though T_c was not significantly different, although $\overline{T}_{sk}$ was elevated (Robinson & Gerking, 1945). Martin and Callaway (1974) also identified an elevated heart rate during two hours of bench stepping in a warm environment (dry bulb: 34.0 °C) when wearing a respirator. Often an increase in heart rate when wearing a respirator is attributable to the associated loaded breathing (Hermansen *et al*., 1972), but in the current experiments, almost all inspiratory resistance of the respirator was removed (Section: 4.4.2). In this study, the lowered heart rate during N_R was most likely due to the lowered thermoregulatory strain during this condition. Although, an elevated heart rate when the respirator was worn could also be associated with anxiety that some individuals might experience during exercise when wearing a respirator (Morgan, 1983) or even hyperventilation that can induce tachycardia (Morgan, 1983). Therefore, it may be that participants felt less anxious when the respirator was not worn, which therefore culminated in a lower heart rate. However, as anxiety was not measured in this study, this was merely speculation.

There were no significant improvements to any perceptual measures during N_R compared to CON, which was not expected as the face was greatly represented on the somatosensory homunculus (Penfield & Rasmussen, 1950) and has been shown to display a greater thermal sensitivity compared to other areas of the body (Cotter & Taylor, 2005) as well as that improved perceptual measures were found in the previous experiment (Chapter 4). Whole body, not local measures of perceptual responses were obtained, which might be the reason that exposing the face did not result in large significant improvements to perceptual measures during the current study. Additionally, as mentioned, it is also possible that there was adaptation of skin thermoreceptors under constant environmental conditions that could diminish any perceptions of improved thermal comfort (de Dear & Brager, 2001; Barwood *et al*., 2009; Davey *et al*., 2013). Furthermore the initial facial heat gain represented by T_{cheek} without subsequent lowering of T_{cheek} further on in the protocol might have resulted in negative thermal perceptual responses, particularly as the work of McIntyre (1980) found that the sensation of warmth is initially dependent upon T_{sk} and then later on T_c. However, as improvements to thermal comfort and thermal sensation were identified during the first study, it was surprising that no improvements were noted during the current study. T_{cheek} was significantly lower from 80 minutes until 110 minutes during Study 1 yet was not significantly lowered at any point during the protocol in the current study. The difference in environmental conditions between the first and second studies was minimal (Study 1: 40.23 °C, 26.8 % rh, Study 2: 40.25 °C, 27.1 % rh) and therefore was most likely not responsible for the different T_{cheek} findings. In any case, the absolute difference in thermal comfort and thermal sensation between the two studies at the final point measured during Work 3 was negligible (thermal comfort SOGAR *vs*. SOGA: 6.0 *vs*. 7.5 and thermal comfort CON *vs*. N_R: 6.1 *vs*. 7.2, thermal sensation SOGAR *vs*. SOGA: 17.6 *vs*. 16.4 and thermal sensation CON *vs*. N_R: 17.2 *vs*. 16.4) and might have been made more distinct with a larger sample size. Furthermore, it may be that as participants got progressively hotter and more uncomfortable, they were less accurate in their perceptual responses or took less time to consider exactly how they were feeling.

Both N_R and N_{BAL} resulted in equal numbers of participants completing the protocol and considering that the surface area of the torso is approximately 14 times that of the face (even though the torso was still covered by the suit whereas the face was completely exposed to the environment), it appeared that exposing the face resulted in physiological thermoregulatory improvements that were greater than expected for its surface area.

5.6.6 Differential Thermal Loading (Study 1 Versus Study 2)

Two methodological approaches were undertaken to estimate the thermal burden imposed by each MVIP item: cumulatively not wearing items thereby progressively lowering the thermal load (Study 1) *vs*. not wearing items in isolation to each other thereby largely maintaining the thermal load between conditions (Study 2). It was anticipated that the progressively lowered thermal load in the first study might have resulted in underestimations of the thermal burden imposed by each MVIP item, particularly the gloves and overboots, which had less of a thermal load over which to demonstrate an improvement being tested whilst the respirator and BAL had already been removed. The PSI is a measure of thermoregulatory strain as it incorporates both T_{re} and heart rate at a given time point and can therefore attribute a single data point indicative of two variables of whole body thermoregulatory strain (Moran *et al.*, 1998). Table XII quantified the differences in the improvement to PSI between the first and second studies at the furthest measure taken during Work 3 where all participants were still stepping (110 minutes) and the final PSI at the end of the protocol (170 minutes).

Table XII: The relative changes to the mean physiological strain index from either the CON condition (second study) or the adjacent condition (first study) at 110 minutes into the protocol and at the end of Recovery 3 (Study 1: n = 12, Study 2: n = 13).

Thermal Load Progressively Lowered (1st Study)		**Thermal Load Maintained (2nd Study)**	
20 minutes into Work 3 (110 minutes)	**Reduction in PSI compared to adjacent condition (%)**	**20 minutes into Work 3 (110 minutes)**	**Reduction in PSI compared to CON (%)**
SOGA (no respirator)	13.1 ($p < 0.001$)	N_R	15.5 ($p < 0.0001$)
SOG (no respirator or BAL)	22.1 ($p < 0.0001$)	N_{BAL}	11.4 ($p < 0.01$)
SO (no respirator, BAL or gloves)	8.4 (ns)	N_G	12.6 ($p < 0.001$)
S (no respirator, BAL, gloves or overboots)	5.9 (ns)	N_{OB}	8.6 ($p < 0.05$)
End of Recovery 3	**Reduction in PSI compared to adjacent condition (%)**	**End of Recovery 3**	**Reduction in PSI compared to CON (%)**
SOGA (no respirator)	4.5 (ns)	N_R	9.7 ($p < 0.01$)
SOG (no respirator or BAL)	13.1 ($p < 0.01$)	N_{BAL}	2.1 (ns)
SO (no respirator, BAL or gloves)	22.3 ($p < 0.0001$)	N_G	5.9 (ns)
S (no respirator, BAL, gloves or overboots)	23.1 ($p < 0.0001$)	N_{OB}	-1.0 (ns)

Table XII shows that 20 minutes into Work 3 (at 110 minutes) in the first study, the impact of not wearing the gloves (condition: SO) and the overboots (condition: S) on PSI were underestimated compared to the second study. Whereas the impact of not wearing the respirator (condition: SOGA) appeared to be evenly matched between the two studies, and not wearing the BAL (condition: SOG) might have been slightly overestimated in the first study compared to the second study. Therefore, during exercise when a lower thermal load was placed upon the body for conditions SO and S particularly; an underestimation of the thermal burden imposed by the gloves (4.2 % difference between Study 1 and Study 2) and overboots (2.7 % difference between Study 1 and Study 2) was evident compared to when the thermal load was maintained. This was most likely because the items (gloves and overboots) had less of a thermal load over which to demonstrate an improvement. The PSI in all conditions, except the first condition (SOGA), at the end of Recovery 3 appeared to be overestimated during the first study compared to the second study. Therefore during recovery, when a lower thermal load was placed upon the body for conditions SO and S particularly, an overestimation of the thermal burden imposed by the gloves and overboots were evident compared to when the thermal load was maintained. This was most likely because of the additional avenues of cooling (uncovered face and no BAL) during the first study. It is unclear why there was a distinction between work and recovery, but it was most likely that evaporative cooling was enhanced during stepping with the additional movement at the extremities. Additionally, concomitant with elevated blood pressure during exercise, there is increased perfusion at the deep body tissues and presumably at the site where T_c was sampled (rectum, 15 cm beyond the anal sphincter). Therefore, enhanced evaporative cooling from small exposed surface areas could have a large impact during exercise but during recovery when there was no movement and less tissue perfusion, cooling from small exposed surface areas might have had a smaller effect.

Reasons why estimations of the thermal burden of items differed depending on thermal loading should be explored. The finding that differential thermal loading alters the estimation of the thermal burden of protective equipment has been reported previously (McLellan *et al*., 1992; Scanlan & Roberts, 2001; Caretti, 2002), although quantifying the thermal burden of MVIP items whilst manipulating the thermal load was not the aim of those studies. The primary avenue for heat loss in a hot and dry environment is through evaporation of sweat (Nielsen & Nielsen, 1965; Åstrand & Rodahl, 1977), and as the two methodologies differed in the proportion of the body covered by MVIP items (which restrict evaporative cooling), this could be the reason for the varying results based upon differential thermal loading of the body. For example, the additional mean whole body rate of sweat evaporation when the gloves were not worn (SO) compared to when the gloves were worn (SOG) in the first study was 0.01 $L.hr^{-1}$, with the mean whole body rate of sweat production being 0.57 $L.hr^{-1}$. Whereas the additional mean whole body rate of sweat evaporation in N_G compared to CON was 0.04 $L.hr^{-1}$, with the mean whole body rate of sweat production being 0.64 $L.hr^{-1}$. Therefore the driving function was greater in the second study as the thermal load on the body was higher and therefore the gloves had a higher thermal load over which to demonstrate an improvement.

Moreover, during exercise arterial blood is required by the working muscles to facilitate metabolic energy production as well as by the skin to facilitate heat dissipation (Rowell *et al*., 1969) and Q is compensatory up until T_c reaches 39.5 °C (Hubbard & Armstrong, 1988). It can therefore be assumed that during both studies Q was not compromised as the maximal average T_{re} reached only 39.1 °C. Furthermore, Caldwell *et al*. (2014) found that maximal blood flow to the extremities (hands and feet) was only accomplished when the core was hyperthermic (38.5 °C) and T_{sk} was elevated (40.0 °C). During the first study the T_{re} at 110 minutes was lowered during SO (37.9 °C) and S (37.7 °C) compared to N_G (38.0 °C) and N_{OB} (38.2 °C) during the second study. Therefore, it is possible that SkBF to the extremities during SO and S was less than during N_G and N_{OB} and therefore, less cooled blood (as sweat evaporates, due to the latent heat of vaporization, the underlying skin, tissue and blood is cooled) might have been circulated around the body during SO and S. However, the control of SkBF does differ throughout the body. Arteriovenous anastomoses are prolific in glabrous skin, the palmar hand, yet absent in non-glabrous skin, parts of the dorsal hand (Grant & Bland, 1931), and modulate the vasomotor response differently, such that SkBF at arteriovenous anastomotic sites increases quickly to maximum with the release of vasoconstrictor tone, whereas SkBF at non-arteriovenous anastomotic sites increases with active vasodilatation as T_c progressively increases (Gaskell, 1956; Fox *et al*., 1962).

To conclude, as there was an underestimation of the thermal burden of items 20 minutes into Work 3 with an overestimation at the end of Recovery 3 compared to the first study, it can be stated that thermal loading influenced the estimation of the thermal burden of items, and in this instance, particularly of the gloves.

The effect of differential thermal loading was not exclusive to physiological responses alone but also perceptual responses. The perceptual benefits of not wearing the overboots were largely undetected in the first study compared to the second. It was possible that exposing other areas in combination with the area of interest, whole body perceptual measures were distorted. For example, when rating thermal perceptions when the overboots were not worn in the first study (progressively lowering the thermal load), the respirator, BAL and gloves were also not worn and therefore the participant might not have been able to accurately perceive the sole burden of the overboots. Whereas in the second study (maintaining the thermal load), the overboots were the only item not worn, thus the participant’s awareness focused on an individual item, allowing for a more accurate response. Furthermore, perceptual improvements were found during SOGA but not N_R. As during SOGA the respirator was the only item to be removed in isolation, it is possible that this perceptual response was exaggerated, as previously mentioned.

To test which methodological approach (progressively lowering the thermal load *vs*. maintaining the thermal load) truly provided the most accurate quantification of the thermal burden of each MVIP item with respect to the end user, it would be advantageous to repeat the method of the first study (progressively lowering the thermal load) except in the reverse order. Such that the first item to not be worn are the overboots with the last being the respirator. It would be hypothesized that due to the progressively lowered thermal load, the quantification of the thermal burden of all MVIP items (but particularly the first and last to be removed) would not match that of the first study and therefore, the methodology whereby the thermal load was maintained between conditions would most likely be the more accurate approach. The advantage however, of progressively lowering the thermal load was that the cumulative benefits of not wearing MVIP items could more accurately be assessed compared to purely adding the improvement from each item during the second study when the thermal load was maintained. For example, if a simple addition of the improvements to evaporative cooling during the second study were made, then it would be estimated that if all the ancillary items were made from 100 % MVP materials the rate of sweat evaporation would improve by 0.127 $L.hr^{-1}$ (42 %), a similar result from the manikin tests whereby whole body vapour resistance was reduced by 40 % (Table IV). However, based upon the data from the first study, it can be accurately calculated that the rate of sweat evaporation would only improve by 0.061 $L.hr^{-1}$ (20 %). Therefore in this case, when aiming to identify the cumulative benefits of making materials 100 % MVP, the methodology adopted in the first study was more accurate.

5.7 Conclusions

As not wearing any one of the CBRN ancillary items significantly decreased physiological and perceptual thermoregulatory strain, the first null hypothesis was rejected and the experimental hypothesis was accepted that not wearing MVIP ancillary items decreased thermoregulatory strain when exercising at a light intensity in hot and dry conditions. As the greatest number of participants completed the full protocol when the gloves were not worn and N_G was the only condition where there was an extended TT during Work 3 of 21.3 % as well as improved thermal comfort, the second null hypothesis was rejected and the experimental hypothesis that when exercising at a light intensity in hot and dry conditions the greatest decrease to thermoregulatory strain would occur when the gloves were not worn was accepted. When the overboots were not worn there were improvements to physiological markers of thermoregulatory strain such as an improved whole body sweat evaporation / production ratio, PSI, T_{re} as well as perceptual measures of thermoregulatory strain such as skin wettedness and thermal comfort. However, as not wearing other items resulted in greater improvements to these measures and there were no significant reductions to other markers of thermoregulatory strain, the third null hypothesis was rejected and experimental hypothesis was accepted that the least decrease to thermoregulatory strain would occur when the overboots were not worn. Regarding the different levels of thermal loading between the first and second studies, it was found that there was an underestimation of the thermal burden of items 20 minutes into Work 3 with an overestimation at the end of Recovery 3 and therefore, differential thermal loading can influence estimations of the thermal burden of equipment.

5.8 Impact of Findings and Future Research

- Based upon the results of this study, it is recommended that the MVP of materials covering the hands should be the prime focus for improvement and that again; the MVP of the combat boots should be improved in conjunction with the overboots.
- It is also advised that the thermal load should be maintained between conditions in future studies that aim to assess the thermal burden of individual pieces of equipment, unless the aim is to assess the cumulative thermal burden.
- This study has also highlighted that exposing areas of a small surface area such as the face (approximately 2.7 % of total body surface area [manikin Newton, Thermetrics, US]) and the hands (approximately 4.6 % of total body surface area [Yu *et al*., 2008]) can have a larger impact on whole body physiological and perceptual responses than what is expected for their given surface area. However, it was uncertain which area was more sensitive to exposure to a hot and dry environment and would therefore affect whole body sudomotor and vasomotor thermoregulatory responses. This was further explored in the next experiment (Chapter 6).

5.9 Theoretical *Versus* Practical Implications

The study directives and aims required that the thermal burden of MVIP ancillary items should be quantified. Therefore, when considering the thermal burden of the BAL for example, the torso was still covered by the suit and not completely exposed to the environment as the face and hands were when the gloves or respirator were not worn. From a theoretical perspective, to truly compare exposing the torso *vs*. the hands or face it would have been preferable to make all materials surrounding the torso 100 % MVP. Although this would not answer the question as to which item should primarily be made MVP, it would allow for accurate comparison between truly exposing only the hands compared to exposing the torso. Practically however, materials surrounding the torso are unlikely to ever be made 100 % MVP as the BA plates need to maintain their protective role against ballistic insults and the soft armour needs to be protected from moisture. Even if in the future more MVP BA could be developed, there is still the issue of load carriage being primarily placed on the torso (Knapik & Reynolds, 2012) that would restrict evaporative cooling, although forced air cooling under the BA could pose an attractive avenue of future research.

Finally, a study (Appendix 10) was undertaken that quantified the reductions to thermoregulatory strain during exercise and recovery when wearing fully encapsulating CBRN protective clothing and covering the hands with air permeable material. It was found that replacing the MVIP gloves with the air permeable gloves resulted in three more participants completing the protocol, a lowered T_{finger} throughout the protocol until 20 minutes into Work 3, reduced T_{re} by 0.23 °C and $\overline{T}_b$ by 0.12 °C, with PSI being reduced by 17 %. The participants also perceived an improved thermal state feeling "warm" and "just uncomfortable" when wearing the air permeable gloves compared to "hot" and "uncomfortable" when wearing the MVIP gloves at the end of the protocol. The study (Appendix 10) again emphasized the large whole body thermoregulatory benefits that could be obtained when evaporative cooling was improved at the hands, even when materials covering the hands were not 100 % MVP.

5.10 Limitations

A limitation of this and the first study was that the quantification of the thermal burden of the MVIP ancillary items was not tested *in situ* with all the associated equipment and load carriage components. Therefore, the results provided a theoretical recommendation for the end user that could be used to conduct more practical *in situ* experiments.

It should be noted that although the thermal load was largely maintained between conditions, it was not truly maintained between CON and the rest of the conditions, but would have always been higher during CON.

A possible limitation to the second and first studies was that T_{re} was used as the measure of T_c. This was mainly due to the robustness of the technique and practical reasons such as wearing a respirator not comfortably allowing for measurement of T_{au} or T_{oe} (which is often not tolerated well by volunteers). It is important to acknowledge that there might have been a lag in the T_{re} measurement as is often reported (Ash *et al*., 1992; Greenes & Fleisher, 2004); however with the slow and progressively increasing thermal strain this was less problematic. Additionally, although T_{re} is slower to respond to change than other measures of T_c such as T_{oe} or T_{au} when rates of change have been established, the technique can track the rate of change well (Figures 53 and 136).

Finally, it is acknowledged that by removing the item and replacing a weight at the area from where the item had been removed as a surrogate for making the item 100 % MVP, both the water vapour permeability and the air permeability was improved. The water vapour permeability provides an indication of the capacity of the material to transfer water vapour whereas the air permeability provides an indication of the capacity of the material to support airflow (Gonzalez *et al*., 2006; McLellan *et al*., 2013b). Often it is reported that convective permeability is a stronger predictor of performance under conditions of uncompensable heat stress compared to evaporative resistance (Gonzalez *et al*., 2006; Bernard *et al*., 2010), and indeed differences in heart rate and $\overline{T}_b$ have been observed for chemical protective ensembles that are similar in insulation and water vapour permeability but differed in air permeability (Havenith *et al*., 2011). Therefore, by not wearing a MVIP item, both air permeability and water vapour permeability were improved and it was impossible to distinguish the contribution from either variable from the data obtained in the first and second studies. Nonetheless, by not wearing items the overall evaporative and thermal resistance of items was still quantified, as was the aim of the studies, as indeed the overall thermal burden incorporates restrictions to both air and water vapour permeability.

CHAPTER VI: REGIONAL TEMPERATURE PERTURBATION ON LOCAL SWEAT RATE, CUTANEOUS BLOOD FLOW AND WHOLE BODY PERCEPTUAL MEASURES

6.1 Background

The second study (Chapter 5) found that exposing the hands resulted in the largest reduction to thermoregulatory strain from a fully encapsulated condition, than either exposing the face or not wearing the BAL or overboots. The surface area of each hand is approximately 2.3 % of total body surface area (Yu *et al*., 2008) and, while there is no widely cited human anthropometry data on the surface area of the face alone, it is estimated to be approximately 2.7 % of total body surface area (manikin Newton, Thermetrics, US). Therefore as the surface area of the hands combined are approximately 1.7 times greater than the surface area of the face, the result that exposing the hands compared to exposing the face, in a hot desert-like environment that encourages evaporative cooling, resulted in a larger reduction to thermoregulatory strain than exposing the face alone was not surprising. However it was interesting that exposing only a small surface area (either the hands or face) would greatly reduce whole body thermoregulatory strain. The results from the previous study did not provide an indication of the sensitivity of either the hands or the face.

It has been proposed that the differential thermosensitivity of various body areas might be more important to consider than merely surface area when assessing relative contributions to whole body thermoregulatory response (Nadel *et al*., 1973; Crawshaw *et al*., 1975; Cotter & Taylor, 2005). For example, Nadel *et al*. (1973) found that the face displayed a thermal sensitivity *i.e*. more sweat was produced per cm^2, that was approximately three times greater than that of the thigh, abdomen and chest while the lower legs were found to possess a lowered thermal sensitivity by as little as one half of the sensitivity at the thigh. Crawshaw *et al*. (1975) found the forehead to be highly sensitive per unit area regarding both autonomic and affective responses compared to any other area stimulated. Additionally, Cotter and Taylor (2005) investigated the contribution of warming or cooling skin at discrete body areas on the whole body sudomotor response in resting humans using an open-loop approach, which by use of a water-perfused suit, T_c and T_{sk} of untreated sites remained clamped ($\overline{T}_b$ remained stable throughout the experiment at 36.79 [0.15] °C) whilst treated sites were warmed or cooled. Cotter and Taylor (2005) found that during moderate active skin cooling, the face was two to three times more sensitive *i.e.* suppressed sweating during cooling, than the chest, abdomen, arm, thigh or foot whereas the face was five times more sensitive than the hand during active local warming. Therefore the result from the previous study in which exposing the hands resulted in a greater decrease to thermoregulatory strain compared to exposing the face now required further investigation as to the impact on thermoregulatory responses (sudomotor and vasomotor) at the rest of the body when these areas were exposed.

The studies mentioned above (Nadel *et al*., 1973; Crawshaw *et al*., 1975; Cotter & Taylor, 2005) monitored sweat rate when warming or cooling discrete skin sites but did not monitor SkBF. While White *et al*. (1995) have suggested that cutaneous vasodilatation and sweating might not be governed by the same mechanisms, the early work of Love and Shanks (1962) on exploring the relationship between SkBF and the sweating response found that cutaneous vasodilatation was preceded by sweat gland activation as clarified by experiments on atropine nerve-blocked forearms. Furthermore, control of the vasomotor response differs between the head (active vasodilatation) and the hands (release of vasoconstrictor tone) (Gaskell, 1956; Fox *et al*., 1962). Additionally it was found that applying a warm stimulus to the face induced a greater peripheral vasodilatory response compared to when the same stimulus was applied to the chest or lower leg (Belding *et al*., 1948). Therefore regional variations in the SkBF response exist and it seems that the face might display a greater sensitivity than at least the chest or lower leg. We questioned whether permitting evaporative cooling at the face or hands would result in different SkBF and LSR responses at non-exposed / untreated areas. The untreated areas selected for observation were the chest, back, forearm and thigh. Indeed when measuring LSR, some studies have only chosen one site for observation such as the thigh (Nadel *et al*., 1973; Crawshaw *et al*., 1975), whilst Cotter and Taylor (2005) measured sweat rates from 7 sites. The sweat measuring system used in this third study was 4-channel and therefore sweat rate was measured at the site common to this area of research such as the thigh, as well as sites that represented majority of the body and have a high rate of sweat production such that any changes to LSR could be observed; chest, back and forearm.

With regards to the second study in this thesis (Chapter 5) generally, as mentioned, exposing the hands resulted in greater reductions to physiological and perceptual thermoregulatory strain compared to exposing the face only. Whether these results reflect a greater thermal sensitivity of the hands compared to the face or that the improvements were purely because of a greater surface area exposed when not wearing the gloves (approximately 4.6 %) compared to the respirator (approximately 2.7 %) are uncertain. The greater reduction to thermoregulatory strain was not seen in every variable measured, for example, during Work 3, the maximum reduction to the rise of $\overline{T}_b$ when the face was exposed was 0.17 °C (9.7 %) compared to CON, and the same reduction to the rise of $\overline{T}_b$ was found when the hands were exposed. Therefore exposing a surface area of approximately 2.7 % (face) elicited similar reductions to the rise of $\overline{T}_b$ as exposing a surface area of approximately 4.6 % (hands). Perceptually, it is also uncertain whether the face or the hands possess a greater thermosensitivity as the literature emphasizes the sensitivity of the face in a warm environment (Zhang, 2003; Cotter & Taylor, 2005) but in the second study of this thesis a greater perceptual improvement was found when the hands were exposed compared to the face. Therefore, the aim of this study was to quantify thermoregulatory responses of LSR and SkBF as well as whole body perceptual measures when permitting evaporative cooling at either the face (approximately 2.7 % of total body surface area) or one hand (approximately 2.3 % of total body surface area) during exercise.

This information could be beneficial to the sponsor who is concerned with minimizing the risk that warfighters encounter when operating in hot environments that have been contaminated with hazardous agents. For example, if the MVP of the respirator was improved and the whole body thermoregulatory strain was lessened, the rate of sweat production might decrease as the thermal drive for cooling would be less. When wearing fully encapsulating protective clothing, a large proportion of the sweat produced does not actually contribute to whole body cooling as the clothing provides a barrier to vapour exchange with the environment (mean sweat evaporation / production ratio of 49 % when fully encapsulated). In this instance, a reduced sweat production would therefore be beneficial to maintain hydration in the fully encapsulated warfighter, but not in the minimally clothed athlete where much of the sweat produced contributes to evaporative cooling. However, consideration must be given to the possibility that sweat production, when wearing encapsulating clothing, might begin to decline after prolonged (usually a duration longer than 60 minutes depending on the environment and work rate) sweating at a high rate in a hot and humid environment (such as the CBRN microclimate). This might occur regardless of evaporative cooling at discrete body areas, due to possible hidromeiosis (Brown & Sargent, 1965) and / or swelling of epidermal cells physically occluding the sweat duct (Randell & Peiss, 1957). Additionally, upon further statistical analysis of the data from Study 2 (Figure 31), no significant difference in whole body sweat production between N_R and N_G was found and therefore it was important to consider local sweat production.

The methodological consideration by Cotter and Taylor (2005) mentioned earlier of clamping T_{sk} of untreated sites whilst manipulating T_{sk} at treated sites was also considered for this study. By clamping $\overline{T}_{sk}$ between conditions there was minimal influence from the untreated sites on the thermoregulatory response and therefore any changes between conditions could be attributed to the temperature perturbation at the treated site (Cotter & Taylor, 2005). In the previous two studies (Chapters 4 and 5) as the CBRN suit was worn, $\overline{T}_{sk}$ did not differ from 20 minutes into the protocol until the end of the final exercise period between conditions. Therefore in the current study, the CBRN suit was worn in an attempt to maintain $\overline{T}_{sk}$ between conditions so that any difference in the thermoregulatory or perceptual response between conditions could be attributed to evaporative cooling at either the face or hand and not from a different $\overline{T}_{sk}$ between conditions.

6.2 Research Aims

The aim of this study was to quantify the contribution of exposing the face or one hand to a hot and dry environment on thermoregulatory responses of LSR and SkBF and whole body perceptual responses during exercise, having approximately controlled for surface area.

6.3 Hypotheses

***H*$_{01}$**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be similar with and without face or hand exposure.

***H*$_{a1a}$**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be reduced when the face or hand is exposed.

***H*$_{a1b}$**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be reduced further when the face is exposed compared to exposing the hand.

***H*$_{02}$**: Whole body perceptual responses would be similar with and without face or hand exposure.

***H*$_{a2a}$**: Whole body perceptual responses would be improved when the face or hand is exposed.

***H*$_{a2b}$**: Whole body perceptual responses would be further improved when the face is exposed compared to exposing the hand.

6.4 Methods

6.4.1 Research Design

A pilot study was conducted to explore the sweat responses at the chest, back, forearm and thigh during rest, exercise and recovery whilst wearing CBRN IPE in a hot (40.5 °C) and dry (20 % rh) environment with either the face or one hand exposed (Appendix 11). These environmental conditions represent the mean conditions in the first and second studies, which had shown to induce controlled hyperthermia whilst still allowing for smaller exposed areas to exert an influence on whole body thermoregulatory and perceptual responses. It was important that the environment was dry, to promote evaporative cooling from the exposed site, as well as hot, to induce a sufficient thermal burden on the participant and promote a sudomotor and vasomotor response that was large enough to be influenced by evaporative cooling at small surface areas such as the hand or face. Due to the small variability in LSR between conditions from the single volunteer pilot study (Appendix 11), the intensity of the driver for change was increased through application of a fan, circulating ambient air at 120 $m.min^{-1}$, directed at the exposed area (face or hand) to force evaporation and amplify differences between conditions. Particularly as, during the pilot study and previous studies, beads of sweat were noticed on participants and therefore not all of the sweat produced was being evaporated.

Fifteen male participants volunteered for the study. The participants' age, height, body mass and percentage of body fat were: mean (SD) 22.1 (4.4) years, 178.8 (5.6) cm, 75.8 (9.5) kg and 13.5 (3.1) % respectively. The study was a five condition, repeated measures design that required participants to lightly exercise (stepping rate of 12 $steps.min^{-1}$) in a hot and dry environment. Environmental conditions were set to 40.5 °C and 20 % rh with the actual conditions achieved being mean (SD): 40.22 (0.63) °C (dry bulb) and 23.29 (0.77) °C (wet bulb) equating to approximately 26.7 % rh. There were no significant differences in environmental parameters between conditions ($p > 0.05$). The conditions varied as to which CBRN items were worn, with weights being secured to the area from where the item was removed, and were annotated as follows (for the first 5 participants):

CON: the participant was dressed in full CBRN military protective equipment.
N1GF: the participant was dressed in full CBRN military protective equipment with the exception of one glove and cotton glove liner (annotated as N1G) thereby exposing one hand. A fan (annotated as F) was directed at the hand throughout the protocol.
N1RF: the participant was dressed in full CBRN military protective equipment with the exception of the respirator (annotated as N1R) thereby exposing the face only as the hood was still worn. A fan was directed at the face throughout the protocol.
In an attempt to quantify the variability within the same condition, the two conditions that involved exposing areas of the body were also repeated and were annotated as follows:
N1GF2: repeat of N1GF

N1RF2: repeat of N1RF

Data were analyzed after the first five participants (Appendix 12) and as there was poor agreement within repeat conditions with a small variation between different conditions, the driver for change was again increased for the remaining ten participants through exposing a greater surface area. Therefore both hands were exposed instead of only one hand (thereby increasing the exposed surface area from 2.3 % to 4.6 % of total body surface area [Yu *et al*., 2008]) whilst the face and head were exposed instead of only the face (thereby increasing the exposed surface area from 2.7 % to 7.2 % of total body surface area [Yu *et al*., 2010]). Thus the remaining 10 participants completed the conditions as follows:

CON: the participant was dressed in full CBRN military protective equipment.
N2GF: the participant was dressed in full CBRN military protective equipment with the exception of both gloves and cotton glove liners (annotated as N2G) thereby exposing both hands. A fan was directed at both hands throughout the protocol.
N2GF2: repeat of N2GF
NRHF: the participant was dressed in full CBRN military protective equipment with the exception of the respirator and hood (annotated as NRH) thereby exposing the head. A fan was directed at the head throughout the protocol.
NRHF2: repeat of NRHF

This alteration introduced a slight bias such that any changes to the thermoregulatory or perceptual responses might be due to a slightly greater surface area being exposed during NRHF and NRHF2 compared to N2GF and N2GF2 rather than a differential sensitivity of the head compared to the hands. Furthermore whilst the sensitivity of both hands was likely to be similar, the sensitivity between the face and head / scalp might differ as parts of the head are covered in hair for example which introduces a slight bias. However, even with these methodological alterations it was still of interest to determine the thermoregulatory (LSR and SkBF) and perceptual responses of exposing the head compared to the hands and the question remained relevant for the end user, perhaps even more so than attempting to match surface area. Particularly as in reality the warfighter is unlikely to wear only one glove, yet the evaporative and thermal resistance of the respirator and hood could be improved with future textile developments. Therefore the hypotheses remained except with the inclusion of both hands and the head as follows:

H**01**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be similar with and without head or hands exposure.

H**a1a**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be reduced when the head or hands are exposed.

H**a1b**: Thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh would be reduced further when the head is exposed compared to exposing the hands.

H**02**: Whole body perceptual responses would be similar with and without head or hands exposure.

H**a2a**: Whole body perceptual responses would be improved when the head or hands are exposed.

H**a2b**: Whole body perceptual responses would be further improved when the head is exposed compared to exposing the hands.

Participants were weighed nude and clothed before and after the experiment and were instrumented with a rectal thermistor, heart rate monitor, skin thermistors at the calf, thigh, arm and chest for estimation of $\overline{T}_{sk}$ using the Ramanathan (1964) equation. Skin thermistors were also placed at the finger to monitor T_{finger} and at the cheek to monitor T_{cheek}. Four sweat capsules and laser Doppler probes were secured to the chest, back, forearm and thigh (General Methods: Section 3.4.2). Participants rested for 30 minutes in the environmental chamber before the commencement of exercise to allow $\overline{T}_{sk}$ and $\overline{T}_{b}$ to rise and for initiation of the thermoregulatory responses as initially the clothing acted as a heat sink. Therefore, as the first 30 minutes of the protocol were primarily to stabilize the $\overline{T}_{sk}$ and $\overline{T}_{b}$ of the untreated sites between conditions, data during this period were not analyzed and as such all graphs are shown from the last 10 minutes of the initial rest period. After the 30 minutes rest, exercise commenced at a light intensity of 12 steps.min^{-1} (step height: 22.5 cm) for the duration of one hour or until reaching a cautionary stopping criterion (General Methods: Section 3.4.4). The participant then stopped stepping and remained seated recovering in the chamber for a further 30 minutes. Perceptual measures (RPE, whole body thermal comfort, thermal sensation and skin wettedness [General Methods: Section 3.4.2.11]) were taken at 15 minutes, 35 minutes and 55 minutes into the exercise period. Participants were provided with 250 mL of moderately chilled water (~ approximately 15 °C) every 20 minutes from 30 minutes into the protocol as water at this volume, temperature and timing results in the greatest volitional intake without greatly affecting thermoregulatory measures (Szlyk *et al*., 1989; Siegel *et al*., 2010) and was most likely to not result in dehydration (Costill & Sparks, 1973) (see Appendix 6 for options of hydration strategies).

Figure 37: A participant resting (left panel) and exercising (middle panel) in the N2GF condition, and exercising (right panel) in the NRHF condition.

6.5 Results

The sample number for this experiment totaled n = 15 however, as the first five participants were subject to a different experiment (one hand or only the face exposed rather than both hands and the whole head) which resulted in a poor agreement between repeated conditions and small variations between different conditions (Appendix 12), the remaining ten participants were subject to the final experiment whereby both hands or the head were exposed. The results presented below include the final experiment only where n = 10.

6.5.1 Mean Skin Temperature

To quantify the contribution of exposing and directing a fan at either the hands or head on LSR and SkBF, it was imperative that the $\overline{T}_{sk}$ and $\overline{T}_{b}$ were similar between conditions. Therefore any differences in the thermoregulatory response could be attributed to manipulation of heat exchange with the environment at the treated (exposed) site alone, with minimal contribution from the T_{sk} of untreated areas.

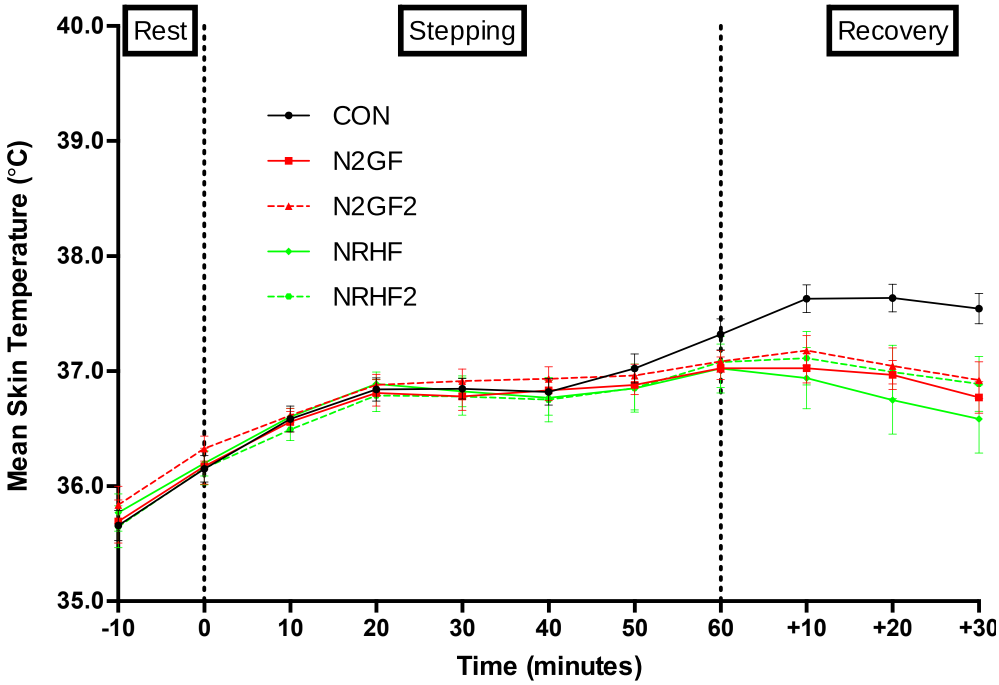

Figure 38: Average (SEM) mean skin temperature during rest, exercise and recovery wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

Note that due to thermistor detachment, T_{sk} data were not available and were subsequently predicted (Appendix 9) for the following:

P5 T_{thigh} from 61 minutes during NRHF2

Stepping

There were no significant differences in $\overline{T}_{sk}$ between any conditions during the exercise bout ($p > 0.05$).

Recovery

Exposing either the head or hand resulted in a significantly lowered $\overline{T}_{sk}$ compared to CON. Exposing the hands lowered $\overline{T}_{sk}$ by a maximum of 0.77 °C compared to CON by the end of recovery ($p < 0.0001$). Exposing the head lowered $\overline{T}_{sk}$ by a maximum of 0.96 °C compared to CON by the end of recovery ($p < 0.0001$).

Additionally, $\overline{T}_{sk}$ was 0.34 °C lower during NRHF compared to N2GF2 by the end of recovery ($p < 0.05$).

6.5.2 Mean Body Temperature

Figure 39 illustrates $\overline{T}_b$ throughout the protocol.

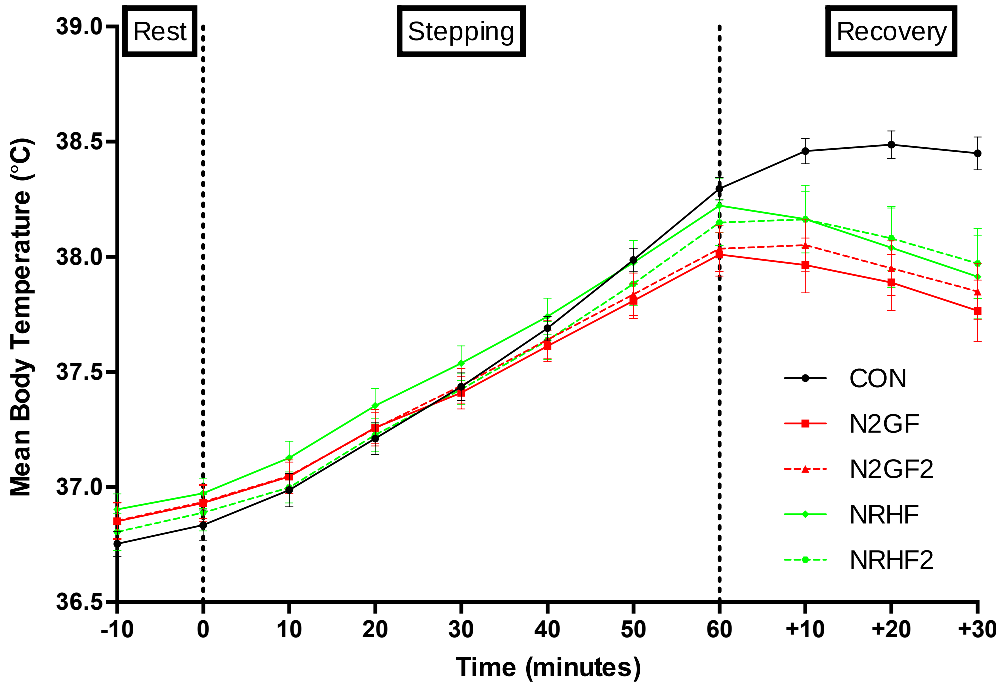

Figure 39: Average (SEM) mean body temperature during rest, exercise and recovery wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

Stepping

During the last 10 minutes of the protocol, the $\overline{T}_b$ during N2GF was significantly lower compared to CON by 0.29 °C ($p < 0.0001$). At the end of the stepping period the $\overline{T}_b$ during both N2GF and N2GF2 were significantly lower compared to CON ($p < 0.001$).

At the end of the stepping period the $\overline{T}_b$ during both N2GF and N2GF2 were significantly lower compared to NRHF and this was by a maximum of 0.21 °C ($p < 0.01$).

Recovery

Throughout recovery, exposing either the head or hands resulted in a significantly lowered $\overline{T}_b$ compared to CON and this was by a maximum of 0.68 °C during N2GF at the end of recovery ($p < 0.0001$).

Throughout recovery $\overline{T}_b$ when the hands were exposed (N2GF) was significantly lower compared to when the head was exposed during NRHF2 and this was by a maximum of 0.21 °C ($p < 0.01$) at the end of the protocol. The $\overline{T}_b$ was also significantly lowered 10 minutes into recovery during N2GF compared to NRHF by 0.20 °C ($p < 0.05$).

6.5.3 Conclusions Based on the Whole Body Thermal Profile

The purpose of wearing the CBRN kit was to control $\overline{T}_{sk}$ between conditions but allow the T_{sk} at the treated sites (head and hands) to be manipulated. Therefore, as there were no significant differences between $\overline{T}_{sk}$ during stepping, any alterations to thermoregulatory responses during this period could either be due to a different $\overline{T}_b$ (and hence T_{re}) between conditions or T_{sk} at the treated sites. The $\overline{T}_{sk}$ during recovery however was different between conditions and therefore comparisons could not be made between conditions during this period. Regarding $\overline{T}_b$, significant differences were identified between conditions during the final 10 minutes of the stepping period as well as during recovery. Therefore, thermoregulatory responses of LSR and SkBF were only analyzed at a $\overline{T}_b$ of 37.5 °C during all conditions as this was above the threshold temperature for sweating (Cotter *et al*., 1996; Cotter & Taylor, 2005) and at this point all participants were stepping and any changes to thermoregulatory responses could be attributed to a changed T_{sk} at the treated area rather than any differences to $\overline{T}_b$.

6.5.4 Skin Temperature at Treated Sites

6.5.4.1 Cheek Temperature

A fan was directed at the face during two out of the five conditions (NRHF and NRHF2) to force evaporation from the head. T_{cheek} is illustrated in Figure 40 at the point when $\overline{T}_b$ was 37.5 °C.

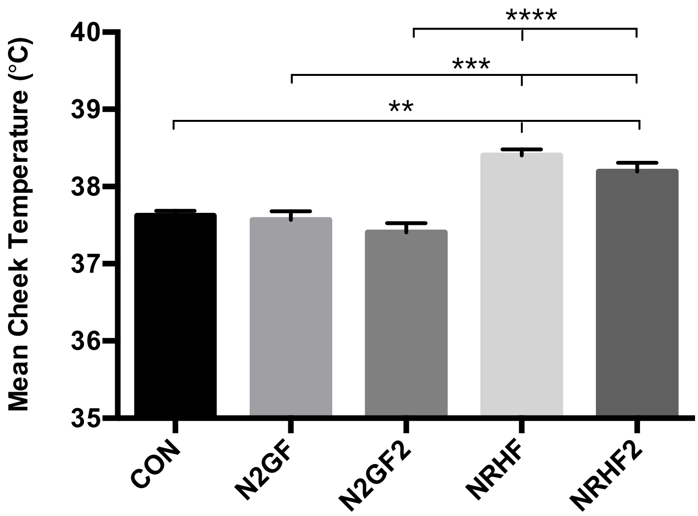

Figure 40: Mean (SEM) right cheek skin temperature when mean body temperature was 37.5 °C during exercise when wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

The mean T_{cheek} when $\overline{T}_b$ was 37.5 °C was elevated when the head was exposed during NRHF (38.40 [0.08] °C, $p < 0.0001$) and NRHF2 (38.19 [0.12] °C, $p < 0.01$) compared to CON (37.62 [0.06] °C). The mean T_{cheek} when $\overline{T}_b$ was 37.5 °C was also significantly elevated when the head was exposed during NRHF ($p < 0.0001$) and NRHF2 ($p < 0.001$) compared to when the hands were exposed during N2GF (37.57 [0.11] °C) and N2GF2 (37.41 [0.12] °C).

6.5.4.2 Finger Temperature

A fan was directed at the hands during two out of the five conditions (N2GF and N2GF2) to force evaporation from the hands. T_{finger} is illustrated in Figure 41 at the point when $\overline{T}_b$ was 37.5 °C.

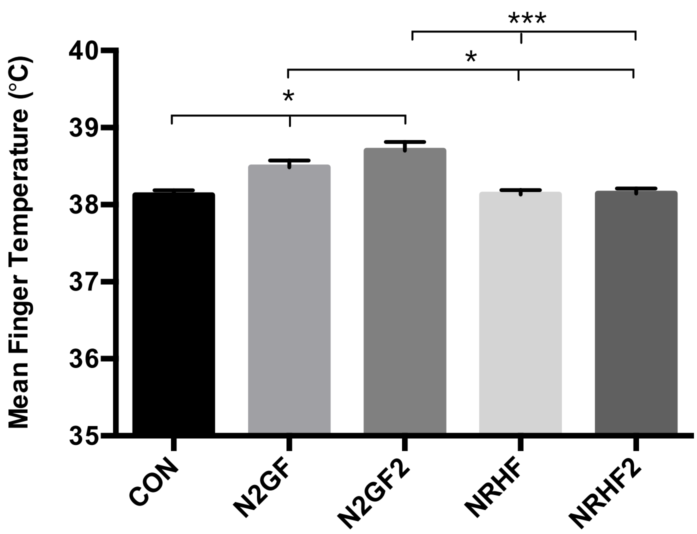

Figure 41: Mean (SEM) right finger pad skin temperature when mean body temperature was 37.5 °C during exercise when wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in in 40.5 °C and 20 % rh air (n = 10).

The mean T_{finger} when $\overline{T}_b$ was 37.5 °C was elevated when the hands were exposed during N2GF (38.49 [0.09] °C, $p < 0.05$) and N2GF2 (38.70 [0.12] °C, $p < 0.0001$) compared to CON (38.12 [0.06] °C). The mean T_{finger} when $\overline{T}_b$ was 37.5 °C was also significantly elevated when the hands were exposed during N2GF ($p < 0.05$) and N2GF2 ($p < 0.001$) compared to when the head was exposed during NRHF (38.13 [0.06] °C) and NRHF2 (38.14 [0.07] °C).

In summary, when $\overline{T}_b$ was 37.5 °C, T_{cheek} was higher when the head was exposed compared to all other conditions and likewise when the hands were exposed T_{finger} was higher than all other conditions. Thus, forced evaporation applied to the head and hands by fans was not sufficient to combat the resultant heat gain of forced convection *i.e.* forcibly directing hot (40.5 °C) air at exposed skin sites.

6.5.5 Local Sweat Rate

Figure 42 illustrates the rate of sweat production at the chest, back, forearm and thigh when $\overline{T}_b$ was 37.5 °C in each condition.

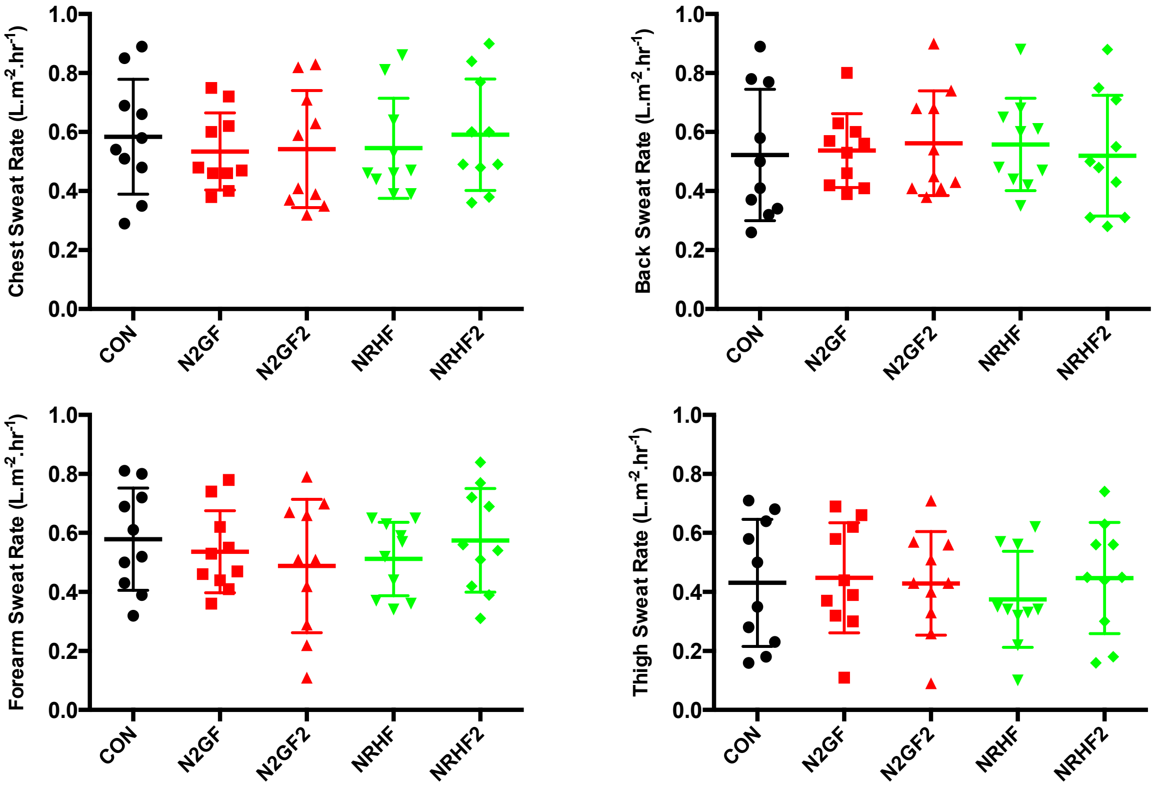

Figure 42: Mean (SD) sweat rate at the chest, back, forearm and thigh when mean body temperature was 37.5 °C during exercise-induced hyperthermia when wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

Note that due to capsule detachment, LSR data were not available for the following (Appendix 9):

P3 thigh during NRHF

P3 thigh during N2GF2

When $\overline{T}_b$ was 37.5 °C there were no significant differences in the rate of sweat production between the chest, back, forearm or thigh regardless of whether the hands or head were exposed ($p > 0.05$).

6.5.6 Local Skin Blood Flow

Figure 43 illustrates the absolute SkBF at the chest, back, forearm and thigh when $\overline{T}_b$ was 37.5 °C in each condition.

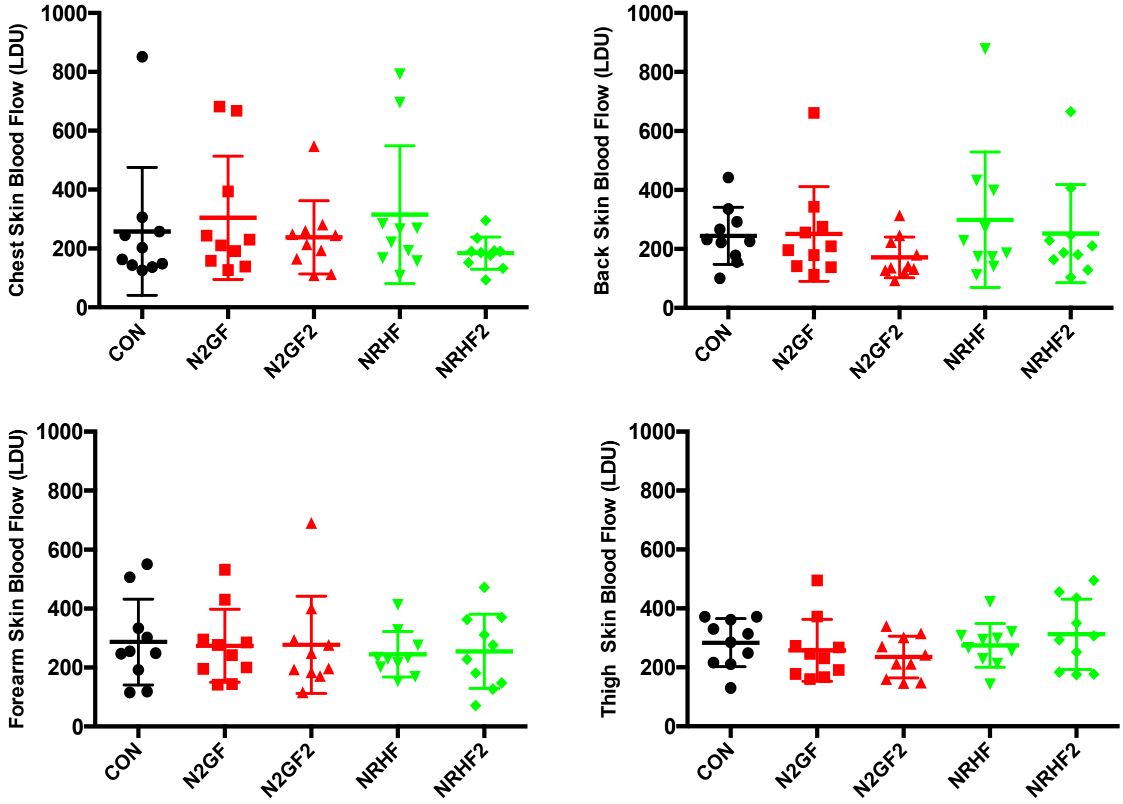

Figure 43: Mean (SD) skin blood flow at the chest, back, forearm and thigh when mean body temperature was 37.5 °C during exercise-induced hyperthermia when wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

When $\overline{T}_b$ was 37.5 °C there were no significant differences in SkBF between the chest, back, forearm or thigh regardless of whether the hands or head were exposed ($p > 0.05$).

6.5.7 Perceptual Responses

Perceptual responses were not taken at a set $\overline{T}_b$ such as 37.5 °C but rather at specific time points of 15 minutes, 35 minutes and 55 minutes into the protocol. The mean time taken to reach a $\overline{T}_b$ of 37.5 °C was 32 minutes into the work period. Therefore perceptual measures were statistically compared between conditions from the data obtained at 35 minutes into the stepping period.

6.5.7.1 Rating of Perceived Exertion

RPE at 35 minutes into the stepping period is illustrated in Figure 44.

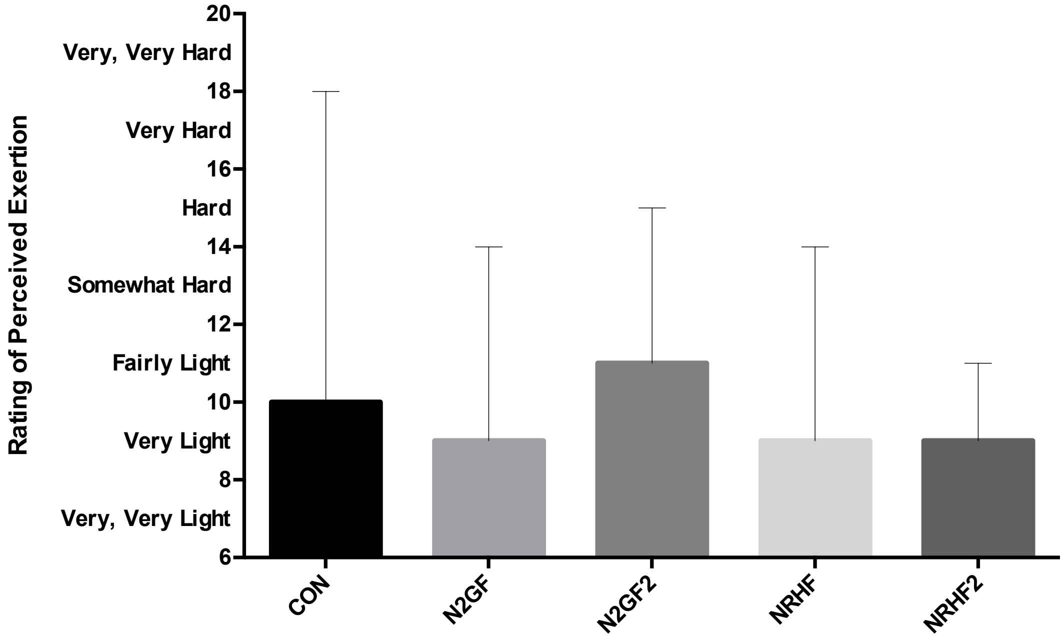

Figure 44: Median (range) rating of perceived exertion during exercise when mean body temperature was 37.5 °C whilst wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

When $\overline{T}_b$ was 37.5 °C there were no significant differences in RPE when either the hands or head were exposed ($p > 0.05$).

6.5.7.2 Perceived Thermal Sensation

Perceived thermal sensation at 35 minutes into the stepping period is illustrated in Figure 45.

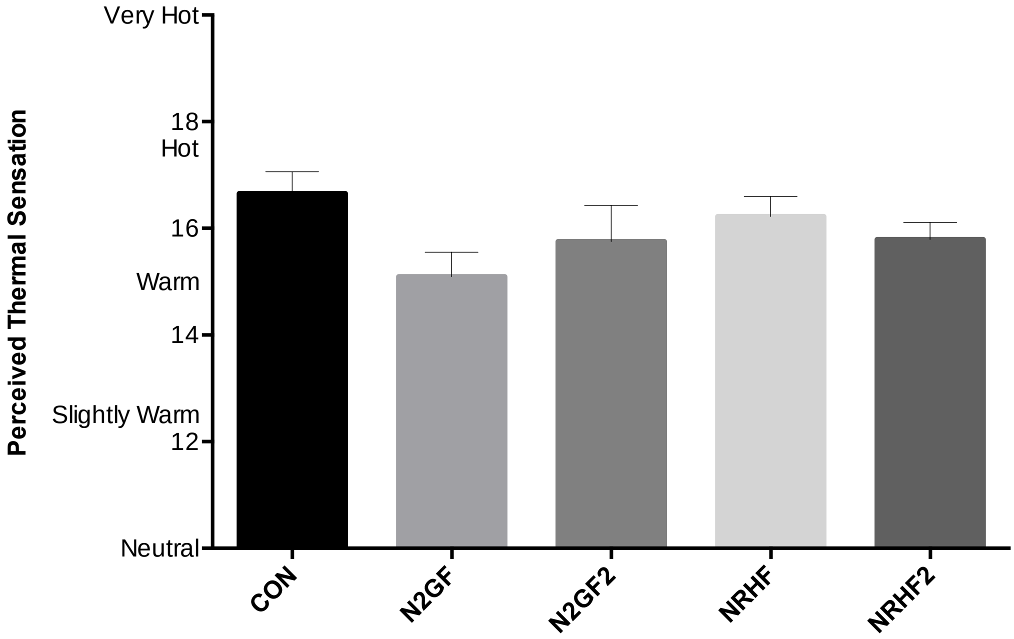

Figure 45: Mean (SEM) rating of perceived thermal sensation during exercise when mean body temperature was 37.5 °C whilst wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

When $\overline{T}_b$ was 37.5 °C there were no significant differences in perceived thermal sensation when either the hands or head were exposed ($p > 0.05$).

6.5.7.3 Perceived Thermal Comfort

Perceived thermal comfort at 35 minutes into the stepping period is illustrated in Figure 46.

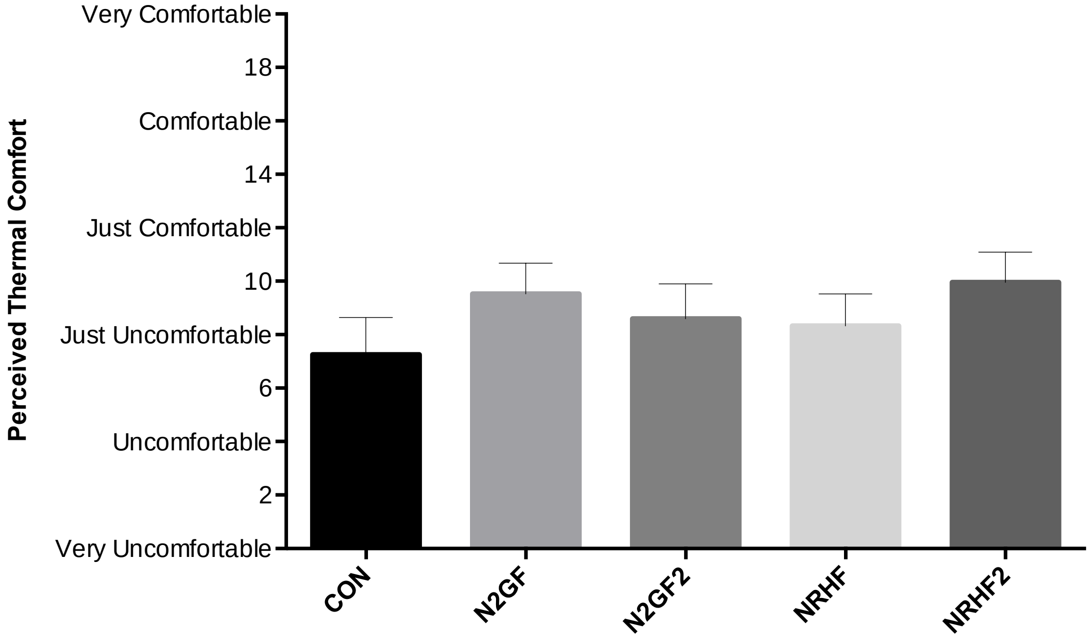

Figure 46: Mean (SEM) rating of perceived thermal comfort during exercise when mean body temperature was 37.5 °C whilst wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

When $\overline{T}_b$ was 37.5 °C there were no significant differences in perceived thermal comfort when either the hands or head were exposed ($p > 0.05$).

6.5.7.4 Perceived Skin Wettedness

Perceived skin wettedness at 35 minutes into the stepping period is illustrated in Figure 47.

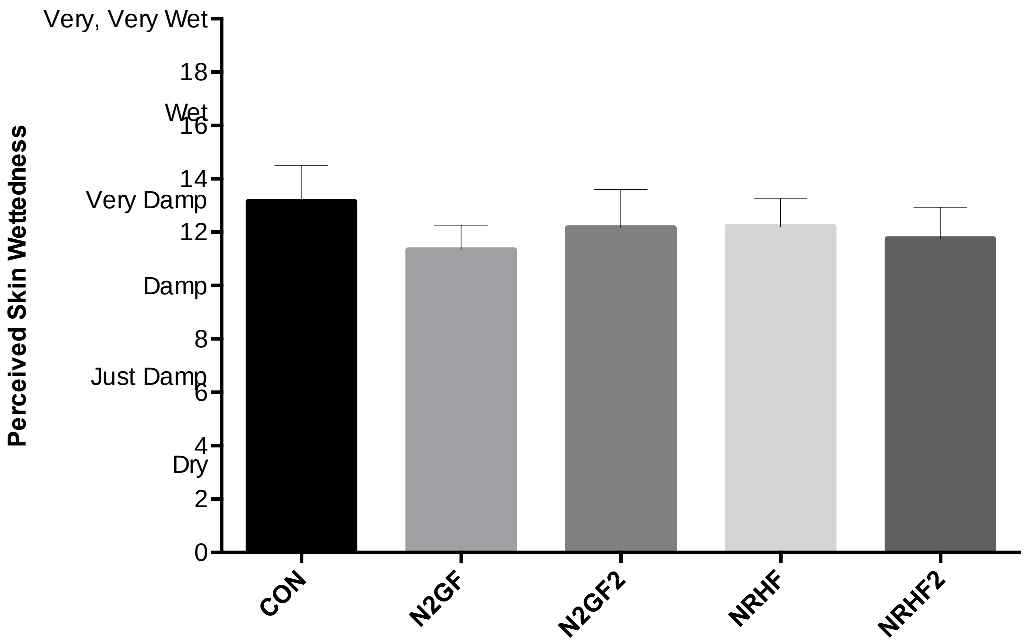

Figure 47: Mean (SEM) rating of perceived skin wettedness during exercise when mean body temperature was 37.5 °C whilst wearing encapsulating clothing whilst varying ratios of the body were exposed and a fan was directed at the exposed site in 40.5 °C and 20 % rh air (n = 10).

When $\overline{T}_b$ was 37.5 °C there were no significant differences in perceived skin wettedness when either the hands or head were exposed ($p > 0.05$).

6.6 Discussion

The aim of this study was to quantify the contribution of local T_{sk} perturbations at the hands or the head on thermoregulatory responses of LSR and SkBF and whole body perceptual responses during exercise. To ensure that any changes to thermoregulatory and perceptual responses were in fact due to the perturbed T_{sk} at the treated areas, it was important to ensure that the $\overline{T}_{sk}$ at the untreated sites was unchanged between conditions. A common method to maintain $\overline{T}_{sk}$ is by way of a water-perfused suit (Jackson & Kenny, 2003; Cotter & Taylor, 2005). The suit used by Cotter and Taylor (2005) covered 93 % of the skin surface. Such equipment was not available to our laboratory however the $\overline{T}_{sk}$ results from the previous studies when a CBRN suit was worn (Chapter 4: Figure 11; Chapter 5: Figure 26) identified that the $\overline{T}_{sk}$ changed by 0.46 °C (Study 1) and 0.68 °C (Study 2) over a 60 minute period of continuous exercise. This minimal change to $\overline{T}_{sk}$ over the hour exercise period was a result of the insulative properties of the CBRN suit with the added benefit of being able to exercise and move freely, made wearing the CBRN suit an attractive alternative to a water-perfused suit. The results of this study indicated that $\overline{T}_{sk}$ differed only by an average of 0.91 °C during the 60-minute exercise period and was not significantly different between conditions during exercise. Thus, the influence of T_{sk} from the untreated tissues on the changes to the whole body thermoregulatory response was minimal.

With the introduction of exercise $\overline{T}_{b}$ did, as expected, rise throughout the 60 minutes of exercise and was significantly different between conditions during the final 10 minutes of exercise as well as during recovery. Therefore, thermoregulatory and perceptual responses were only compared at the same $\overline{T}_{b}$ of 37.5 °C for each condition before differences arose. The first null hypothesis stated that LSR and SkBF at the chest, back, forearm and thigh would be similar with and without head or hands exposure. When either the head or hands were exposed, T_{sk} at the cheek or finger respectively was greater than when either area was covered by MVIP materials. This was not expected as in the previous experiments (Chapters 4 and 5), exposing either of these areas resulted in a lowered, although not always significantly lowered, T_{cheek} or T_{finger} during continuous exercise and this response was expected to be augmented when a fan was directed at each exposed area. Particularly as it was noted during the previous studies that beads of sweat were still visible on the exposed face or hands and therefore it was anticipated that by forcing evaporation from these areas, most of the sweat that was produced would then be evaporated and a greater degree of cooling would be evident at the treated sites. Instead, directing a fan at the exposed areas especially from the moment the participants first entered into the hot and dry environment, actually resulted in convective heat gain at the cooler skin (mean starting T_{cheek} during NRHF and NRHF2: 35.41 °C; mean starting T_{finger} during N2GF and N2GF2: 34.57 °C) from the hotter (40.5 °C) environment. Had the environment been cooler or the items (respirator, hood, gloves) only been removed after $\overline{T}_{sk}$ had been elevated and skin wettedness increased during the initial 30 minute rest period, it might have been that the T_{sk} of the exposed areas would have been cooler during exercise compared to when the areas were covered by MVIP materials. Nonetheless, Nadel *et al*. (1973) and Cotter and Taylor (2005) found significant differences to the sweating response when either the face or hands were heated and therefore differences were still expected in the current study.

There were no significant differences to either LSR or SkBF at the chest, back, forearm or thigh when either the head or hands were exposed with a fan directed at those areas during exercise when $\overline{T}_b$ was 37.5 °C. It was expected that differences would be found between conditions particularly as large whole body thermoregulatory gains were identified in the previous studies when exposing only the hands or face (Chapter 5), furthermore it was expected that LSR would be altered when either the head or hands were exposed as has been found previously (Nadel *et al*., 1973, Cotter & Taylor, 2005). There are four possible reasons why the results did not support previous literature:

i. The change in T_{sk} when either the head or hands were exposed might not have been adequate to elicit a measurable response. The temperature change during warming induced by Nadel *et al*. (1973) was approximately 3.0 °C and by Cotter and Taylor (2005) was by 4.0 °C. The temperature change at the treated sites in this study, whilst significant, was only 0.48 °C (T_{finger}) and 0.68 °C (T_{cheek}). Thus, there appears to be a threshold over which improvements are most likely to be noticed that is between 0.68 °C and 3.0 °C.
ii. Exercise might have raised the T_{sk} threshold for which changes to thermoregulatory responses could be observed particularly as decreased sensitivity has been found when measuring perceived thermal sensitivity during exercise (Ouzzahra *et al*., 2012) possibly due to contributions of noradrenaline (Kozyreva, 2006), activation of the stress analgesia mechanism (Lewis *et al*., 1980) or arousal (Bentley *et al*., 2003).
iii. The equipment used in this study (ventilated sweat capsule system: Q-Sweat^{TM} and laser Doppler flowmetry: moorVMS-LDF) might not have been sensitive enough to detect small differences between conditions.
iv. The day-to-day variation in thermoregulatory responses in different participants, as well as the possible slight and unintentional variation in capsule or probe placement between days, might have outweighed any measurable differences.

Differences in the thermoregulatory responses were expected when discrete areas were heated as the distribution of thermoreceptor densities are not homogenously distributed throughout the body (Strughold & Porz, 1931; Nadel *et al*., 1973; Cotter & Taylor 2005; McGlone & Reilly, 2010), there is differential relaying of thermal information to the thalamus between the hands and head (Hellon & Mitchell, 1975; Poulos & Molt, 1976), as well as that glabrous skin (approximately half of the hand) possesses a lower threshold for heat detection (Granovsky *et al*., 2005). Nonetheless this study found that at a $\overline{T}_b$ of 37.5 °C during exercise, heating the hands by 0.48 °C (T_{finger}) or the head by 0.68 °C (T_{cheek}) did not significantly alter LSR or SkBF. Therefore the hypotheses (H_{a1a} and H_{a1b}) that exposing the head or the hands would result in different thermoregulatory responses of LSR and SkBF at the chest, back, forearm and thigh were not accepted.

The second null hypothesis stated that whole body perceptual responses would be similar with and without head or hands exposure. Frank *et al*. (1999), when successfully manipulating T_{sk} and T_c independently found that T_{sk} and T_c contributed equally to whole body thermal comfort. The work of Cotter *et al*. (1996) provided the first inter-regional partitioned study whereby $\overline{T}_c$ (mean of T_{re}, T_{oe} and T_{au}) and $\overline{T}_{sk}$ were clamped above the sweating threshold (36.9 °C and 36.2 °C respectively) whilst T_{sk} was manipulated at treated, local areas. Cotter *et al*. (1996) found that by raising local T_{sk} at the face by 4 °C, local and whole body thermal sensation and discomfort were lowered whereas when raising local T_{sk} at the hands (and feet) by 4 °C only local, not whole body, thermal discomfort and sensation were reduced.

These results, taken with the findings of whole body thermal discomfort by Cotter and Taylor (2005) when the face was heated, along with the SkBF results of Belding *et al*. (1948) and with the experiment conducted by Nadel *et al*. (1973), showed that local perturbation of T_{sk} could affect whole body perceptual responses. The results from the current study however, resulted in no significant differences to whole body perceptual responses when $\overline{T}_b$ was 37.5 °C and either the hands or head were exposed with a fan directed at those areas. There are four possible reasons for this:

i. Again, the magnitude of the change in T_{sk} at the treated areas was not large enough to elicit a measureable response. For example, the magnitude of the difference used by Cotter *et al*. (1996) was 4 °C compared to the mean difference in this study of 0.48 °C (T_{finger}) and 0.68 °C (T_{cheek}). Thus, the threshold to possibly obtain a measurable perceptual response lies between 0.68 °C and 4.0 °C.
ii. It is possible that upon first entering the hot and dry chamber from a thermoneutral environment, the immediate warm stimulus applied to either the exposed hands or the head raised the threshold for any subsequent cooling to overcome to result in improvements in perceived thermal state. Therefore, had the equipment (respirator, hood or gloves) been removed only after the initial 30-minute rest period, significant differences might have been identified.
iii. Had both local and whole body perceptual responses been recorded, significant changes to the perceptual response might have been noticed, although arguably the magnitude of change in T_{sk} might not have been sufficient to elicit any significant change regardless. Furthermore, it was of interest in this study to quantify the

effects of perturbed T_{sk} at discrete areas on the whole body, not local, response. Improvements to whole body perceptual measures were noticed in the previous studies (Chapters 4 and 5) when either the hands or face were exposed, which suggests that T_c does exert a large influence on the whole body perceptual response as it was different in previous studies but analyzed at the same $\overline{T}_b$ in the current study. Additionally, in the current study, with the application of a fan, any possible improvements to the perceived thermoregulatory strain when exposing local areas might have been diluted by convective heat gain from the fan.

iv. The introduction of exercise might have lowered the possibility of detecting any changes to the perceived thermal state as it has been suggested that during exercise there is a more homogenous body map of subjective thermal sensitivity (Ouzzahra *et al*., 2012).

Therefore, as no differences to the perception of the whole body thermal state was apparent during this study, the second hypothesis (H_{a2a}) was not accepted, that whole body perceptual responses would be improved with head or hands exposure as well as the hypothesis (H_{a2b}) that whole body perceptual responses would be further improved when the head was exposed compared to exposing the hands.

6.7 Conclusions

In conclusion, heating the head or the hands by up to 0.68 °C did not affect whole body thermoregulatory or perceptual responses during exercise when $\overline{T}_b$ was 37.5 °C. Based on previous literature and the results from this study, it is suggested that a threshold to obtain differences might exist, and that threshold lies at some point between 0.68 °C and 3.0 °C for sudomotor responses and between 0.68 °C and 4.0 °C for perceived responses. However, it was possible that with the introduction of exercise, any differences in LSR or SkBF with local perturbations in T_{sk} were outweighed by the driving function of exercise. Furthermore, to identify small differences between conditions, any sources of potential error or variation should be minimized, such as day-to-day variations in the thermoregulatory response or placement of equipment.

6.8 Impact of Findings and Future Research

- A practical outcome of this study was to determine whether removing the thermal resistance of materials covering the head or the hands would assist in fluid conservation of the exercising warfighter in a contaminated environment. However, no differences in sudomotor or vasomotor responses or perception were identified when both the head or hands were slightly heated at the same $\overline{T}_b$, and future research could examine whether cooling these local areas would significantly alter fluid conservation. Furthermore, investigations should determine whether cooling either the head or the hands would improve the sweat evaporation / production ratio of the warfighter, allowing for more efficient thermoregulatory control in a contaminated environment.

- Recommended future studies include investigating regional thermosensitivities for thermoregulatory responses during exercise that is intermittent or of a short duration and therefore would not greatly impact on T_c.
- Additionally, manipulating the T_{sk} at either the head or hands within the range of 0.68 °C and 4.0 °C should also be undertaken to determine at what T_{sk} threshold would measurable responses of LSR, SkBF and perceptual measures be found or if this threshold was indeed raised during exercise, and additionally whether this threshold differs regionally.
- During this study, comparisons between conditions were made when $\overline{T}_b$ was 37.5 °C as all participants reached this $\overline{T}_b$ during exercise in each condition. However it is recommended that future studies should investigate regional thermosensitivities for thermoregulatory and perceptual responses during exercise through a wider $\overline{T}_b$ range to determine if the relationship changes when at different thermal states.

When LSR and SkBF responses at all four sites (chest, back, forearm and thigh) during CON were plotted against time, instead of $\overline{T}_b$, it was noted that SkBF and LSR at all sites, except LSR at the chest, declined post-exercise even though $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and the local T_{sk} at each site increased and plateaued (Figures 48, 49 and 50).

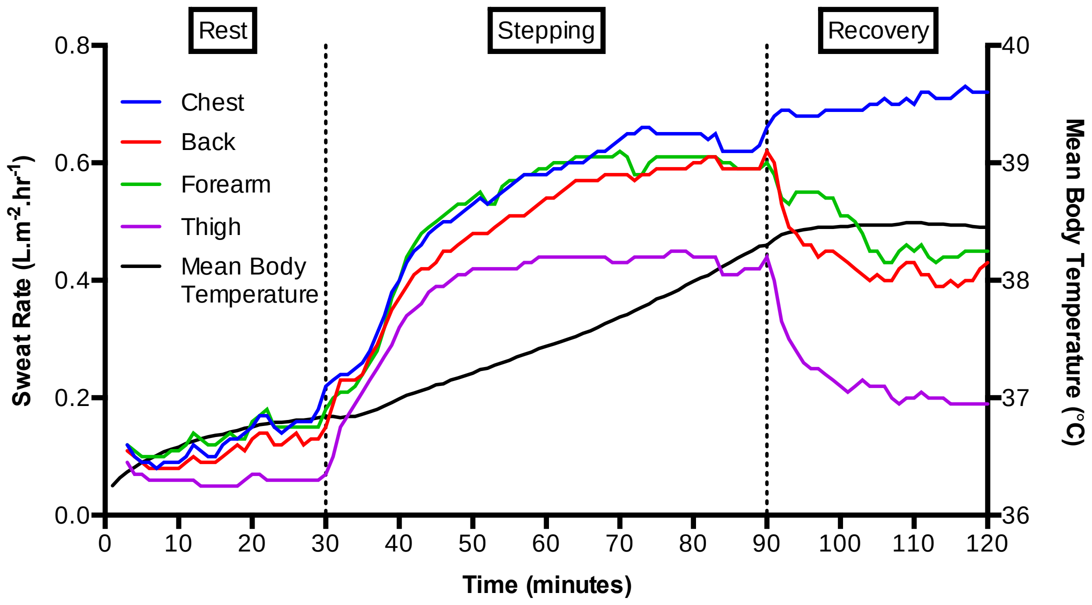

Figure 48: Mean body temperature and mean sweat rate at the chest, back, forearm and thigh during rest, stepping and recovery in 40.5 °C and 20 % rh air whilst wearing the full chemical and biological clothing ensemble (n = 10).

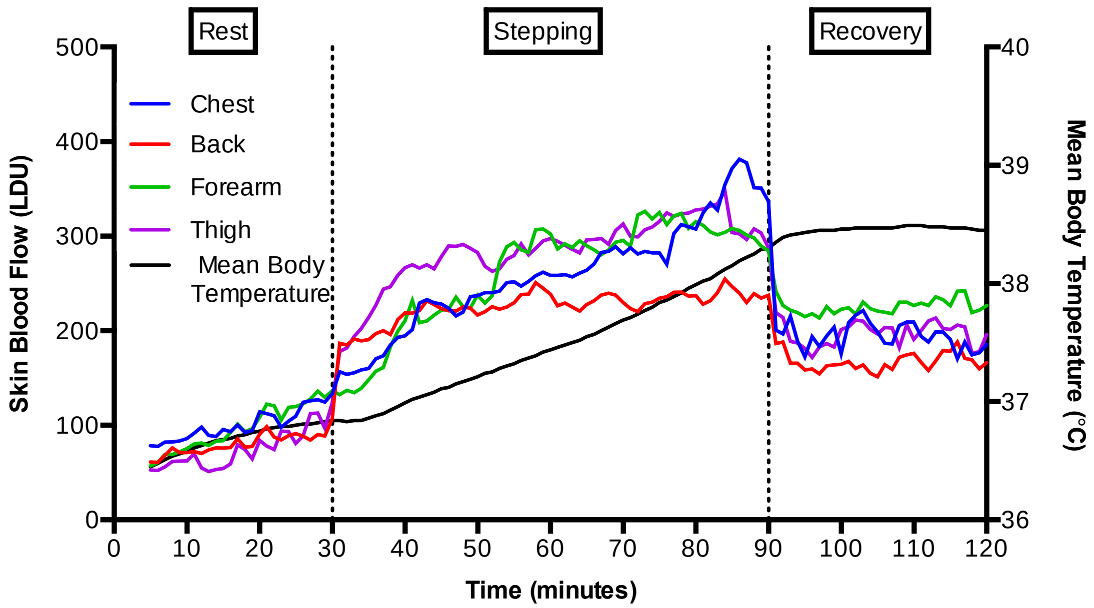

Figure 49: Mean body temperature and mean skin blood flow at the chest, back, forearm and thigh during rest, stepping and recovery in 40.5 °C and 20 % rh air whilst wearing the full chemical and biological clothing ensemble (n = 10).

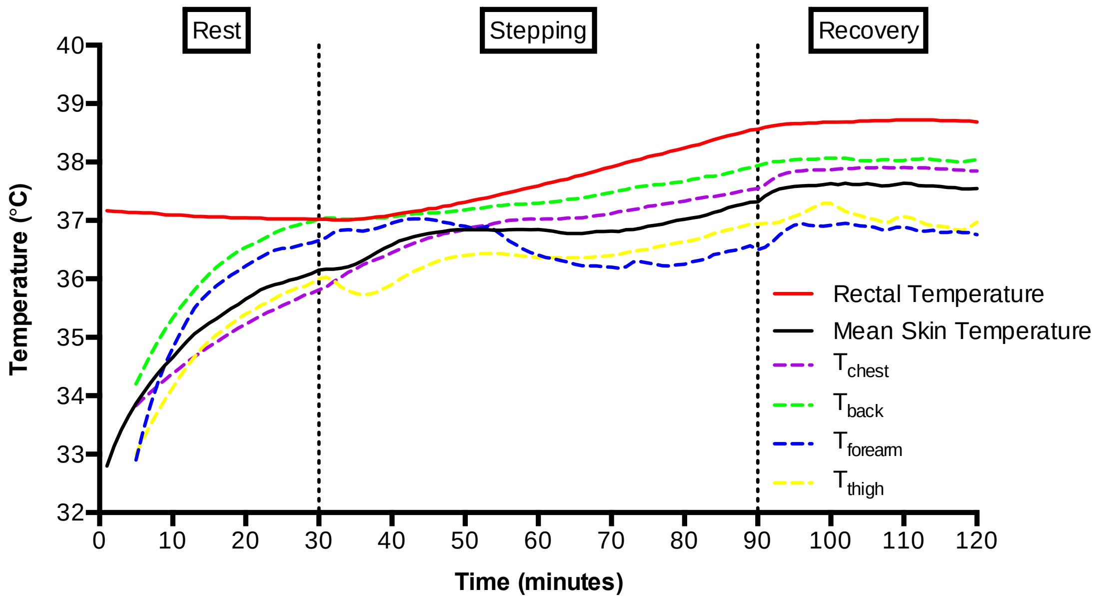

Figure 50: Mean rectal, skin, chest, back, forearm and thigh temperature during rest, stepping and recovery in 40.5 °C and 20 % rh air whilst wearing the full chemical and biological clothing ensemble (n = 10).

Therefore, even though $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and the local T_{sk}, were elevated, and thus the driver for cooling was present, LSR and SkBF declined at all sites except LSR at the chest at the onset of seated recovery. The final study of this thesis (Chapter 7) therefore aimed to identify what the non-thermoregulatory influence controlling the LSR and SkBF responses was, and additionally, whether this mechanism was regional, systemic or methodological.

6.9 Limitations

In retrospect the methodology would have been improved by sampling LSR and SkBF at both treated and untreated sites. For example, when using one 4-channel ventilated capsule system it would have been advantageous to sample at either the head or hands and then at three untreated areas such as the chest, back and thigh. This, along with the change in treated, local T_{sk}, would have enabled calculation of the thermosensitivity of the head or hands.

Use of a water-perfused suit could have enabled a more effective control of $\overline{T}_{sk}$ between conditions compared to the 0.91 °C change in $\overline{T}_{sk}$ observed during the 60 minutes of exercise. Additionally, using a more advanced sweat detection system such as the Vaisala systems that allows for real-time monitoring of flow rates, uses compressed nitrogen gas that is dry and allows for a greater measurement range, might have increased the accuracy of the measurements. The Q-Sweat™ is designed for clinical estimations of the severity of autonomic disorders that modify the normal sweating response and as such is calibrated only up to 1000 $nL.min^{-1}$ for a small capsule (0.787 cm^2) equating to 0.76 $L.m^{-2}.hr^{-1}$ with a 5 % accuracy and reproducibility[12]. Thus, the Q-Sweat™ is not designed for use at maximal human sweating rates that can exceed 0.76 $L.m^{-2}.hr^{-1}$. Although the mean sweat response in this study did not exceed 0.6 $L.m^{-2}.hr^{-1}$, values of 0.9 $L.m^{-2}.hr^{-1}$ were recorded for some participants and therefore using a more appropriate sweat detection system would have been favourable.

To avoid possible and unintentional error in the difference of day-to-day placement of the capsules and probes, it would have been preferable to have the participant complete all conditions during one experiment. Additionally, allowing $\overline{T}_{sk}$ to rise and stabilize before removing an item (respirator, hood or gloves) might have allowed for a more controlled change in T_{sk} at discrete areas from a baseline value. Furthermore, conducting the experiment in an environment where the ambient temperature was just below T_{sk} might have avoided convective heating. Finally, it might have been advantageous to actively cool or heat the treated area to a set temperature thereby allowing a controlled thermoregulatory response to a set change in temperature, as well as a greater change in T_{sk} at the face and hands would provide a greater driving force for a response.

Another limitation of this study was that the surface area of the treated sites was not matched although the results might have been more appropriate to the end user to know whether there were any LSR or SkBF changes when exposing the head compared to the hands. By treating the same surface area but at different parts of the body (hands *vs*. head), the magnitude of the thermosensitivity difference between the sites would have been clearer had any changes to LSR, SkBF or perceptual measures been identified.

As summarized by Cotter & Taylor (2005) in their elegant experiment to determine differential cutaneous sudomotor and alliesthesial thermosensitivity using an open loop approach, many previous limitations from other studies were accounted for in their study through clamping of untreated tissues, standardizing the magnitude of the change in T_{sk} at the treated areas and standardizing the surface area treated. Thus, those three considerations should be at the core of future research in this field when attempting to

[12] Q-Sweat Hardware User's Guide, Version 1.4. Quantitative Sweat Measurement System, Model 1.0. WR Medical Electronics Co. 2001-2007

incorporate the novelties of this current study: introduction of exercise, monitoring of SkBF and other perceptual responses such as RPE, skin wettedness and thermal sensation.

CHAPTER VII: NON-THERMAL INFLUENCES ON SWEATING WITH CONSIDERATIONS OF THE SYSTEMIC *VERSUS* REGIONAL RESPONSE

7.1 Rationale for the Fourth Study

Thermoregulatory responses of LSR and SkBF appeared to be influenced by non-thermal factors immediately upon the cessation of exercise during the third study (Chapter 6). Additionally, it was noted that regional variations in this response existed such that LSR and SkBF declined at all sites except LSR at the chest. Therefore, the aim of this fourth study was to identify the non-thermal mechanism that could be responsible for the sudomotor and vasomotor responses and whether this mechanism was regional, systemic or a methodological artifact.

7.2 Background

As mentioned in the Review of Literature: Section 2.7, there has been much work on investigating non-thermal regulation of sweating (van Beaumont & Bullard, 1966; Fortney *et al*., 1981; Vissing *et al*., 1991; Dodt *et al*., 1995; Takamata *et al*., 1995; Jackson & Kenny, 2003; Shibasaki *et al*., 2003a). During the third study, post-exercise two possible mechanisms might have governed the LSR and SkBF responses observed when $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and local T_{sk} were elevated and stable post-exercise. The first being a cessation of exercise, the second a change in posture, as post-exercise participants sat down on a stool in the chamber for the recovery period. Therefore a supplementary review of literature specific to the role of exercise and posture on regulation of sweating is provided below.

7.2.1 Exercise as a Non-Thermal Regulator of Sweating

Yamazaki *et al*. (1994) used sinusoidal cycling of a short duration (1.3 minutes), at moderate ambient conditions (25 °C and 35 % rh) to demonstrate the magnitude of exercise on modulating the sweating response. Sinusoidal cycling lasting a total of 40 minutes with work rate first increasing to 60 % VO_{2max} and then decreasing to 10 % VO_{2max} within a 1.3 minute period, resulted in an increased forearm sweat rate of 0.044 $mg.cm^{-2}.min^{-1}$ and demonstrated a sinusoidal pattern whilst T_{oe} and $\overline{T}_{sk}$ remained almost constant changing by only 0.01 °C and 0.03 °C respectively. Yamazaki *et al*. (1994) acknowledged that T_{oe} might not accurately represent deep brain temperature, although arguably aortic temperature (which T_{oe} reflects) is a similar blood temperature to the circle of Willis that supplies blood to the brain (Shiraki *et al*., 1986). Nonetheless, Yamazaki *et al*. (1994) stated that as changes to sweat rate preceded any changes to thermal status (T_{oe}

and $\overline{T}_{sk}$) during exercise lasting only 1.3 minutes in duration, non-thermal factors such as exercise, as well as thermal factors, regulate the sweating response.

Shibasaki *et al*. (2003b), when elaborating on the findings from Yamazaki *et al*. (1994), postulated that non-thermal modulators of sweating could therefore include stimulation of afferent muscle nerve endings and / or a drive from the motor cortex by central command. Further research to quantify the input from central command on the sweating response involved heat-stressed participants undertaking IHG exercises under partial neuromuscular blockade (using curare derivatives) in an attempt to augment the central drive (Shibasaki *et al*., 2003a). Partial neuromuscular blockade weakens the ability of the muscles and therefore results in the participant exaggerating the degree of voluntary effort when attempting movement thereby augmenting the input from central drive. The results are illustrated in Figure 51 below.

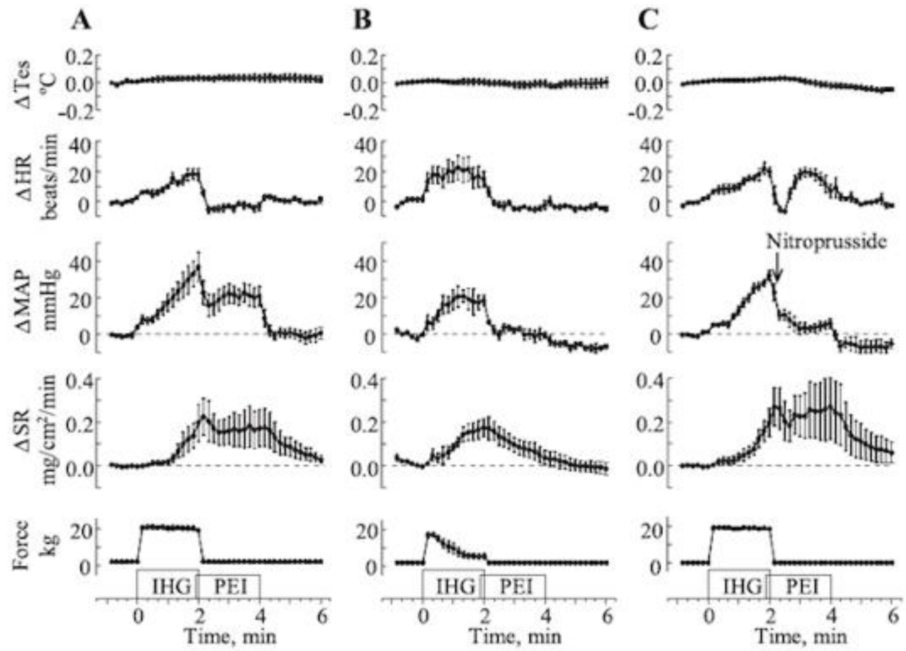

Figure 51: Change in oesophageal temperature (given as ΔT_{es}), heart rate (ΔHR), mean arterial pressure (ΔMAP), sweat rate (ΔSR) and absolute force production responses during isometric handgrip (IHG) exercises and post-exercise ischaemia (PEI) in heat-stressed participants under control conditions (panel A), augmented central command by partial neuromuscular blockade (panel B) and sodium nitroprusside infusion (panel C) (Taken from Shibasaki *et al*., 2003a. Used with author's permission).

Due to the partial neuromuscular blockade, participants were unable to maintain adequate force production (Figure 51, panel B), yet sweat rate was still maintained and even peaked when force production had fallen to almost 0 kg, thereby highlighting the influence from central command in regulating the sweating response. PEI is useful in isolating muscle metaboreceptor stimulation. Considering Figure 51 panel A, during IHG exercise, while T_{oe} remained stable, there were increases in heart rate, mean arterial pressure and sweat rate. PEI resulted in a decreased heart rate, however sweat rate and, after a brief depression, mean arterial pressure remained elevated, evidence of a muscle metaboreceptor influence in modulating the sweating response. In addition, Shibasaki *et al*. (2003a) questioned whether the sustained mean arterial pressure during PEI (Figure 51, panel A) was the cause for the sustained sweat response due to loading of baroreceptors. In an attempt to maintain muscle metaboreceptor activity whilst unloading baroreceptors, intravenous infusions of sodium nitroprusside were administered (Figure 51, panel C). Nitroprusside restored mean arterial pressure to resting levels during PEI, yet the sweat response remained elevated. This provided evidence that stimulation of muscle metaboreceptors could regulate sweating independently of baroreceptor loading or indeed T_{oe}.

Kondo *et al*. (1997) investigated the contribution of muscle mechanoreceptors to the sweating response (measured at the chest and forearm) during active or passive limb movement lasting 2 minutes while the $\overline{T}_{sk}$ was clamped at 37.0 °C using a water-perfused suit. Mechanoreceptors are activated during both active and passive limb movement, however, during passive limb movement there was no influence from central command as external forces flex the limb joints. Kondo *et al*. (1997) found that sweat rate was elevated during the active limb movement compared to the passive limb movement even though T_{oe}, $\overline{T}_b$ and $\overline{T}_{sk}$ remained unchanged between active and passive limb movement. A greater $\dot{V}O_2$ was found during active compared to passive limb movement and the authors acknowledged the influence that the greater heat production would have had on the sweating response, however Kondo *et al*. (1997) argued that it would be central command that would prompt the changes to heart rate and $\dot{V}O_2$ and therefore concluded that central command was as a prominent driver for regulation of the sweating response. In addition, sweat rate did increase during passive limb movement, although to a lesser degree than during active limb movement, even with no significant alterations to T_{oe} suggesting that activation of mechanoreceptors in the absence of the drive from central command do contribute, albeit minimally, to the sweating response. Influence from chemical changes due to slight muscle activation during passive limb movement, as shown by the electromyography data, was also possible, albeit minimal. To be noted is that Kondo *et al*. (1997) did not measure palmar sweat rate, which might provide an indication of the psychogenic influence to the sweating response that could differ between active and passive limb movement. Furthermore, local muscle temperature was not measured even though there was significantly greater muscle activity during active limb movement. As local muscle temperature has been known to influence sweat rate during exercise (Saltin & Gagge, 1971), this was an important consideration that was absent from the Kondo *et al.* (1997) experiments. Nonetheless, the experiments from Kondo *et al*. (1997) suggest that the influence from muscle mechanoreceptors, while present, is minimal and that the greater drive for the non-thermal sweating response is derived from central command.

Dehydration and sweating that are exacerbated during exercise in the heat, result in a loss of blood volume if fluid is not replenished which may cause reductions to blood pressure. A reduction to blood pressure would be sensed by any of the three types of baroreceptors (cardiopulmonary, carotid or aortic). Baroreceptor stimulation is prevalent during alterations to posture.

7.2.2 Posture as a Non-Thermal Regulator of Sweating

Dodt *et al*. (1995) induced baroreceptor unloading in passively heated individuals (warming lamp) through either a 30° head-up tilt, -5 mmHg lower body negative pressure (LBNP) or -10 mmHg LBNP and found that unloading of the cardiopulmonary baroreceptors through induction of these postures resulted in inhibition of SSNA and reduced sweating. Contrary to the findings of Dodt *et al*. (1995), Wilson *et al*. (2001) pharmacologically manipulated mean blood pressure through infusions of sodium nitroprusside that reduces blood pressure and phenylephrine that elevates blood pressure. Pharmacological manipulation of blood pressure eliminated any possible influence from emotional state or skin cooling that could occur with some methodologies such as LBNP due to air leakage cooling the skin when evacuating the air. Wilson *et al*. (2001) found that during both normothermia and mild hyperthermia, SSNA and sweat rate were largely unaffected by either nitroprusside or phenylephrine infusion and therefore the role of baroreceptors in the modulation of the sweating response was brought into question. Participants in the Wilson *et al*. (2001) study rested supine for only 5 minutes post-exercise and subsequent studies have suggested that the role of baroreceptors may be masked during the first 5 minutes of recovery (McInnis *et al*., 2006). The authors did however mention that a possible reason for the contradictory results from other studies could be due to the unloading of different baroreceptor populations. For example, the baroreceptor population primarily manipulated in the Dodt *et al*. (1995) study was cardiopulmonary whereas the baroreceptor population primarily affected in the Wilson *et al*. (2001) study was arterial.

Journeay *et al*. (2004) further investigated the role of baroreceptor loading (using LBPP of + 45 mmHg) and unloading (LBNP of – 20 mmHg) on the post-exercise physiological response that included mean arterial pressure, $\overline{T}_{sk}$, T_{oe}, SkBF and LSR. Whilst acknowledging that other non-thermal factors could contribute to the post-exercise thermal status, the authors found that the thermoregulatory responses of SkBF and sweating were primarily modulated by baroreceptor stimulation. This was evidenced by a T_{oe} decay post-exercise that was augmented under LBPP conditions, perhaps due to the augmented thermoregulatory responses (LSR and SkBF), compared to both LBNP and control conditions. The authors postulated that the augmented thermoregulatory response was a result of a reversal of blood pooling at the extremities post-exercise as indicated by the re-establishment of hemodynamic parameters (SV, heart rate and mean arterial pressure). The re-establishment of hemodynamic parameters post-exercise was absent during LBNP suggesting that the hemodynamic responses and subsequently the thermoregulatory responses might have been dependent upon baroreceptor perturbations post-exercise that impact on the rate of T_{oe} decay.

Expanding on findings of Journeay *et al*. (2004), McInnis *et al*. (2006) hypothesized that recovering in a 15° head-down tilt posture, which reduced baroreceptor unloading and promoted venous return, compared to blood pooling during upright-seated rest, would augment hemodynamic and thermoregulatory responses that would accelerate the rate of T_{oe} decay. It was found that during post-exercise recovery in the 15° head-down tilt posture thermoregulatory (sweat rate and cutaneous vascular conductance) and hemodynamic responses (SV and mean arterial pressure) were elevated in combination with a faster decay in T_{oe} compared to recovery in the upright-seated position. The authors highlighted however that as a significant difference in mean arterial pressure was identified between the 15° head-down tilt posture and upright-seated rest post-exercise, the cardiopulmonary baroreceptors were not isolated by this posture as has been previously suggested in resting studies where no exercise was undertaken (Fu *et al*. 1999). Rather both the arterial and cardiopulmonary baroreceptors might have been stimulated resulting in the augmented thermoregulatory and hemodynamic responses that led to the faster T_{oe} decay.

Overall, it has been well established that non-thermal factors can influence the whole body sweating response and therefore a series of pilot studies (Appendices 13 and 14) were conducted in an attempt to indicate which non-thermal factor/s (exercise or posture) might have been responsible for the post-exercise sweat responses observed in the third study (Figures 48 and 49). The pilot studies found that whilst both exercise and posture affected the sweating response, manipulating posture appeared to have a greater influence on modulating the sweating response compared to exercise.

7.2.3 Systemic Versus Local Response

During the pilot studies it was also noticed that not all sites responded uniformly to each postural manipulation. This result was also apparent from the sweat responses during the third study whereby sweat rate at the chest did not respond as the other sites (Figure 48). As many of the proposed mechanisms of non-thermal regulation of sweating would elicit a whole body systemic response rather than a local response (Shibasaki *et al*., 2003a), the observed regional sweat responses (for example, sweat rate at all sites decreasing but plateauing at the chest) in the third study and pilot studies were questionable. Particularly as SkBF data at all four sites (chest, back, forearm and thigh) did not mimic the pattern observed in the sweating response, but rather all sites, including the chest, followed a similar pattern of response at the cessation of exercise in that there was a decrease in SkBF (Figure 49). White *et al*. (1995) suggested that cutaneous vasodilatation and sweating might not be governed by the same mechanisms as hemihidrosis (ipsilateral reduction of sweating in response to unilateral skin pressure). Hemihidrosis was induced by lateral lying, and concentrated pressure on the gluteal and axillary regions resulted in an ipsilateral reduction in sweating that was not accompanied by an ipsilateral decreased SkBF. Therefore, during the third study, as the chest was the only site that exhibited a declining SkBF in the presence of a sustained sweat rate at the cessation of exercise; it was questioned whether this was a true physiological response or a mechanical artifact from the experimental design or measurements.

The evidence is substantial that non-thermal factors can influence LSR and this is often with the presumption that the mechanism governing the sudomotor response is systemic. The rate of sweat production differs between body segments (Weiner, 1945; Cotter *et al*., 1995a; Smith & Havenith, 2011) and can also vary within body segments (Havenith *et al*., 2007; Machado-Moreira *et al*., 2008; Smith *et al*., 2013b). Intra-segmental variations may be due to differences in sweat gland density and the rate of sweat secretion (Weiner, 1945; Park & Tamura, 1992), sudomotor thresholds (Hertzman *et al*., 1952) and regional sensitivities (Cotter & Taylor 2005). With regional variations established (Smith & Havenith, 2011; Taylor & Machado-Moreira, 2013) and intra-segmental variations in the local sweat response evident (Machado-Moreira *et al*., 2008), we questioned whether the sudomotor response to a non-thermal stimulus such as posture would occur homogenously throughout the body. This is particularly important when considering that many studies investigating non-thermal modulation of sweating tend to only measure one (upper back: Jackson & Kenny [2003]; inferior region of the trapezius: Journeay *et al*. [2004] and McInnis *et al*. [2006]) or two (calf and forearm: van Beaumont & Bullard [1963]) sites. Additionally, when reviewing the literature, evidence of regional variations to non-thermal regulation of sweating has come from the early work of Kuno (1956) when investigating hemihidrosis. Elaborating on the findings of Kuno (1956), investigations supporting the role of skin pressure in reducing the local sweating response were conducted over the next 50 years (Kawase, 1952; Ogawa, 1979; Ogawa *et al*., 1992; Okagawa *et al*., 2003; Inukai *et al*., 2005; details of these studies are found in Appendix 15), although not all studies supported the skin pressure hypothesis (Watkins, 1956). Consideration of sweat capsule placement over specific dermatomes (the area of skin supplied by a single nerve) could also result in regional variations to the sweating response depending on the neural pathway to the spinal cord of cutaneous thermoafferents. However this consideration has not yet been investigated.

Therefore, before identifying a possible mechanism that could be responsible for regional variations in the sweating response, a series of mechanical tests were conducted that authenticated the response time of the equipment (Q-Sweat™) to a changing humidity as well as the detection of the rate of evaporation when changing the orientation of the sweat capsules such as would be present when changing posture (Appendix 16). The results from the mechanical tests highlighted that the capsules displayed a quick response time, approximately 30 seconds, to a changing humidity and that the mechanical orientation of the capsule did not affect accurate measurement of water vapour present in the system.

To eliminate the potential confounding influence of the CBRN equipment that was worn during the third study and pilot studies, further pilot experiments were conducted that investigated sudomotor responses to non-thermal stimuli when wearing minimal clothing (Appendix 17). As the sweat patterns seen in response to a changing posture were noted within a few seconds of the postural shift, it was expected that responses would still be observed even with the lack of CBRN clothing elevating $\overline{T}_b$ post-exercise. The results from the first pilot study showed that CBRN clothing might have been confounding the sweating response during seated rest, as both the chest and back displayed similar sweat patterns upon assuming a seated posture when no CBRN clothing was worn. Part A of the second pilot study showed that when external pressure was applied to the capsule LSR decreased, although LSR also decreased when no external pressure was applied to the capsule, apart from the minimal pressure from clothing. Part B of the second pilot study showed that LSRs followed a similar pattern between sites when posture was manipulated and no CBRN clothing was worn. Therefore, the regional variations in the sudomotor response observed in the previous experiments could have been due to the influence of the CBRN clothing acting directly on the sweat capsule or direct pressure applied to the capsule due to the posture adopted. However, as a decreased LSR was also observed in the absence of applied external pressure, further investigation was required that minimized the clothing effects. Pressure on certain parts of the capsule might disrupt accurate sampling. As the Q-Sweat™ was primarily designed for clinical use, it was important to confirm these findings using a different sweat measurement system.

7.3 Research Aims

The aims of this study were to:

7.3.1 Investigate the impact of manipulating posture on LSR and SkBF responses at the chest, back, forearm and thigh.

7.3.2 Assess whether regional responses in LSR and SkBF were homogenous between the chest, back, forearm and thigh when posture was manipulated.

7.4 Hypotheses

H_{01}: Manipulating posture would not modulate LSR and SkBF responses at the chest, back, forearm and thigh.

H_{a1}: Manipulating posture would modulate LSR and SkBF responses at the chest, back, forearm and thigh.

H_{02}: The regional responses in LSR and SkBF would be homogenous between the chest, back, forearm and thigh when manipulating posture.

H_{a2}: The regional responses in LSR and SkBF would not be homogenous between the chest, back, forearm and thigh when manipulating posture.

7.5 Methods

7.5.1 Research Design

Ten male participants volunteered for the study however due to both laser Doppler and sweat capsule detachment from one participant during an experiment, data from only nine participants were analysed. The participants' age, height, body mass and percentage body fat were: mean (SD) 24.7 (4.2) years, 173.0 (7.3) cm, 74.6 (8.9) kg, 15.4 (3.1) % respectively. The experiment involved participants coming into the laboratory on a single day and completing an 80-minute protocol (Table XIII) in a hot (40.0 °C) environment. The participant wore underwear and trainers to minimize the influence of clothing on the equipment and subsequent sweating response. The participant also wore a lightweight poncho made from thin and flexible MVIP plastic that provided an insulative and vapour impermeable upper body microclimate in an attempt to maintain post-exercise $\overline{T}_b$. All experiments took place at the Human and Environmental Physiology Research Unit, School of Human Kinetics at the University of Ottawa. Professor Kenny kindly supervised all experiments due to his extensive research in the area of non-thermal regulation of sudomotor and vasomotor responses (Jackson & Kenny, 2003; Journeay *et al*., 2004; McInnis *et al*., 2006; Gagnon *et al*., 2008; Lamarche *et al*., 2015).

Participants were weighed before and after the experiment and were instrumented with a rectal and oesophageal thermistor, heart rate monitor, skin thermocouples at the calf, thigh, arm, chest to estimate $\overline{T}_{sk}$. Four sweat capsules and laser Doppler probes were secured to the chest, back, forearm and thigh (General Methods: Section 3.4.2). The hydration level of each participant was measured from a urine sample provided before the start of the experiment to ensure euhydration amongst all participants (General Methods: Section 3.4.1).

After instrumentation, participants were escorted into the environmental chamber and rested, seated on a stool, for 10 minutes to obtain baseline measures. Participants then stepped to a height of 22.5 cm at a rate of 14 steps.min^{-1} to elevate LSR and SkBF. A series of postures were then adopted according to Table XIII (standing, sitting, lying on the side, lying prone and lying supine). During the lying down postures, padded boxes were strategically positioned to support the participants, such that no external pressure was directly exerted on the sweat capsules or laser Doppler probes, which were positioned between the supporting padded boxes. After each posture, LSR was "reset" by stepping for 3 minutes and then standing for 2 minutes. This was important as during some postures LSR was reduced and therefore the LSR response for subsequent postures would be biased, or the response would not be measurable, due to the lowered starting LSR. The pilot studies showed that from a lowered sweat rate, LSR could be increased again in a five-minute period that involved either stepping or standing (Appendix 14). It was important that participants stood after the stepping period to minimize any potential effects of immediately stopping exercise on LSR and SkBF responses.

Table XIII: The protocol to investigate the non-thermal modulation of local sweat rate and skin blood flow in response to postural manipulations.

Time (minutes)	**Activity**
0 - 10	Baseline Resting Measures
10 - 35	Stepping to a height of 22.5 cm at a rate of 14 $steps.min^{-1}$
35 - 40	Stand
40 - 45	Reset Sweat Rate (Step for 3 minutes and Stand for 2 minutes)
45 - 50	Sit (on stool with back unsupported)
50 - 55	Reset Sweat Rate (Step for 3 minutes and Stand for 2 minutes)
55 - 60	Lying on the side
60 - 65	Reset Sweat Rate (Step for 3 minutes and Stand for 2 minutes)
65 - 70	Lying prone
70 - 75	Reset Sweat Rate (Step for 3 minutes and Stand for 2 minutes)
75 - 80	Lying supine

Figure 52: A participant standing (left), lying supine (middle) and lying prone (right).

7.6 Results

Mean T_{oe}, T_{re}, LSR and SkBF responses are illustrated in the figures below.

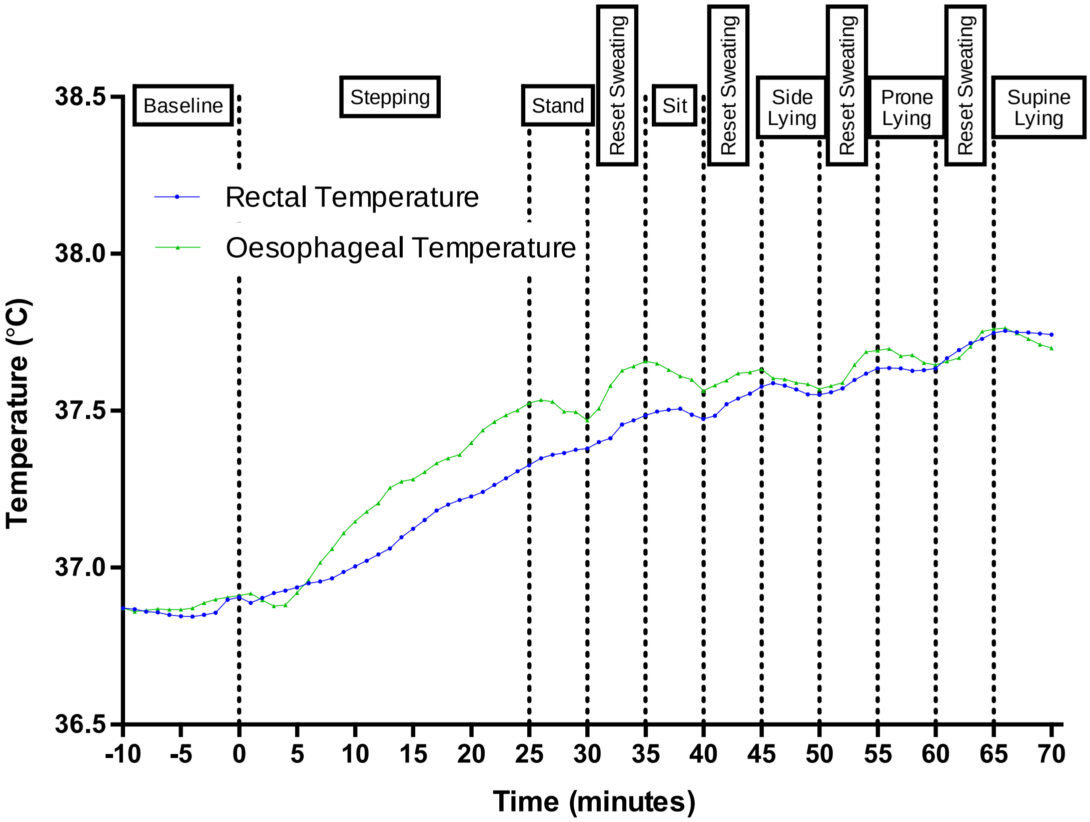

Figure 53: Mean rectal and oesophageal temperatures during exercise and posture manipulations in a 40.0 °C environment whilst minimally clothed with a poncho (n = 9).

Note that due to equipment malfunction, temperature data were not available for the following (Appendix 9): P1 T_{oe} from 30 minutes

Both T_{re} and T_{oe} increased during exercise and the reset-sweating periods. T_{oe} displayed a quicker response time to a change compared to T_{re}. The mean change in T_{re} throughout the protocol from the end of the 25-minute stepping period until the end of the final posture (supine lying) was 0.41 °C, whereas the change in T_{oe} was only 0.18 °C.

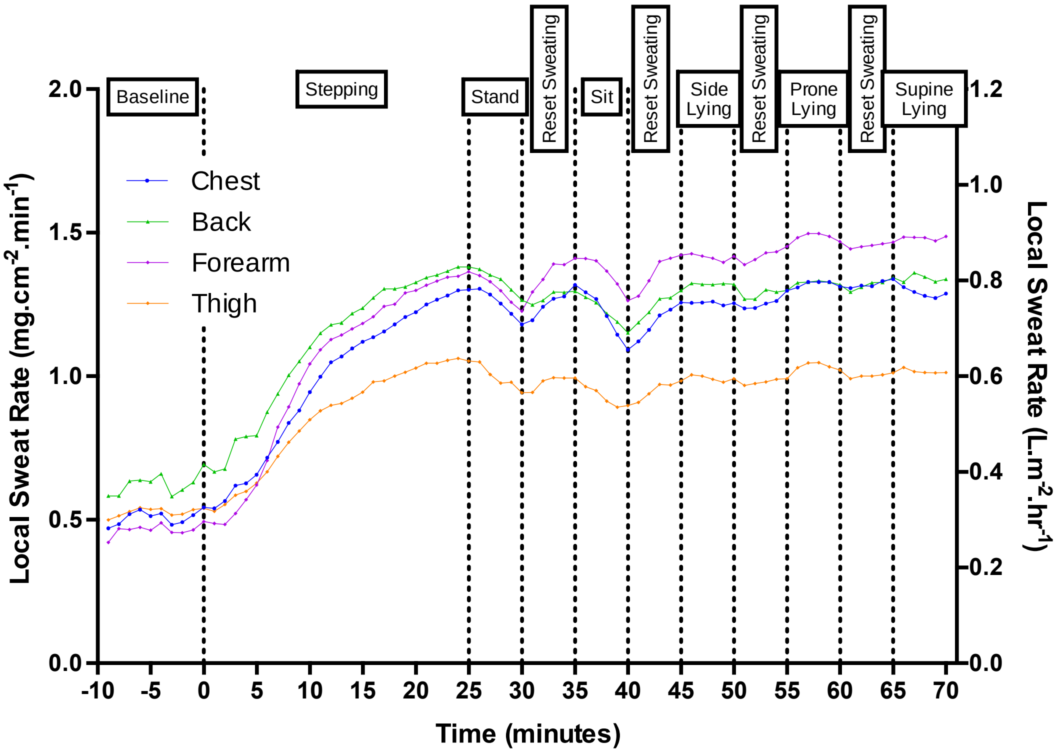

Figure 54: Mean sweat rate at the chest, back, forearm and thigh during exercise and posture manipulations in a 40.0 °C environment whilst minimally clothed with a poncho (n = 9).

Note that due to capsule detachment, LSR data were not available for the following (Appendix 9):

P1 thigh from 30 minutes

P3 chest from 56 minutes

LSR increased during the stepping exercise period and during all the reset-sweating periods except the final reset-sweating period where LSR appeared to plateau. LSR during the standing and sitting postures appeared to decrease more so than the LSR during the lying postures (side, prone and supine). All sites (chest, back, forearm and thigh) followed a similar response throughout the protocol.

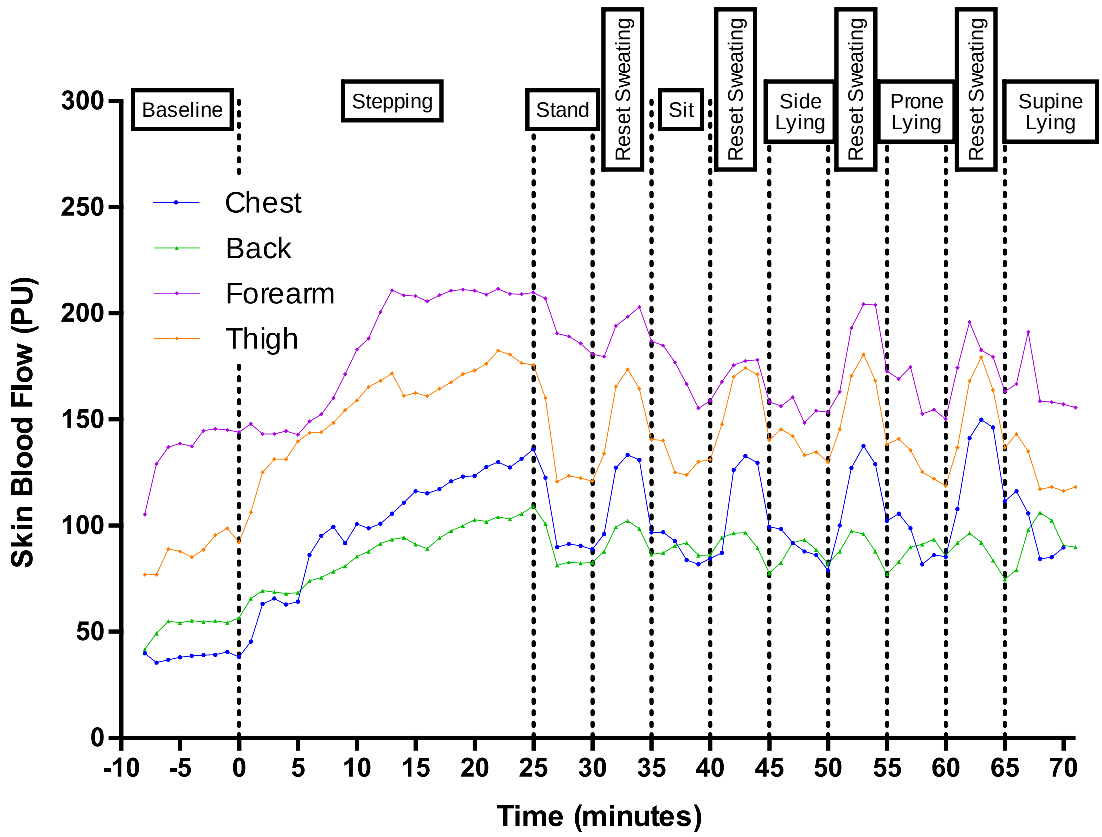

Figure 55: Mean skin blood flow at the chest, back, forearm and thigh during exercise and posture manipulations in a 40.0 °C environment whilst minimally clothed with a poncho (n = 9).

Note that due to laser probe detachment, SkBF data were not available for the following (Appendix 9): P8 chest from 65 minutes

SkBF increased during the stepping exercise period and during all the reset-sweating periods and decreased when adopting a posture and no exercise was being undertaken. All sites (chest, back, forearm and thigh) followed a similar response throughout the protocol.

7.7 Discussion

The first null hypothesis stated that manipulating posture would not modulate LSR and SkBF responses at the chest, back, forearm and thigh. LSR, SkBF and T_c (T_{oe} and T_{re}) at all sites increased during exercise and the resetting periods as expected. T_{oe} displayed a quicker response time to change compared to T_{re}. For example, when considering the T_c responses at the cessation of exercise during the first standing period, T_{oe} began to fall after approximately two minutes of standing whilst T_{re} continued to rise throughout the entire five-minute standing period. Thus the lag in T_{re} was made apparent in these experiments and might have confounded the results from the pilot studies thereby highlighting the advantage of using T_{oe} as a measure of T_c over T_{re} as well as aural temperature (T_{au}) that was used in some pilot studies (Cooper & Kenyon, 1957; Kondo *et al.*, 2010; Taylor *et al.*, 2014b). The rate of change of T_c however, was not largely different between T_{re} and T_{oe}, thus justifying earlier use of T_{re} for analysis when a rate of change had been established, as already mentioned previously. To be remembered also, was that in the pilot experiments, $\overline{T}_b$ was largely maintained post-exercise due to wearing fully encapsulating protective equipment thus accentuating the influence from changes to posture or activity while the thermal drive remained largely unchanged, at least when measured with T_{re} or T_{au}. CBRN clothing was not worn in the current study but rather a lightweight and largely MVIP poncho was worn that covered the upper body only. Therefore, it is uncertain whether T_c measured during the pilot studies would have resulted in a similar fall in T_c if T_{oe} had been measured in place of T_{re} or T_{au}, or whether the CBRN clothing would have maintained T_{oe} post-exercise. SkBF appeared largely affected by T_{oe} and exercise rather than posture, as the magnitude and pattern of response was similar throughout the protocol (increased SkBF during exercise with a decreased SkBF during non-exercise). The LSR responses displayed different magnitudes of response throughout the protocol.

The greatest decrease to LSR at all sites was found during the first two postures (standing and sitting) with the magnitude of the response lessening later in the protocol. This might have been due to a number of considerations as described below:

i. The postural manipulations of standing and sitting exerted a greater influence on LSR compared to lying down (laterally, supine or prone).
ii. The 25 minutes of exercise preceding the standing posture might have exaggerated the response and this was still evident 10 minutes later during the sitting posture. Robinson (1962) and Kondo *et al*. (2010) stated that for the same T_c, sweat rate during exercise was higher than sweat rate during rest. Varying sweat responses during exercise and rest might explain why the reduction to LSR was greatest after 25 minutes of exercise during standing and possibly sitting but less so during lying that occurred later in the protocol and thus was less influenced by the 25 minute exercise period. Although exercise was interspersed between each posture to elevate LSR, it was only of a short duration (three minutes) and was followed by two minutes of standing, compared to the initial 25 minutes of continuous exercise. To test the hypothesis that the duration of exercise preceding postural manipulation would affect the magnitude of the response to LSR, 25 minutes of exercise should precede all postures or the order of postures adopted should be balanced.
iii. Changes to T_{oe} might have affected the magnitude of the LSR response. Throughout the protocol, it was important that the T_c at which each posture was adopted was similar (Kondo *et al*., 2002) although the work of Gagnon *et al*. (2008)

found that non-thermal modulation of the sweating response was still observed even in the presence of a large thermal drive (T_{oe} > 39.5 °C). During the current study, T_{oe} at the first posture (standing) was 37.52 (0.08) °C and at the last posture (lying supine) was 37.76 (0.11) °C. Therefore the mean T_{oe} was 0.24 °C less than T_{oe} at the final posture (supine lying). However, the mean T_{oe} at the start of the sitting posture (when a large reduction to LSR was observed) was 37.66 (0.10) °C and at the start of the prone lying posture (where a lesser change in LSR was observed) was 37.69 (0.13) °C, a difference of 0.03 °C. Therefore it was unlikely that these marginal differences in T_{oe} (greatest range of 0.24 °C) were entirely responsible for the magnitude of change to LSR during different postures. Nonetheless, the contribution from thermal drive *vs*. non-thermal mechanisms, such as exercise or posture, would in the future be best explored if T_{oe} remained clamped post-exercise such that each posture was adopted at the same T_{oe}. However, without introducing unwanted mechanical or pressure effects from clothing or a water-perfused suit itself, this methodological consideration requires further experimentation.

Based upon the T_{oe} results that displayed a quicker response time than T_{re} it was impossible from the results obtained to compartmentalize the influence of purely thermal or non-thermal factors on regulating LSR and SkBF responses and therefore the null hypothesis was not rejected that manipulating posture would not modulate LSR and SkBF responses at the chest, back, forearm and thigh. However, it was likely that non-thermal factors affected LSR to a greater degree than SkBF and possibly that the postures of standing and sitting reduce LSR more so than lying down (laterally, prone or supine). These speculations required further investigations that clamped T_{oe} post-exercise, controlled the duration of exercise pre-posture or balanced the order of postures.

The second null hypothesis stated that regional responses in LSR and SkBF would be homogenous between the chest, back, forearm and thigh when manipulating posture. This hypothesis was based on the fact that many of the mechanisms proposed for the non-thermal influence on sweating are systemic in nature, such as baroreceptor stimulation (Dodt *et al*., 1995; Shibasaki *et al*., 2003a). All sites followed a similar pattern of response, that being elevated during exercise and reduced when no exercise was being undertaken, therefore no regional differences in LSR or SkBF responses were present. Thus, during the current study all sites responded uniformly to perturbations in T_c, posture or exercise.

Speculation as to possible reasons why regional variations were observed in the third study and some pilot work included the influence of clothing and / or mechanical pressure imposed on the sweat capsules. During the current study when participants laid down laterally, supine or prone, padded boxes were strategically placed so as to support the participant (thereby minimizing muscle activation which could influence the sudomotor response [Gisolfi & Robinson, 1970]) but also allowing the area surrounding the sweat capsule and laser Doppler probe to be entirely free of contact from the padded box. In this way, mechanical forces acting directly on the sweat capsules or laser Doppler probes were minimized unlike during the pilot studies. However, this method also removed skin pressure from the site of LSR and SkBF sampling that would be present if a participant was to lie down in a practical, not laboratory, setting. Although the influence of skin pressure on modulating the sweating response is still debated (Inukai *et al*., 2005; Watkins, 1956), skin pressure during the current study, unlike the pilot studies, was absent from the sampling site, although present near to the sampling site. During the pilot studies when direct pressure was applied to the sweat capsule LSR decreased, although LSR also decreased when no external pressure was applied to the capsule, apart from the minimal pressure from clothing, for example when lying supine and LSR at the chest was reduced (Appendix 14). Even when wearing minimal clothing (shorts and trainers only), LSR at the chest, as well at the three other sites sampled (back, forearm and thigh), were reduced upon adopting a supine posture (Appendix 17). As a homogenous LSR response was observed in the current study, the regional variations in LSR found during the third study and the pilot studies might have been due to the CBRN clothing or external pressure applied directly on the sweat capsule.

In summary, during this study, all sites (chest, back, forearm and thigh) followed a similar pattern of response, that being elevated during exercise and reduced when no exercise was being undertaken, with no regional differences in LSR or SkBF responses being present and therefore the null hypothesis that the regional responses in LSR and SkBF would be homogenous between the chest, back, forearm and thigh when manipulating posture was not rejected. Furthermore, the regional responses observed in the pilot and previous studies were therefore possibly a product of the confounding effects of the CBRN clothing, mechanical pressure on the Q-Sweat^{TM} system or both.

7.8 Conclusions

The results from this study have shown that estimating T_c from T_{re} introduced a lag that is not present when using T_{oe}. Therefore, in future when investigating non-thermal regulation of sweating a sensitive measure to change of T_c, such as T_{oe}, should always be used, particularly when T_c might be expected to fall for example at the cessation of exercise depending upon the ambient conditions. Nonetheless, the thermal drive from T_c was most likely the primary regulator of LSR and SkBF responses in this study, although the influence of adopting a standing or sitting posture on the reduction to LSR being greater compared to adopting a lying down posture requires further investigation. Future studies exploring this should ensure T_{oe} is clamped post-exercise and that the duration of exercise pre-posture is equal before all postures. The chest, back, forearm and thigh all produced a homogenous sweat pattern in response to a changing T_c, posture or exercise thereby confirming that if there was a non-thermal mechanism governing the thermoregulatory responses of LSR and SkBF, the mechanism was most likely systemic in nature.

7.9 Impact of Findings and Future Research

- Although the exact contribution of posture manipulations to the non-thermal regulation of sweating requires further investigation, others have clearly identified the role of posture perturbation on the sudomotor response (Dodt *et al.*, 1995; Inukai *et al.*, 2005) and this could have important clinical and ergonomic implications. For example, McInnis *et al.* (2006) identified that placing participants in the head-down tilt posture significantly enhanced the rate of T_{oe} decay and venous return following exercise-induced hyperthermia and therefore suggested that positioning hyperthermic patients in a similar posture would augment recovery. Furthermore, the authors emphasized the practical advantage of the head-down tilt posture over other methods that may be equally as effective at enhancing the rate of T_c decay but might be difficult to implement in the field *e.g.* LBPP methods. Indeed depending on the environmental conditions, cooling by convection and conduction would, where possible in the field, be the cooling methods of choice (House *et al.*, 1996; Smith, 2005; Barwood *et al.*, 2009b). White *et al.* (1995), when exploring the phenomenon of hemihidrosis on selective brain cooling through measurement of sweating and blood flow to the head, suggested that as a prophylactic, patients should avoid a lateral lying position that might induce hemihidrosis and thus potentially attenuate brain cooling. Therefore, the authors emphasized the adoption of a prone or supine posture in treating the hyperthermic patient. However, this advice should be used with caution, as unless the airway is supported, there is a greater risk of airway occlusion. These interventions are useful in the patient with heat illness however, when patients develop heat stroke, sweating ceases and therefore these methods would not be effective. The methods adopted in the current study allowed for investigation of postural perturbations on the LSR and SkBF response from a practical perspective such that any of the postures adopted could easily be used in the field and did not require complicated and expensive equipment such as tilt tables or pressure chambers.

- Further investigations should explore whether the reduced sweating response is indeed greatest when adopting a standing or sitting posture compared to lying down (laterally, prone or supine). From a military perspective when operating in a hot environment, identifying a posture that possibly attenuates sweating during recovery and avoids excessive dehydration would be useful to adopt when wearing fully encapsulating clothing whereby evaporation of sweat is largely impeded anyway by the protective clothing. Moreover, identifying a posture that augments sweating during recovery when T_c is maintained would be useful to adopt when wearing CC whereby evaporation of sweat is much less impeded and would therefore contribute to evaporative cooling.

7.10 Limitations

During the pilot studies, CBRN clothing was used to maintain $\overline{T}_b$ post-exercise thereby isolating the non-thermal contribution to the LSR and SkBF response. During the main experiment wearing the poncho was an attempt to maintain $\overline{T}_b$ post-exercise and this proved ineffective as shown by the T_{oe} responses. However, as T_{oe} was not used for the pilot studies, the extent of $\overline{T}_b$ maintenance when wearing the CBRN clothing cannot be confirmed although it is likely that the CBRN clothing maintained $\overline{T}_b$ to a greater extent than wearing the poncho that only covered the upper body thereby accentuating the influence of non-thermal factors in regulating LSR and SkBF responses.

CHAPTER VIII: GENERAL DISCUSSION, SUMMARY AND CONCLUSIONS

The minimally clothed human is well adapted for working in a hot environment (Nielsen & Nielsen, 1965; Åstrand & Rodahl, 1977). However, working in the heat can be debilitating, resulting in an increased frequency of accidents and reducing both physiological and cognitive performance compared to thermoneutral (Chrenko, 1974; Tatterson *et al*., 2000) and even sleep-deprived (Pepler, 1959) conditions. The decrements to performance and risks to health are worsened when wearing protective clothing that impedes evaporative cooling, thereby increasing thermoregulatory strain (McLellan *et al*., 1992; Amos & Hansen, 1997). Protective clothing that covers certain body areas may induce a greater thermal burden on the wearer, as not all areas of the body elicit the same reduction to thermoregulatory strain when evaporative cooling is permitted, due to varying surface areas, densities of sweat glands, rates of sweat production and thresholds of sensitivity (Cotter *et al*., 1996; Cotter & Taylor, 2005; Taylor & Machado-Moreira, 2013). Perceptually, there appears to be a hierarchy of sensory feedback to the somatosensory cortex between body areas, most likely due to the heterogeneous distribution of thermoreceptors (Penfield & Boldrey, 1937; Nadel *et al*., 1973; Hensel, 1981). Given that the temperature fluctuations are usually far greater at the extremities compared to the core, the human body seems well adapted to soliciting environmental thermal information through the locally sensitive hands and prioritizing feedback for thermoregulation from the highly sensitive face (Benzinger, 1976; Frank *et al*., 1999).

The work described in this thesis addressed a specific, applied question raised and funded by the UK MoD. The experiments in this thesis have examined regional variations in the thermal and non-thermal modulation of thermoregulation in humans. The first study aimed to quantify the individual and cumulative thermal burden imposed by MVIP ancillary items when worn during exercise in a hot, desert-like environment. The BAL was identified as the item that imposed the greatest thermal burden on the wearer, as when not worn, there were improvements to both physiological and perceptual thermoregulatory strain. This extends the current literature that supports the torso as an area of high heat dissipation due to a large surface area and high rate of sweat production (Weiner, 1945; Smith & Havenith, 2011). However, as loads are often carried at the level of the torso (Knapik & Reynolds, 2012) and BA is unlikely to be made more permeable whilst still maintaining protection from ballistic insults, it was recommended that the MVP of the respirator or gloves be improved to reduce the thermoregulatory strain of wearing CBRN IPE.

Removing the evaporative resistance of materials covering the face, by not wearing the respirator, improved both physiological and perceptual measures without any forced cooling. This extends the findings of studies where the face was actively cooled and provided alliesthesial alleviation of thermal strain (Kissen *et al*., 1971; Rasch *et al*., 1991; Mündel *et al*., 2007). Furthermore, this finding brings together research that emphasizes the cooling potential of the face, and forehead specifically (Szabo, 1962; Knip, 1969; Cotter *et al*., 1995a; Smith & Havenith, 2011), with literature that emphasizes the perceptual sensitivity of the face (Penfield & Boldrey, 1937; Cotter & Taylor, 2005).

At the sponsor's request, the experimental design of the first study followed on from manikin tests conducted at the University of Loughborough (Havenith *et al*., 2013). As an aside, the results from this study offered the unique perspective of comparing data obtained from manikins to that from humans. The results tended to agree well, although the manikin results quantified a greater whole body thermal burden of covering the head that was not matched in the human studies. While the reasons for this were discussed in detail in Chapter 4, it was most likely confounded by not removing the respirator and hood in combination in the human studies thereby exposing only the face and not the entire head, which was a specific methodological choice to isolate the thermal burden imposed solely by the respirator.

The experimental design of the second study considered that the lowering thermal load on the participant during the first study with more items not being worn as conditions progressed, might have resulted in inaccurate estimations of the thermal burden of the ancillary items. Therefore, the aim of the second study was to quantify the thermal burden of the MVIP ancillary items again, but in isolation to each other, thereby maintaining the thermal load across conditions. Indeed differences were identified between the first and second studies the most important of which were that the first study underestimated the thermal burden imposed by the gloves and overboots during exercise compared to the second study, most likely because during Study 1 the items had less of a thermal load over which to demonstrate an improvement. Therefore a recommendation was made that future experiments quantifying the thermal burden of items should ensure a maintained thermal load across conditions.

The results from the second study showed that exposing the hands to a hot and dry environment resulted in the greatest improvement to thermoregulatory strain compared to exposing the face, or not wearing the BAL or overboots. To our knowledge this is the first experiment that directly compared exposing the hands or exposing the face in a hot and dry environment during exercise without active cooling, while the rest of the body was covered in CBRN equipment thereby largely maintaining $\overline{T}_{sk}$ between conditions. Theoretically the hands, even with a small surface area of approximately 4.6 % of total body surface area (Yu *et al*., 2008), should contribute to reducing whole body thermoregulatory strain when evaporative cooling is permitted due to the high density of sweat glands, with the capacity to permit large increases of blood flow due to the high density of capillaries and large arteriovenous anastomoses (Grant & Bland, 1931; Hales, 1985; Taylor & Machado-Moreira, 2013; Caldwell *et al*., 2014). The results from the second study supported this theoretical contribution from the hands in reducing whole body thermoregulatory strain, and were probably enhanced by forced sweat evaporation during stepping, as the range of motion at the extremities is greater than that of central areas of the body (Graves *et al*., 1988; Dorman & Havenith, 2005; Wang *et al*., 2012). Less information in the literature is available for the perceived thermal benefits of permitting evaporative cooling from the hands. Although the hands are well represented on the somatosensory homunculus (Penfield & Boldrey, 1937), much of the literature focuses on the thermally sensitive face (Nadel *et al*., 1973; Cotter & Taylor, 2005). During the second study whilst exposing the face alone did not result in any significant improvements to whole body perceptual measures, exposing the hands resulted in participants feeling less thermally uncomfortable towards the end of the protocol.

Permitting evaporative cooling at small body surface areas such as the hands and face, resulted in measurable reductions to whole body thermoregulatory strain during the first and second studies. It was questioned whether exposing these areas might have influenced thermoregulatory responses of LSR and SkBF at unexposed areas (torso, forearm and thigh) if the $\overline{T}_b$ was unchanged and furthermore, whether these responses would have been influenced to a similar degree during hands or face exposure. Particularly as it has been proposed that the differential thermosensitivity of various body areas might be more important to consider than merely surface area when assessing relative contributions to the whole body thermoregulatory response (Nadel *et al*., 1973; Crawshaw *et al*., 1975; Cotter & Taylor, 2005). Thus, the aim of the third study was to quantify the contribution of exposing the head or the hands to a hot and dry environment on LSR and SkBF responses at the torso, forearm and thigh and whole body perceptual responses during exercise. From a theoretical point of view the results of the third study would be useful in adding to the work previously conducted by others on resting individuals who found that the face was five times more sensitive than the hand during local warming by 4.0 °C (Cotter & Taylor,

2005) and produced three times more sweat than the thigh, abdomen or chest when heated by 3.0 °C (Nadel *et al*., 1973). From a practical point of view, the results from this study could offer a novel approach to fluid regulation when wearing CBRN IPE where much of the sweat produced does not actually contribute to evaporative cooling due to the vapour restrictive properties of the clothing (mean sweat evaporation / production ratio of 49 % when fully encapsulated). The results of the third study, whereby no significant changes to whole body perceptual or thermoregulatory responses of LSR and SkBF at the untreated sites (chest, back, forearm and thigh) were found when $\overline{T}_b$ was 37.5 °C, suggested that heating of discrete areas such as the hands or head might only affect those perceptual and thermoregulatory measures during rest, based on previous literature (Nadel *et al*., 1973; Cotter & Taylor 2005), or potentially when the stimulus at the treated site is greater than 0.68 °C during exercise.

The results from the third study prompted an investigation into the post-exercise thermoregulatory responses of LSR and SkBF that decreased, at all sites (chest, back, forearm and thigh) except LSR at the chest, even in the presence of an elevated $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and local T_{sk}. Therefore, the fourth study investigated whether LSR and SkBF might not be wholly driven by T_c or local T_{sk}, but might be influenced by non-thermal mechanisms such as exercise and / or posture that were both altered post-exercise in the third study. Before the fourth experiment was undertaken, six separate pilot experiments were conducted to isolate the influence of exercise or posture on LSR. The results indicated that posture, and to a lesser extent, exercise, were responsible for the decline in LSR post-exercise (Appendices 13 and 14). Two mechanical tests were also conducted to investigate the response time of the sweat monitoring system to detect a change in humidity, as well as the potential artifact of changing the orientation of the sweat capsules on detecting water vapour content (Appendix 16). A further two pilot studies were also undertaken that investigated the possible confounding effects of clothing and pressure applied to the sweat capsules on LSR (Appendix 17).

Based on the results of the pilot experiments, the fourth study involved minimally clothed participants exercising and recovering in a series of postures while LSR and SkBF responses were monitored. It was found that the thermal drive from T_c was most likely the primary determinant of LSR and SkBF responses. However it was recommended that the finding that adopting a standing or sitting posture post-exercise results in a larger decrease to LSR compared to a lying posture should be further investigated, as this could have implications for recommended recovery positions for those wearing clothing that either restricts or permits evaporative cooling. Furthermore, as all four sites exhibited a corresponding response to a changing T_c, exercise or posture, any thermal or non-thermal mechanisms influencing sudomotor and vasomotor responses were most likely systemic. This finding has important methodological implications as it validates previous studies that have investigated non-thermal regulation of the sudomotor response by sampling from only one site (Jackson & Kenny, 2003; Journeay *et al.*, 2004; McInnis *et al.*, 2006).

In summary, the results from the experiments undertaken, with the caveats defined within, allow for rejection of the general null hypothesis and acceptance of the experimental hypothesis that improving the MVP of CBRN ancillary items alleviated thermoregulatory strain when worn in a hot, desert-like environment. Furthermore the reduced thermoregulatory strain differed between items, with not wearing the gloves, exposing only 4.6 % of total body surface area, alleviated thermoregulatory strain by the largest amount, with not wearing overboots the least.

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APPENDICES

Appendix 1: Counter-balanced Latin Square Design

Table XIV: A counter-balanced Latin square design showing the order of conditions for the first, second and third studies.

Participant	Day				
	1	2	3	4	5
1 & 11	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
2 & 12	Condition 2	Condition 4	Condition 1	Condition 5	Condition 3
3 & 13	Condition 4	Condition 5	Condition 2	Condition 3	Condition 1
4	Condition 5	Condition 3	Condition 4	Condition 1	Condition 2
5	Condition 3	Condition 1	Condition 5	Condition 2	Condition 4
6	Condition 5	Condition 4	Condition 3	Condition 2	Condition 1
7	Condition 3	Condition 5	Condition 1	Condition 4	Condition 2
8	Condition 1	Condition 3	Condition 2	Condition 5	Condition 4
9	Condition 2	Condition 1	Condition 4	Condition 3	Condition 5
10	Condition 4	Condition 2	Condition 5	Condition 1	Condition 3

Appendix 2: Applicability of the Physiological Strain Index in Determining Thermoregulatory Strain when Wearing Fully Encapsulating Protective Clothing

The PSI as proposed by Moran *et al*. (1998) combines measures of rectal temperature (T_{re}) and heart rate to elicit one value between 0 and 10 that is indicative of thermoregulatory strain. The model was developed using 100 healthy men (mean ± SEM: 20 ± 3 years, 178 ± 10 cm, 74.6 ± 10.5 kg, body surface area of 1.92 ± 0.15 m^2) who rested (10 minutes), exercised (120 minutes walking at 1.34 $m.s^{-1}$ at a 2 % gradient) and then recovered (10 minutes, although not explicit in the manuscript) in a chamber set to 40 °C and 40 % rh wearing only shorts and trainers. The model was validated on seven men wearing a partially protective clothing ensemble with an insulation coefficient of 1.3 who exercised only (180 minutes walking at a $\dot{V}O_2$ of 1.5 $L.min^{-1}$) in hot (43 °C) and dry (20 % rh) as well as hot (35 °C) and wet (50 % rh) environments. Calculation of PSI is based on the following equation:

$$PSI = 5\ (T_{ret} - T_{re0})\ ^{*}\ (39.5 - T_{re0})^{-1} + 5\ (HR_t - HR_0)\ ^{*}\ (180 - HR_0)^{-1}$$

Where: T_{ret} and HR_t are rectal temperatures and heart rate measures taken at any time during the protocol

T_{re0} and HR_0 are initial measures

This assumes that the maximal difference in T_{re} from normothermia to exercise-induced heat stress is 3.0 °C (36.5 °C to 39.5 °C) with the maximal difference in heart rate being 120 $beats.min^{-1}$ (60 $beats.min^{-1}$ to 180 $beats.min^{-1}$), giving a range in PSI from 0 to 10.

Ambiguity of "Initial Measures"

There is ambiguity in determining the T_{re0} and HR_0 measures. When following the specific instructions of the PSI equation, T_{re0} and HR_0 are constantly referred to as "initial" measures. It seems appropriate to base a measure of thermoregulatory strain during an intervention on the initial state of the individual and to subsequently determine the extent of thermoregulatory strain from the change from baseline. When this is done, negative values are obtained as found in our laboratory when wearing fully encapsulating protective clothing in a hot environment (Figure 56).

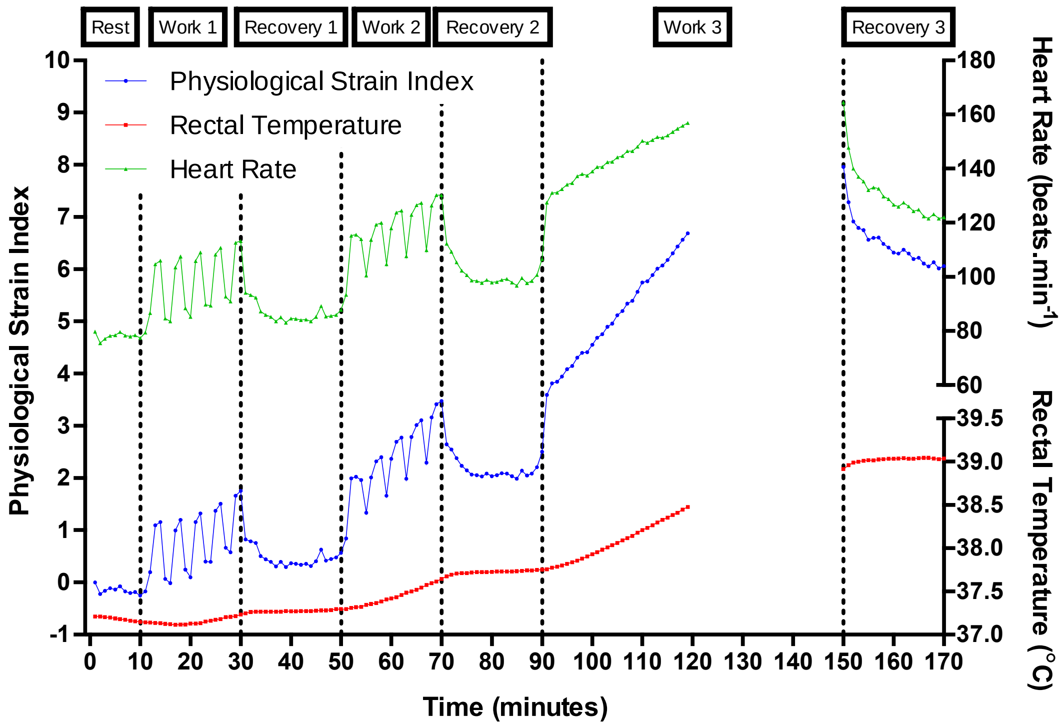

Figure 56: Mean physiological strain index (PSI), rectal temperature and heart rate during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in a 40.5 °C and 20 % rh air chamber (n = 13). With varying tolerance times, data are shown to the last point where n = 13. Initial rectal temperature and heart rate at time zero were used to calculate PSI.

Negative PSI values for the mean (n = 13) are obtained during the first 10 minutes (rest) primarily due to the initial heart rate not being the lowest recorded heart rate. Adjusting for the lowest heart rate obtained during the 10-minute rest period increases the PSI and results in no negative values for the mean (n = 13) (Figure 57).

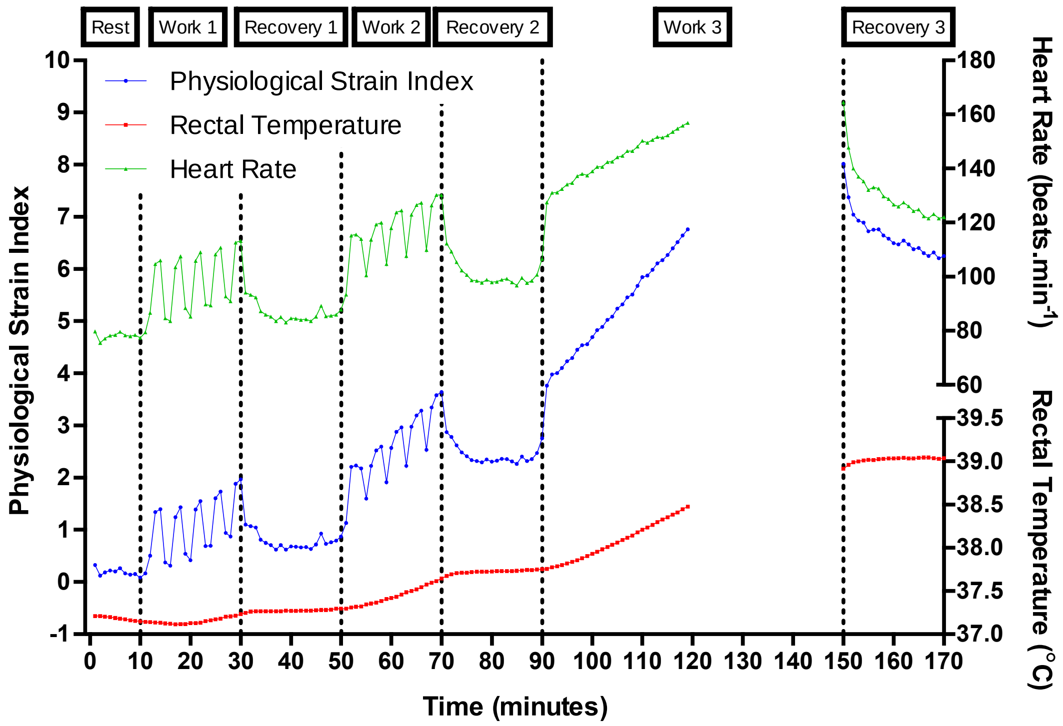

Figure 57: Mean physiological strain index (PSI), rectal temperature and heart rate during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 13). With varying tolerance times, data are shown to the last point where n = 13. Initial rectal temperature (time zero) and the lowest heart rate during rest were used to calculate PSI.

Considering individual responses, in some participants (7 out of 13), negative values were still noticed even when the lowest heart rate during rest was used as the initial heart rate (HR_0). This may be due to two reasons, firstly the lowest heart rate was present later on in the protocol not during the initial rest period (Figure 58); secondly, and more influentially, a lower T_{re} than the initial T_{re} was found later in the protocol (Figure 59). This can occur when warmer blood from the core mixes with cooler blood from peripheral tissues when the vasoconstrictor tone is released upon exposure to the heat. Furthermore as seen on the mean trend, when using the lowest T_{re} value throughout the protocol as T_{re0} rather than initial T_{re} in combination with the lowest heart rate throughout the protocol as HR_0 rather than the initial heart rate, the magnitude of the PSI increases, particularly during the early stages of the protocol (Figure 60).

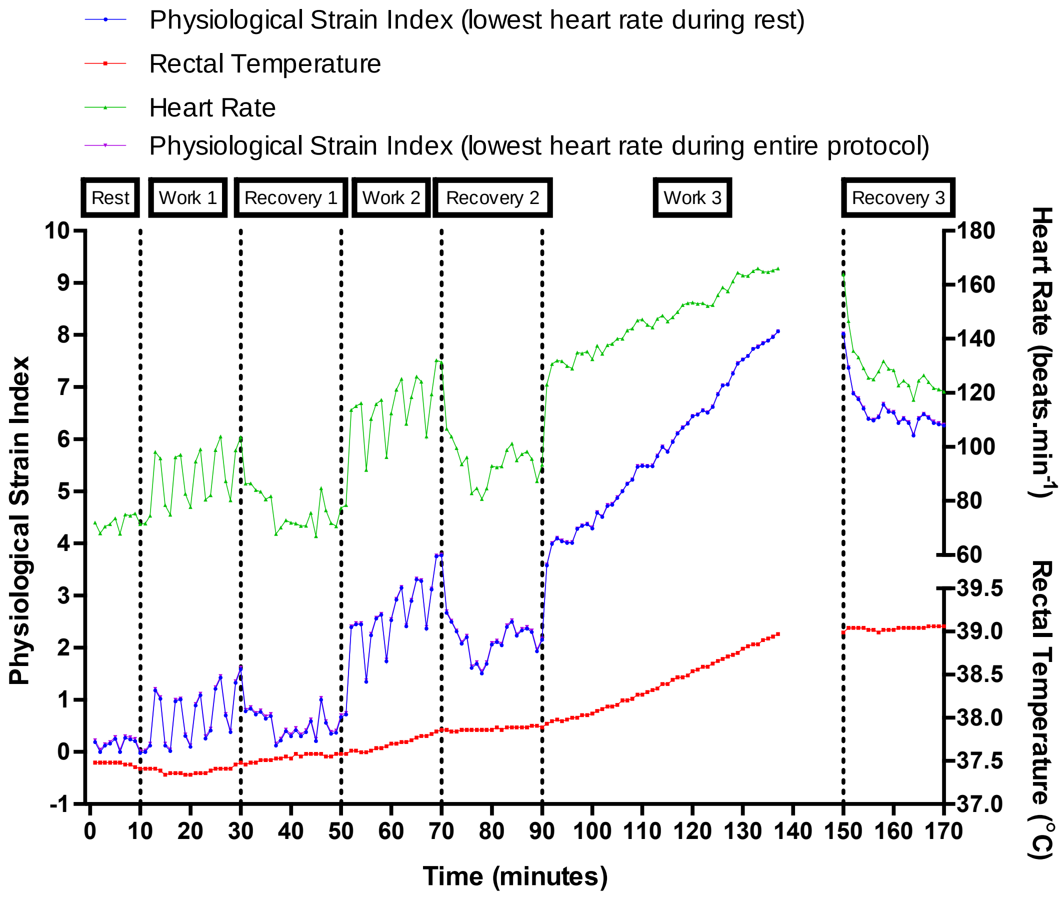

Figure 58: Individual physiological strain index (PSI), rectal temperature and heart rate during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 1, P11). The initial rectal temperature (time zero) and the lowest heart rate throughout the entire protocol were used to calculate the adjusted PSI (purple).

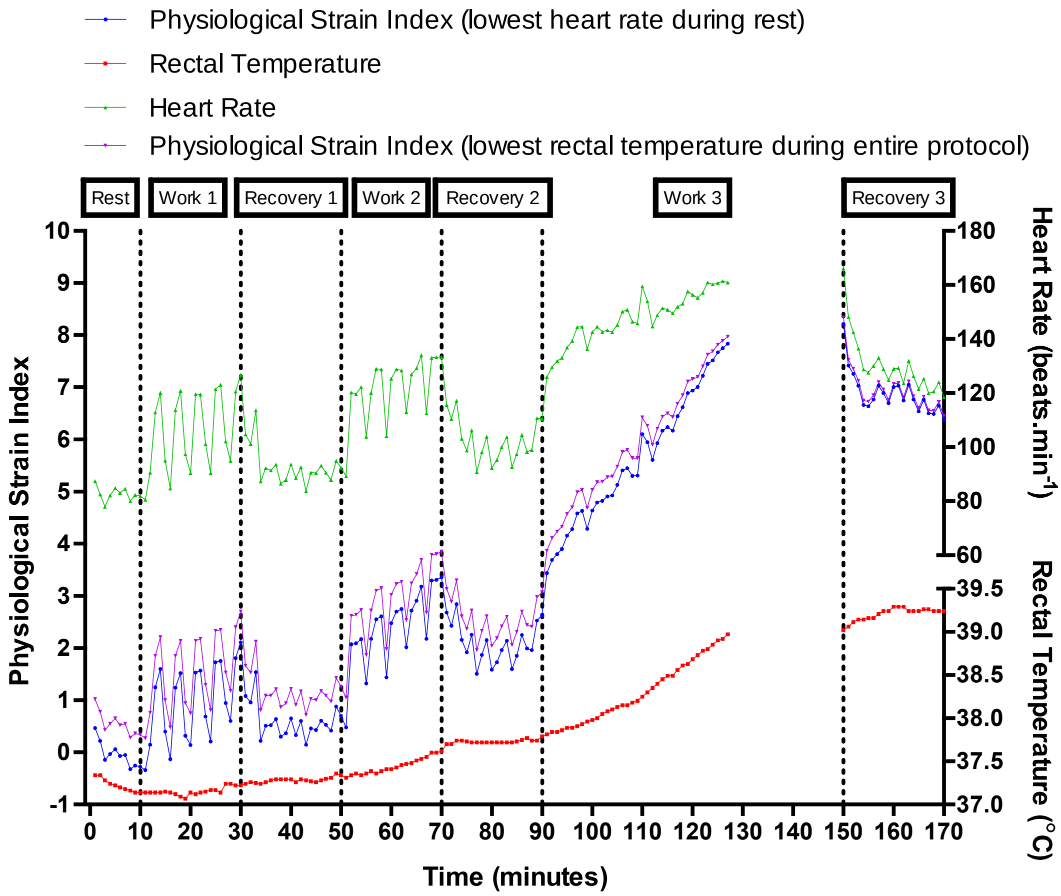

Figure 59: Individual physiological strain index (PSI), rectal temperature and heart rate during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 1, P5). The lowest rectal temperature throughout the entire protocol and the lowest heart rate during rest were used to calculate the adjusted PSI (purple).

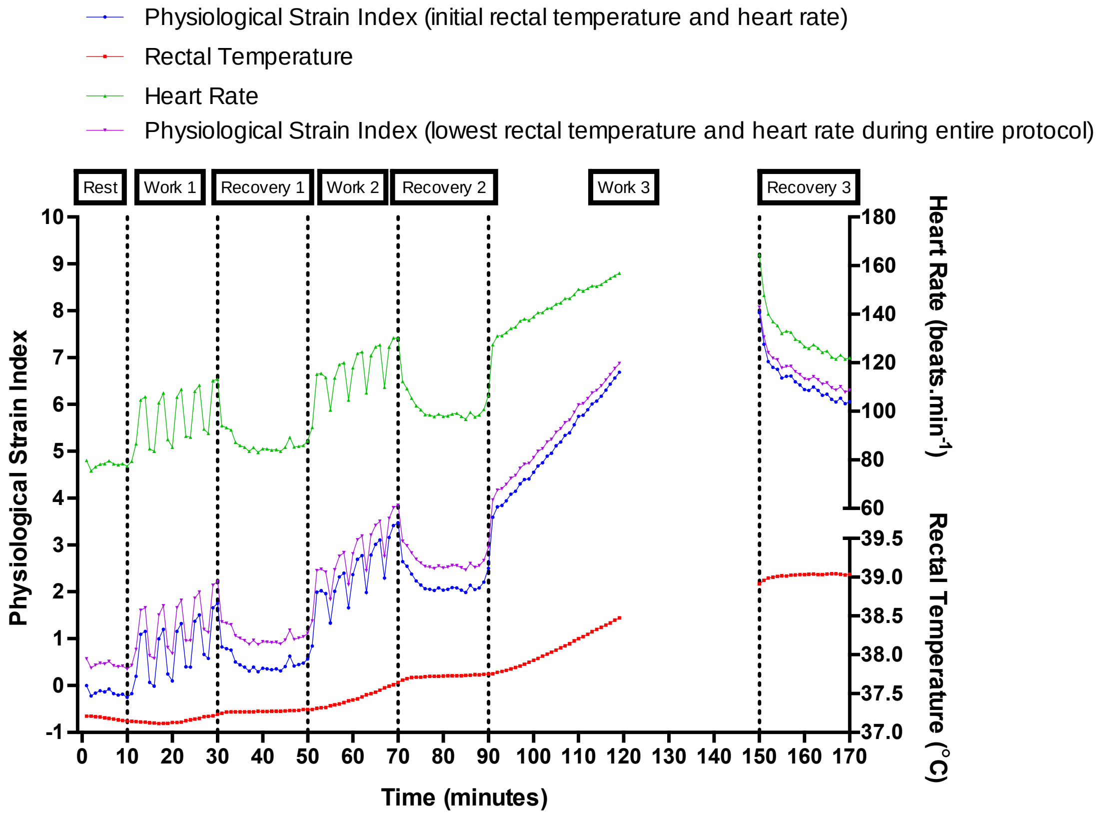

Figure 60: Mean physiological strain index (PSI), rectal temperature and heart rate during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 13). With varying tolerance times, data are shown to the last point where n = 13. The lowest rectal temperature and heart rate throughout the entire protocol were used to calculate the adjusted PSI (purple).

Why Mean Body Temperature is Important

The strength of the PSI compared to other models of predicting thermoregulatory strain is that it considers both the variables of T_{re} and heart rate that can be viewed in real time simply. Moran *et al*. (1998) acknowledged the usefulness of including sweat rate and T_{sk}, but stated that these measures were not included in the PSI as sweat rate is more difficult to measure in real time (particularly outside a laboratory) and that heart rate is an adequate measure to include the influence of T_{sk}. In a generalized and over simplified explanation the authors state that as T_{sk} increases so too does SkBF that is associated with reduced cardiac filling and SV in which case heart rate increases to maintain Q and heart rate is therefore an adequate measure of a higher T_{sk}. Whilst the PSI equation certainly is simple and can be recorded in real time, it appears that in the pursuit of such a user friendly measure of obtaining heat stress the authors, while acknowledging that heart rate and T_{re} are used in combination rather than just heart rate alone, may have oversimplified the fundamentals of cardiac physiology such that heart rate does not always increase with an increase in T_{sk} (Figure 61).

Indeed during passive heat stress Q doubles to maintain arterial pressure whilst SkBF increases 40 times from 200 $mL.min^{-1}$ up to 8000 $mL.min^{-1}$ accompanied by an elevated heart rate and a redistribution of blood flow from the splanchic regions to the periphery (Rowell *et al*., 1969; Kenney, 2008). To test the hypothesis that a reduced SV during exercise in the heat is directly due to an elevated SkBF, Gonzalez-Alonso *et al*. (2000) conducted an experiment with euhydrated male trained cyclists. The participants cycled at 72 % $\dot{V}O_{2max}$ either in the heat (35.0 °C) or cold (8.0 °C) for 30 minutes. The authors found that whilst oesophageal temperature (T_{oe}) was similar between the hot and cold environments, SkBF was greatly increased when exercising in the hot environment as expected, yet SV was not different between the conditions. Thus the authors concluded that in the exercising and euhydrated individual a reduced SV was not solely dependent on an increased SkBF but rather an interaction of multiple factors such as T_c, Q in combination with a lower visceral blood flow, blood volume and elevated sympathetic activity such as elevated noradrenaline levels. In support of the conclusion by Gonzalez-Alonso *et al*. (2000), Lee *et al*. (2015) conducted experiments with non-trained individuals cycling for 20 minutes at 69 % $\dot{V}O_{2max}$. It was found that heart rate was higher but SV lower when both the skin and core were warm compared to when the skin was cool but the core was warm. Furthermore, it was found that heart rate was higher but SV unchanged when the skin was warm and the core was cool compared to when both the skin and core were cool. Thus the authors concluded that SV would only be reduced during exercise when T_c is elevated above 38.0 °C with an elevated T_{sk} and heart rate. Therefore excluding T_{sk} from the PSI equation seems inappropriate as discussed below.

Whilst substituting T_{re0} and HR_0 for the lowest values obtained either at rest or throughout the entire protocol in place of the initial measure at time 0 or 1 alters PSI such that no negative values are obtained, the pattern of the PSI during the first 10 minutes of rest is still of a plateau or slightly decreasing thermoregulatory strain (Figure 61). Thus the PSI predicts that during 10 minutes (possibly longer) of rest, even when T_{re0} and HR_0 are the lowest values rather than initial values, that there is no change, or a slight decrease, to thermoregulatory strain upon entering a hot environment wearing fully encapsulating protective clothing (Figure 61). As found in our laboratory, T_{re} decreases up to 20 minutes (10 minutes of rest followed by 10 minutes of intermittent low intensity exercise; Figure 61) as warmer blood from the core mixes with the cooler blood from peripheral tissues when vasoconstrictor tone is released in response to a hot exposure. $\overline{T}_{sk}$ calculated by Ramanathan's (1964) equation however increases due to the exposure and subsequently $\overline{T}_b$, that includes a weighting of both $\overline{T}_{sk}$ and T_{re} (Colin *et al.*, 1971), increases (Figure 61). A predicted plateau or decrease in thermoregulatory strain (PSI) while body heat storage ($\overline{T}_b$) increases is contradictory and inaccurate.

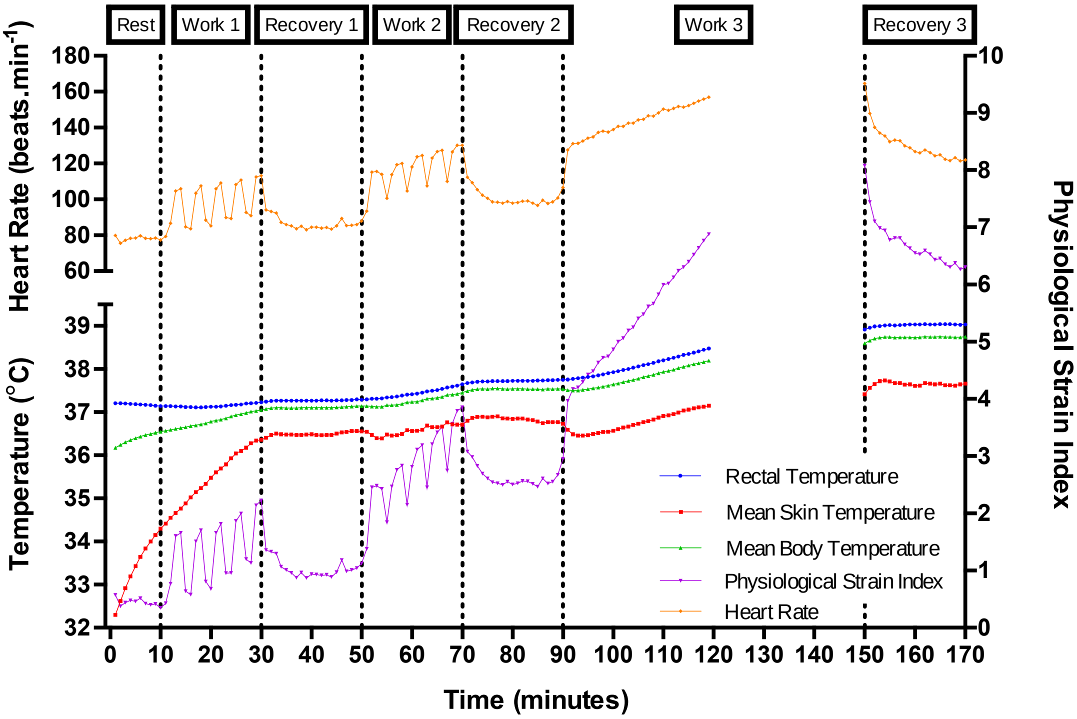

Figure 61: Mean physiological strain index (PSI), heart rate, rectal temperature, mean body temperature and mean skin temperature during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 13). With varying tolerance times, data are shown to the last point where n = 13. PSI was calculated using the lowest rectal temperature and heart rate throughout the entire protocol.

Therefore we proposed a modified PSI (mPSI):

$$mPSI = 5\ (\overline{T}_{bt} - \overline{T}_{b0})\ ^{*}\ (39.5 - \overline{T}_{b0})^{-1} + 5\ (HR_t - HR_0)\ ^{*}\ (180 - HR_0)^{-1}$$

Where: $\overline{T}_{bt}$ and HR_t are mean body temperature and heart rate measures taken at any time during the protocol

$\overline{T}_{b0}$ and HR_0 are the lowest or pre-testing resting measures

The mPSI equation was applied to a cohort of 13 young and healthy men (mean ± SD: 21.5 ± 2.4 years, 178.3 ± 5.0 cm, 75.7 ± 9.7 kg, body fat of 14.4 ± 4.1 %) during rest (10 minutes), exercise (stepping at an average $\dot{V}O_2$ of 13.6 $mL.kg^{-1}.min^{-1}$ to a height of 22.5 cm as the duration of work increased from 50 % during Work 1 to 100 % during Work 3) and recovery (20 minute intervals). The participants wore fully encapsulated CBRN protective clothing. Environmental conditions were set to hot (40.5 °C) and dry (20 % rh). Thermoregulatory strain is depicted in Figure 62 using the original PSI equation (Moran *et al*., 1998) as well as the mPSI equation that we propose more accurately represents actual thermoregulatory strain.

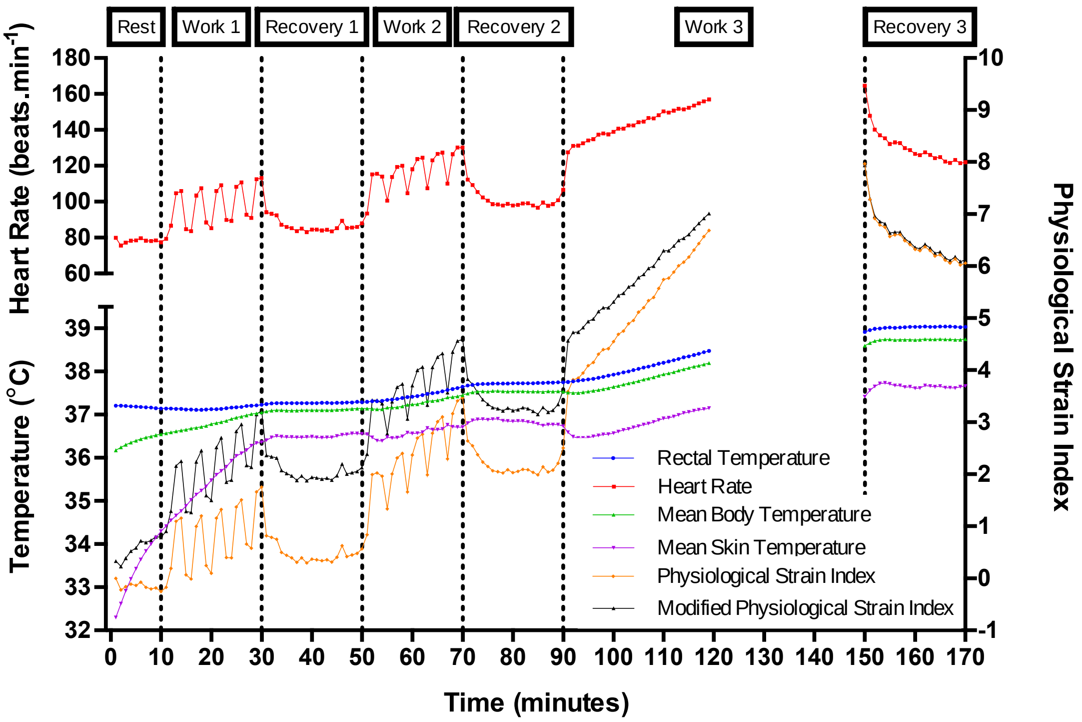

Figure 62: Mean physiological strain index (PSI), modified PSI (mPSI), heart rate, rectal temperature, mean body temperature and mean skin temperature during rest, exercise (of increasing duration from Work 1 to Work 3) and recovery whilst wearing fully encapsulating protective clothing in 40.5 °C and 20 % rh air chamber (n = 13). With varying tolerance times, data are shown to the last point where n = 13. PSI was calculated using the formula proposed by Moran *et al*. (1998), mPSI was calculated with mean body temperature in place of rectal temperature with the lowest mean body temperature and heart rate throughout the entire protocol taken as the initial values.

Discussion

The original PSI proposed by Moran *et al*. (1998) underestimates actual thermoregulatory strain and we advocate that our mPSI better represents this. The strengths of the PSI as highlighted by Moran *et al*. (1998) include a simple to use and easy to interpret index of thermoregulatory strain which can compare thermoregulatory strain between varying climates and clothing that can be viewed in real time with the added ability to predict thermoregulatory strain during rest and recovery periods. However we have found shortcomings of the PSI in terms of the values associated with T_{re0} and HR_0 as well as the failure to include T_{sk} that results in an inaccurate absolute measure of thermoregulatory strain. The impact that these considerations have on the results obtained during our first and second studies appears substantial upon initial exposure to a hot environment but lessen as the protocol progresses and thermoregulatory strain increases. This occurred as individuals' T_{re} and heart rates got closer to the maximum values of 39.5 °C and 180 beats.min^{-1} and as the change in $\overline{T}_{sk}$ was less. Therefore as our study design for the first two studies was repeated measures and the difference between calculating the PSI with the lowest T_{re} or heart rate and $\overline{T}_b$ in place of T_{re} was less significant as the thermoregulatory strain increased, our results for the first and second studies are presented as per the Moran *et al*. (1998) equation.

Appendix 3: Normalization of Skin Blood Flow Data

Laser Doppler data is a relative measure of SkBF as the disruption to the light source is detected by a receiver and displayed as a value measured in LDU. Even when using a multi-channel system, the diameter of the receiving channels is only 2 mm and therefore if day-to-day positioning of the laser Doppler probes varies even by 1 mm, there may be large differences in the absolute reading of SkBF depending on the microvasculature of the skin below the laser. Therefore normalizing SkBF data measured with laser Doppler is common practice in an attempt to eliminate the unintentional positioning variability.

Laser Doppler data from the third study was normalized to the average of the first five minutes of data during rest. This occurred at time = 5 minute to 10 minutes as the first SkBF data were obtained only from 5 minutes into the protocol due to the time taken to connect the laser Doppler probes (and sweat capsules that were connected first). It is important to note that the resting data would have been influenced by the condition on the day as the participants first entered the chamber dressed in the state required by the condition *e.g.* without gloves or respirator. Therefore data were only normalized to the average of the initial five minutes during rest and not for a longer duration or later in the protocol. Stable maximal SkBF readings during exercise did not occur and therefore normalizing the data to exercise would have been influenced by whether the site was truly at maximum or not which could also vary per the condition. Examples of the normalized compared to absolute data are shown below for the chest during CON and N2GF conditions.

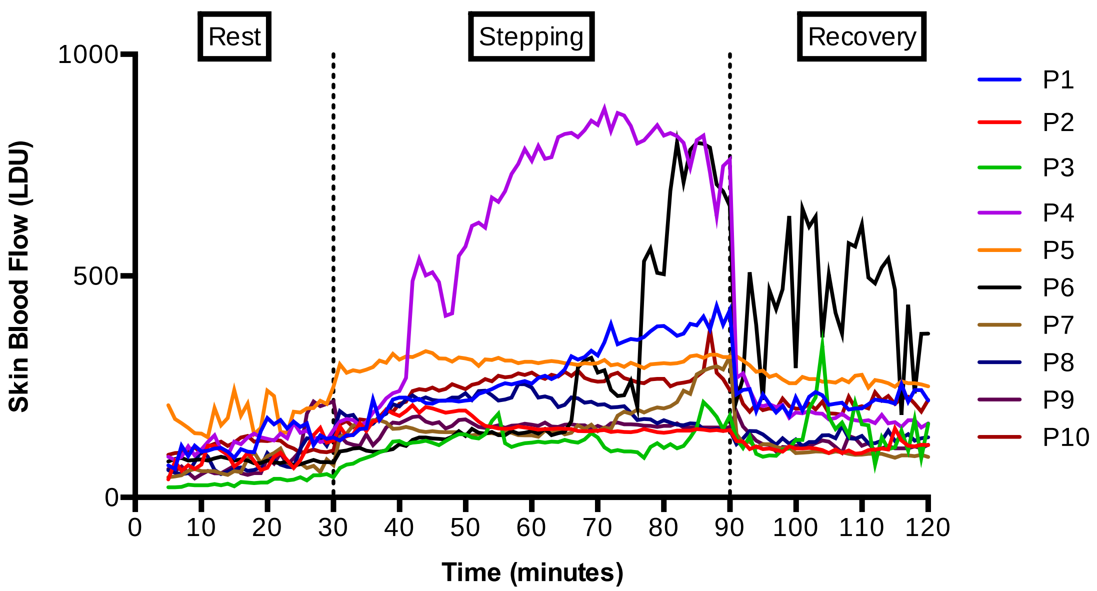

Figure 63: Individual absolute skin blood flow at the chest during rest, exercise and recovery when wearing encapsulating clothing in 40.5 °C and 20 % rh air (n = 10).

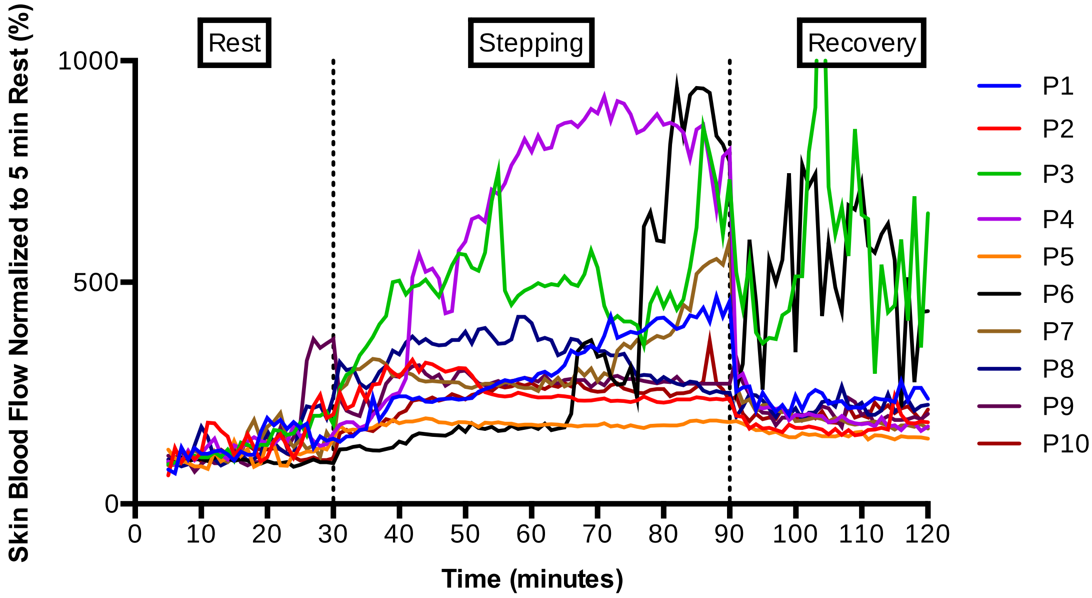

Figure 64: Individual normalized to rest (5 min) skin blood flow at the chest during rest, exercise and recovery when wearing encapsulating clothing in 40.5 °C and 20 % rh air (n = 10).

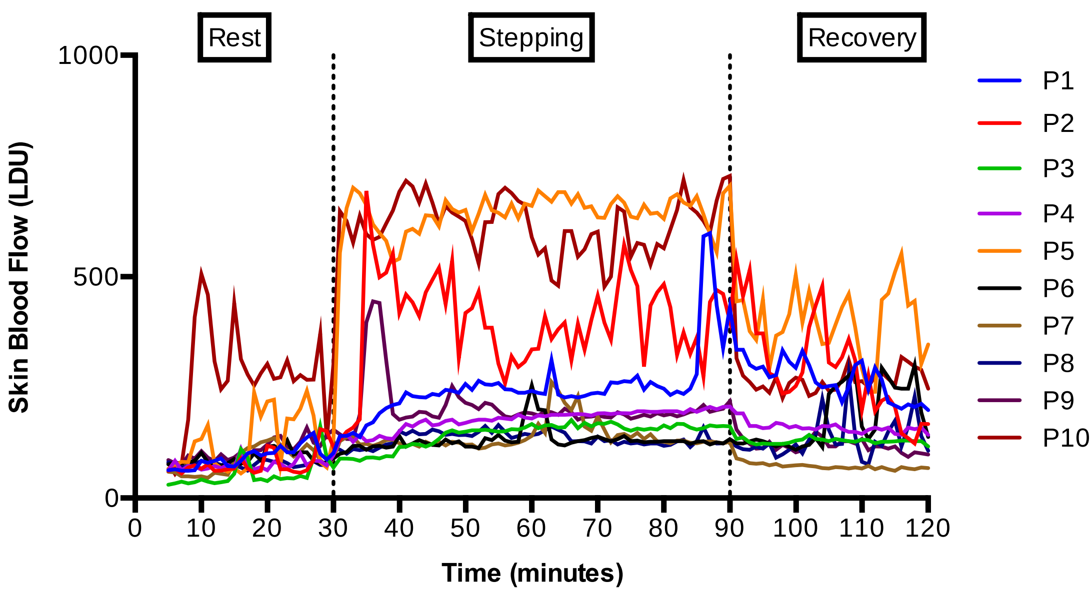

Figure 65: Individual absolute skin blood flow at the chest during rest, exercise and recovery when wearing encapsulating clothing without the gloves with a fan in 40.5 °C and 20 % rh air (n = 10).

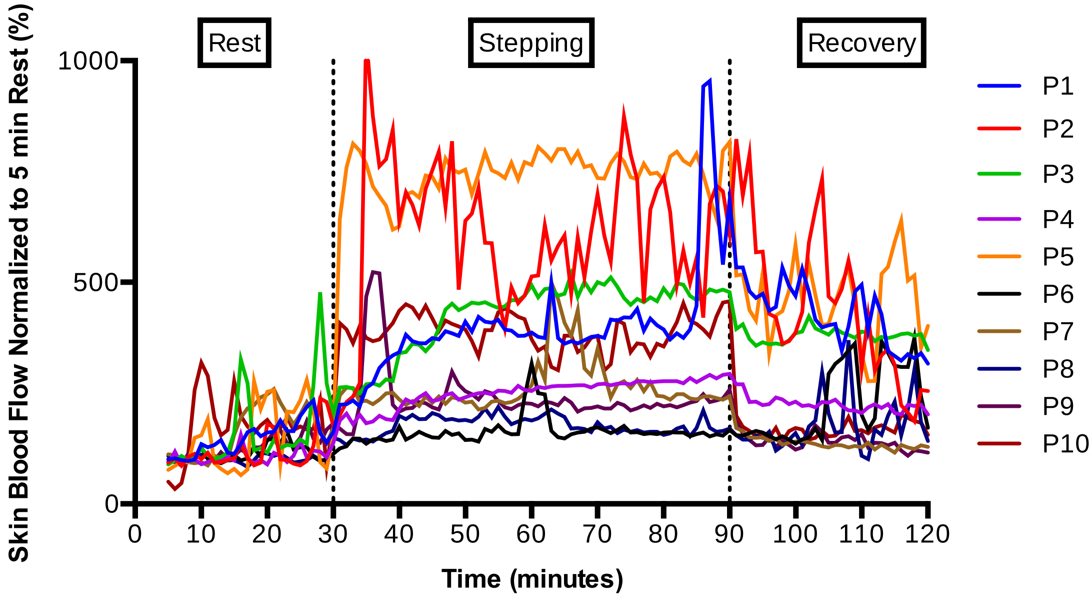

Figure 66: Individual normalized to rest (5 min) skin blood flow at the chest during rest, exercise and recovery when wearing encapsulating clothing without the gloves with a fan in 40.5 °C and 20 % rh air (n = 10).

The results show that normalizing the data, whilst eliminating the variability in day-to-day positioning of the probes, did not reduce the variability in the SkBF measurement between participants and therefore did not impact on the main findings from the study.

Appendix 4: Pilot Experiments for the First and Second Studies

Pilot studies were conducted to determine the protocol that would be used to distinguish significant differences in thermoregulatory strain between conditions with varying proportions of body surface area being covered by MVIP materials. The aim of the pilot studies was to produce a thermal stress that would be sufficient to differentiate between conditions, but not overwhelm participants in a single condition. Careful consideration was made to challenge participants sufficiently such that the thermal burden of CBRN IPE in a hot and dry environment could be compared, ideally in workloads or intensities that would be valid for military operations. Goetz *et al*. (2011), when quantifying the metabolic heat production of law enforcement personnel during CBRN training, stated that over the entire day of training the average metabolic heat production was approximately 213 W and involved periods of recovery (standing or sitting) with bursts of high energy activities that raise metabolic heat production. Therefore the workload of the CBRN warfighter is most likely not constant and it was important to incorporate varying rates of heating in the study design to represent this type of workload.

Pilot 1

Aim: Develop a protocol that allowed for varying rates of rise of T_{re} to allow for the identification of differences between conditions, where these exist.

Method: The environmental chamber conditions were set to 40.5 °C and 20 % rh. The participant (female, 27 years, 172 cm, 59.53 kg) self-inserted a rectal thermistor and wore a heart rate monitor. The participant stepped to a height of 22.5 cm at a rate of 12 steps.min^{-1} for 30 minutes after which the stepping rate was increased to 15 steps.min^{-1} for another 30 minutes. The participant then rested in the chamber for 30 minutes following the one-hour of stepping exercise. The participant wore the full CBRN protective ensemble including a BAL. The experimental end-points for all pilot studies were as those defined in the main thesis (General Methods: Section 3.4.4).

Results: As shown in Figure 67, the participant completed the first stepping section (full 30 minutes), but when the stepping rate was increased to 15 steps.min^{-1}, the participant was withdrawn upon reaching an end-point criterion (heart rate exceeded 10 beats less than the age predicted maximum).

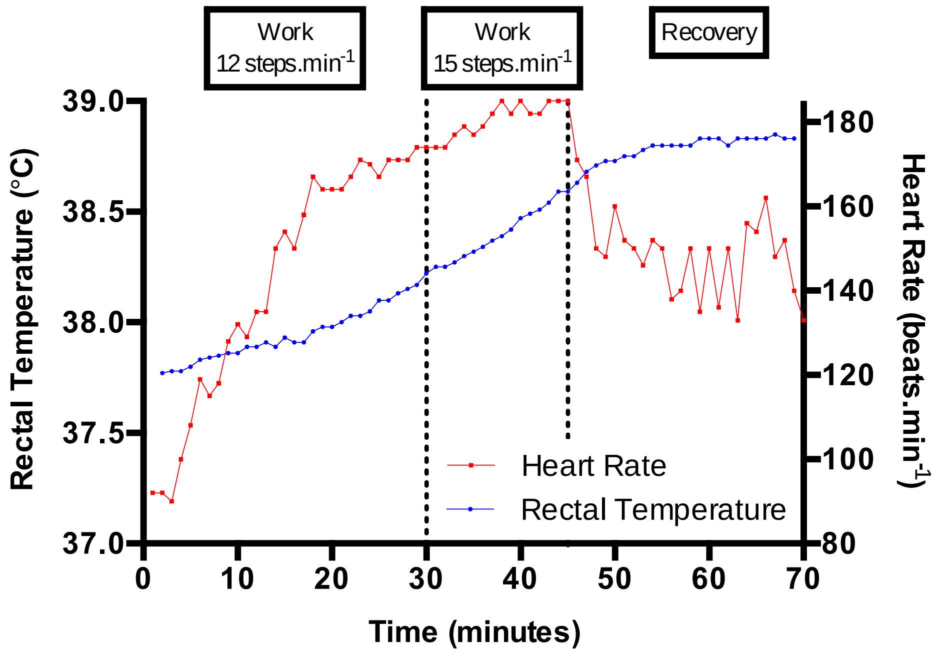

Figure 67: Rectal temperature and heart rate whilst stepping at two rates and recovering wearing fully encapsulating chemical protective equipment in an environmental chamber set to 40.5 °C and 20 % rh (n=1).

Conclusions: The first pilot study illustrated that the participant reached a state of uncompensable heat stress early in the protocol. Uncompensable heat stress refers to the point where the mechanisms employed for cooling the body (such as sweat evaporation) are inadequate to stop the rate of rise of T_c (Lind, 1963; Montain *et al.*, 1994). By entering into this condition early on in the protocol, if the differences between conditions were not large then the differences might not have been easily distinguished between conditions due to the high thermal load being placed upon the body. This thermal load was primarily from the moisture vapour restrictive and insulative CBRN clothing but also from the environment and exercise requirements. Reducing the burden from exercise and therefore the metabolic heat production would allow for a longer TT, which might amplify the differences between conditions as well as being more representative of military patrol operations that are unlikely to last only 45 minutes. Either lowering the step height, the rate of stepping or the duration of stepping might accomplish this. Stepping at a rate slower than 12 steps.min^{-1} is cumbersome and therefore the duration of stepping was manipulated.

Pilot 2

Aim: To amplify the differences in T_{re} between conditions, it was thought that keeping the work rate constant (12 steps.min^{-1}) throughout the protocol but introducing varying work durations would elicit varying rates of rise of T_{re}.

Method: The environmental chamber conditions were set to 40.5 °C and 20 % rh. The same participant as in Pilot 1, instrumented with a rectal thermistor and heart rate monitor, stepped to a height of 22.5 cm at a rate of 12 $steps.min^{-1}$ for four 40-minute work periods. Each work period involved the participant stepping for a different duration of time. The first work period (40 minutes) involved stepping for only 25 % of the time whereby the participant stepped for 1 minute and recovered seated for 3 minutes before stepping for 1 minute again. The second work period (40 minutes) involved stepping for 50 % of the time (2 minutes stepping and 2 minutes of seated recovery cycles). The third work period (40 minutes) involved stepping for 75 % of the time (3 minutes stepping with 1 minute of seated recovery cycles). A final 40-minute stepping period was also planned and would have involved stepping continuously, followed by seated recovery in the chamber for 40-minutes. The participant wore the full CBRN protective ensemble including a BAL.

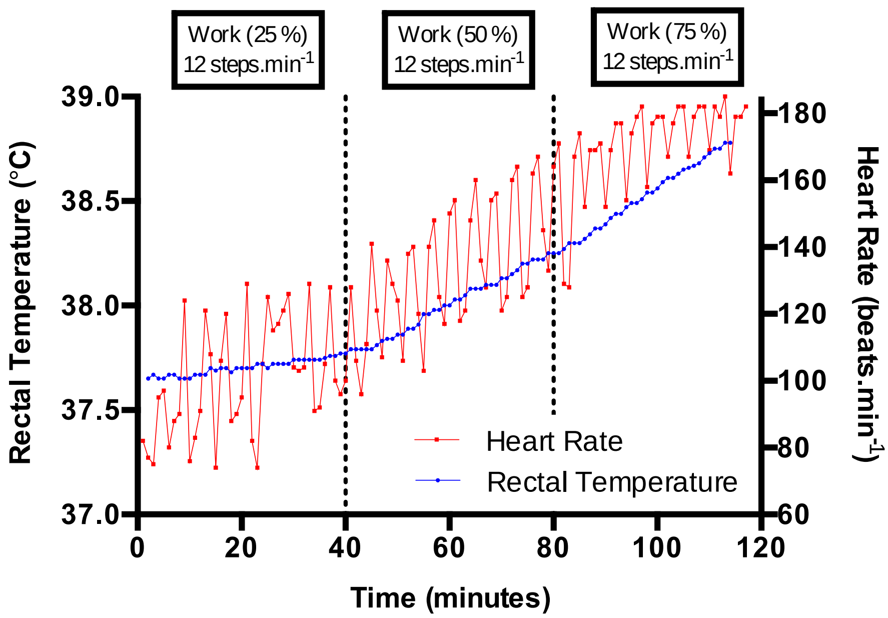

Figure 68: Rectal temperature and heart rate during intermittent stepping with progressively increasing work durations wearing fully encapsulating chemical protective equipment in an environment set to 40.5 °C and 20 % rh (n=1).

Results: The participant completed the first and second work periods but could not complete the full 40 minutes for the third work period (only stepped for 33 minutes) and was withdrawn from the chamber based on reaching an experimental end-point (heart rate exceeded 10 beats less than the age predicted maximum).

Conclusions: Figure 68 shows that again, the participant reached a state of uncompensable heat stress early in the protocol. A protocol that is too demanding for participants might not only result in a high drop out rate, but might also prevent a clear distinction between conditions being made due to the too high thermal burden, which might be better characterized using a longer total exercise period.

Pilot 3

Aim: To determine if interspersing recovery periods in between work periods would allow for a plateau in T_{re}, or indeed a rate of cooling in T_{re} for lower burden conditions (with some CBRN MVIP items removed). It was thought that by keeping the work rate constant (12 steps.min^{-1}) and removing the progressively increasing durations of work (25 %, 50 % and 75 %) but introducing periods of recovery, the differences between rates of heating and cooling might become evident.

Method: The environmental chamber conditions were set to 40.5 °C and 20 % rh. The same participant as in Pilot 1 and 2 instrumented with a rectal thermistor and heart rate monitor, stepped continuously to a height of 22.5 cm at a rate of 12 steps.min^{-1} for 15 minutes after which the participant recovered seated for 15 minutes before stepping for another 15-minute period. This method was repeated until the participant reached a stopping criterion. The participant wore the full CBRN protective ensemble including a BAL.

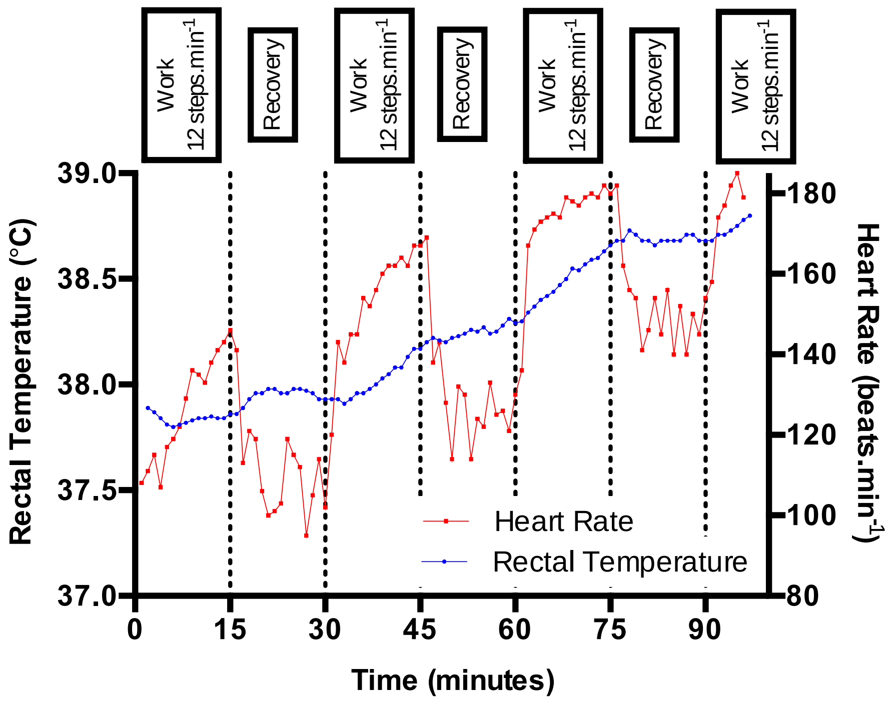

Figure 69: Rectal temperature and heart rate whilst stepping at a constant rate of 12 steps.min^{-1} interspersed with seated recovery periods when wearing fully encapsulating chemical protective equipment in a chamber set to 40.5 °C and 20 % rh (n=1).

Results: The participant accomplished three full 15-minute stepping periods. In the fourth stepping period the participant was withdrawn from the chamber based on reaching an experimental end-point (heart rate exceeded 10 beats less than the age predicted maximum).

Conclusions: Figure 69 illustrates that whilst a T_{re} plateau was apparent during the seated recovery periods, the rate of rise of T_{re} was high during exercise. With a high rate of metabolic heat production, the TT to reaching a T_{re} of 39.0 °C (one of the stopping criterion) would be reduced and could reduce the likelihood of detecting differences between conditions, whilst also possibly eliciting a high drop out rate of volunteers as the rate of rise of T_{re} strongly influences perceived thermoregulatory strain (Tucker *et al*., 2006).

Pilot 4

Aim: Develop a protocol that delays the onset of uncompensable heat strain, allowed T_{re} to plateau or fall during recovery periods and that maximized differences between conditions. Pilot 3 was repeated but with the addition of varying work durations (as was included in Pilot 2).

Method: The environmental chamber conditions were set to 40.5 °C and 20 % rh. The participant (male, 28 years, 174 cm, 73.55 kg) was instrumented with a rectal thermistor and heart rate monitor and stepped to a height of 22.5 cm at a rate of 12 steps.min^{-1} for 20-minute work periods. The work periods were separated with 20-minute seated recovery periods. As before (Pilot 2), the first stepping period involved the participant stepping for 25 % of the time, in the second stepping period the participant stepped for 50 % of the time, this was increased to 75 % in the third stepping period and a final stepping period of one hour, or until reaching a stopping criteria, involved stepping 100 % of the time. After the final stepping period, the participant was required to recover in the chamber for 20 minutes. The participant donned the full CBRN ensemble on one day (Condition: Full), with the full ensemble but without the respirator (hood up) on another day (Condition: N_R) and just the CBRN suit and trainers (the respirator, BAL, gloves and overboots removed) on a final day (Condition: Light).

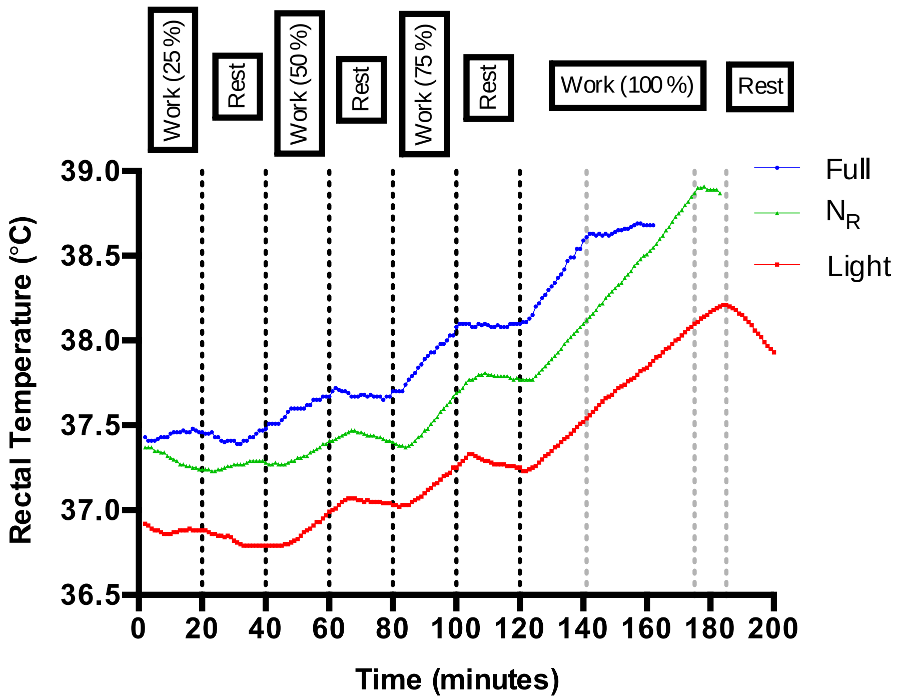

Figure 70: Rectal temperature during varying intermittent protocols separated with recovery periods whilst wearing varying degrees of fully encapsulating chemical protective equipment in a chamber set to 40.5 °C and 20 % rh (n=1).

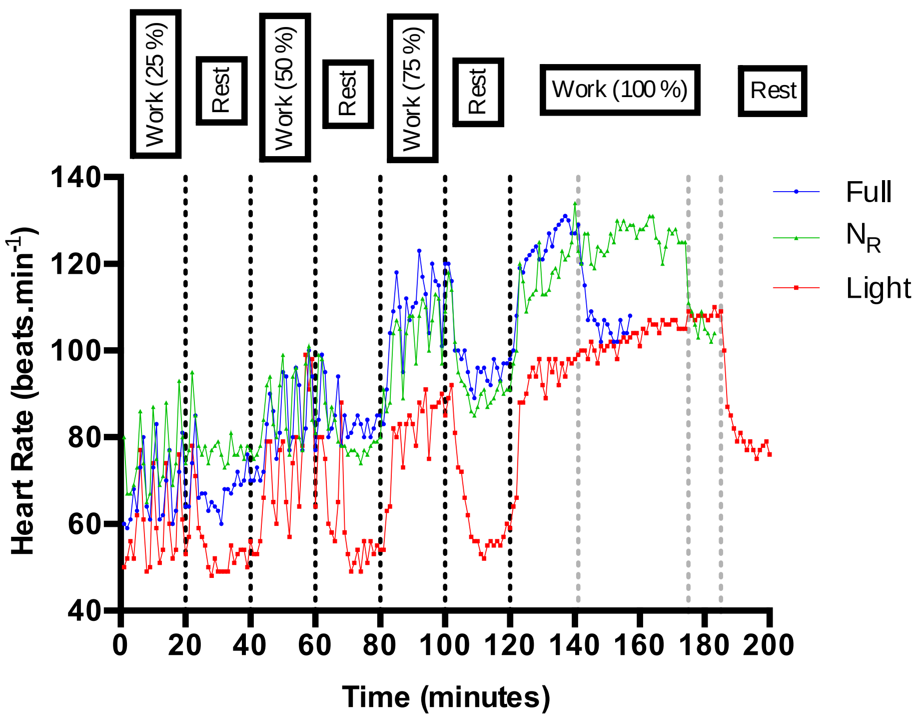

Figure 71: Heart rate during varying intermittent protocols separated with recovery periods whilst wearing varying degrees of fully encapsulating chemical protective equipment in a chamber set to 40.5 °C and 20 % rh (n=1).

Results: In all conditions the participant reached the continual stepping period. During the final stepping period the TT varied depending on the condition, with the TT during Full being the shortest at 20 minutes, followed by N_R at 54 minutes and finally Light at 62 minutes. Varying rates of change of T_{re} were evident in all conditions during stepping and recovery periods. For example, during the final work period, based upon the linear rate of rise of T_{re} the rate of change of T_{re} per hour was calculated (General Methods: Section 3.4.2.1) and was 1.62 °C.hr^{-1} (Full), 1.29 °C.hr^{-1} (N_R) and 0.97 °C.hr^{-1} (Light).

Conclusions: The fourth pilot study protocol allowed for the development of plateaus in T_{re} as well as the calculation of differing rates of heating or cooling (depending on the condition). It was decided that this design would allow for detection of differences between conditions, if such differences actually exist, through varied TT and rates of change to T_{re}. The first work period (25 %) was removed for the final experimental design as minimal differences between conditions were observed.

Appendix 5: Study 1 - Participant Protocol Tolerance

Table XV: Experimental protocol completion information with reasons that participants did not finish the experimental protocol (n = 12).

Participant	Condition				
	SOGAR	**SOGA**	**SOG**	**SO**	**S**
1	T_{re} (55 min)^	T_{re} (54 min)	✓	✓	✓
2	T_{re} (47 min)	T_{re} (57 min)	✓	✓	✓
3	T_{re} (28 min)	T_{re} (31 min)	T_{re} (38 min)	T_{re} (40 min)	T_{re} (58 min)
4	T_{re} (41 min)	✓	✓	✓	✓
5	Dizzy (34 min)	Dizzy (43 min)	T_{re} (49 min)	✓	✓
6	T_{re} (23 min)	T_{re} (37 min)	T_{re} (54 min)	✓	✓
7	T_{re} (53 min)	✓	✓	✓	✓
8	Fatigue (41 min)	✓	✓	✓	✓
9	T_{re} (52 min)	T_{re} (50 min)	✓	T_{re} (58 min)	✓
10	HR (35 min)	T_{re} (32 min)	✓	✓	✓
11	Dizzy (42 min)	✓	✓	✓	✓
12	Nausea (35 min)	Nausea (42 min)	✓	✓	✓

Note: TT are presented for early cessation of exercise during Work 3. A tick indicates that the participant completed the full 60-minutes of stepping during Work 3.

^This means that 55 minutes of stepping was completed during the continuous stepping period when the participant's T_{re} reached the experimental end-point of 39.0 °C.

Appendix 6: Hydration Strategy

When water was permitted during all studies except the fourth study. Participants were provided with 250 mL of chilled water (approximately 15 °C) every 20 minutes as water at this temperature was preferred for greatest volitional intake without greatly affecting thermoregulatory measures (Szlyk *et al*., 1989). While fluid replacement was essential during exercise to maintain plasma volume (Candas *et al*., 1988) and avoid dehydration as classified as a body mass loss > 4 % (Costill & Sparks, 1973), care was taken not to provide water in excess of that required to maintain euhydration, which could induce hyponatraemia (Shopes, 1997). Neufer *et al*. (1989) asserted that when exercising in the heat, gastric emptying was delayed and therefore the amount of water was controlled so as to not induce gastric discomfort. During all conditions where the respirator was worn, water was provided from a canteen through a drinking tube that feeds into the respirator, thus eliminating the need to remove the respirator for water ingestion. If the participant chose to not finish the 250 mL volume at the set time periods then the volume of water not drunk was weighed.

There were essentially three other options for hydration:

a. Volitional intake of chilled water (approximately 5 °C) – With this method, there is a risk of different volumes of water being consumed across conditions (*e.g*. probably less when wearing the respirator). Less water drunk in some conditions could result in dehydration possibly causing an increased rate of rise in T_c, increased heart rate and increased plasma osmolality (Szlyk *et al*., 1989; McLellan *et al*., 2013b). Also, it is not clear what the average temperature of the water would actually be when consumed, as it will warm-up over time in the chamber if supplied in 0.5 L or 1.0 L water bottles to allow volitional intake. Furthermore, in conditions where sweat evaporation is not possible or when sweat starts dripping (such as when wearing CBRN IPE), Bain *et al*. (2015) stated that ingesting cold fluids would decrease T_c, therefore if some participants drank more than others or drank more in one condition over another, this would introduce a bias in T_c between participants and / or conditions. When sweat is free to evaporate however, drinking cold water allows for temperature change of fluids internally, stimulating gastrointestinal temperature sensors that could result in a decreased sweat output (Morris *et al*., 2014).

b. Volitional intake of 38 °C water – This would avoid any thermal issues, but is unpleasant and may risk nausea and early withdrawal of participants as well as unnaturally reducing water intake (Szlyk *et al*., 1989).

c. No water intake – This method may result in significant dehydration of participants and increased risk of heat illness. This would also be unpleasant for participants, and may lead to early withdrawal.

The option to provide a set-amount of chilled water (approximately 15 °C), which was consumed within a few minutes, was the most appropriate method to use.

Appendix 7: Study 2 - Participant Protocol Tolerance

Table XVI: Experimental protocol completion information with reasons that participants did not finish the experimental protocol (n = 13).

Participant	Condition				
	CON	N_R	N_{BAL}	N_G	N_{OB}
1	T_{re} (49 min)^	T_{re} (47 min)	T_{re} (48 min)	T_{re} (46 min)	T_{re} (51 min)
2	✓	T_{re} (55 min)	✓	Fatigue (52 min)	✓
3	T_{re} (51 min)	✓	✓	✓	T_{re} (55 min)
4	T_{re} (36 min)	✓	T_{re} (55 min)	✓	T_{re} (52 min)
5	T_{re} (38 min)	✓	T_{re} (41 min)	✓	T_{re} (36 min)
6	T_{re} (32 min)	T_{re} (26 min)	T_{re} (29 min)	T_{re} (43 min)	T_{re} (34 min)
7	T_{re} (33 min)	HR (38 min)	T_{re} (36 min)	Fatigue (51 min)	HR (44 min)
8	T_{re} (48 min)	Fatigue (58 min)	T_{re} (55 min)	✓	T_{re} (47 min)
9	Fatigue (39 min)	T_{re} (54 min)	T_{re} (58 min)	T_{re} (40 min)	Fatigue (43 min)
10	Fatigue (45 min)	Fatigue (37 min)	T_{re} (46 min)	✓	T_{re} (44 min)
11	T_{re} (48 min)	✓	✓	✓	T_{re} (32 min)
12	T_{re} (30 min)	T_{re} (42 min)	✓	HR (25 min)	HR (38 min)
13	T_{re} (52 min)	✓	✓	✓	✓

Note: TT are presented for early cessation of exercise during Work 3. A tick indicates that the participant completed the full 60-minutes of stepping during Work 3.

^This means that 49 minutes of stepping was completed during the continuous stepping period when the participant's T_{re} reached the experimental end-point of 39.0 °C.

Appendix 8: Measuring Skin Temperature

Aim: It was considered that the skin thermistors that were used to measure T_{sk} were attached using a Tegaderm™ tape. Tegaderm™, as a transparent, sticky and sterile dressing, is designed primarily for wound care as a barrier to liquids, viruses and bacteria[13]. As such Tegaderm™ is completely waterproof and thus impermeable to moisture vapour. The characteristics of the tape might have fostered an insulative microclimate surrounding the thermistor, restricting evaporative cooling and creating an artificially high T_{sk} at the covered site (Buono & Ulrich, 1998). A short, additional study was conducted to determine whether the rest of the exposed skin not covered by Tegaderm™ was at a lower T_{sk}. A secondary aim of the additional study was to identify an alternative, more permeable textile that could be used to secure the thermistor in place thereby measuring a T_{sk} that was closer to the true value.

Method: The Pinsent environmental chamber conditions were set to 40.5 °C and 20 % rh. The participant (female, 28 years, 172 cm, 58.59 kg) was dressed in a full CBRN protective ensemble except without wearing the respirator or hood (thereby exposing the head) and was instrumented with a heart rate monitor, a rectal thermistor and four skin surface thermistors at the calf, thigh, arm and chest to estimate $\overline{T}_{sk}$ (Ramanathan, 1964). Two surface skin thermistors were positioned on the right cheek of the participant with either a Tegaderm™ or Transpore™ tape (Figure 72). Transpore™ is a transparent, plastic surgical tape that is porous[14] and therefore offers a greater degree of permeability compared to Tegaderm™. A thermal imaging camera (A320G, FLIR Systems, US) was directed at the participant's left cheek to estimate skin surface temperature when no dressing or thermistors were present that could influence the T_{sk}. Image stills were taken once every five minutes throughout the protocol. An average temperature was generated for a standardized square on the left cheek that measured close to the size of the surface thermistor. As the thermal imaging camera reads to only one decimal place and image stills were taken once every five minutes during the protocol the trace on the graphs appeared slightly jagged.

[13] http://solutions.3m.com Wound care product information. 3M™ Tegaderm™ HP Transparent Film Dressing Frame

[14] http://solutions.3m.com Critical and chronic care product information. 3M™ Transpore™ Surgical Tape

The participant entered into the chamber and remained seated for 30 minutes. The participant then stepped continuously to a height of 22.5 cm at a rate of 12 $steps.min^{-1}$ for 60 minutes followed by a further 20 minutes of seated recovery in the chamber.

Figure 72: The participant resting in a hot and dry chamber wearing a full military chemical protective ensemble (without the hood or respirator) with two skin surface thermistors attached to the right cheek with either a Tegaderm™ (lower thermistor) or Transpore™ (upper thermistor) tape.

Results: Exercise-induced hyperthermia resulted in an elevated T_{re}, $\overline{T}_b$ and heart rate during exercise (Figure 73).

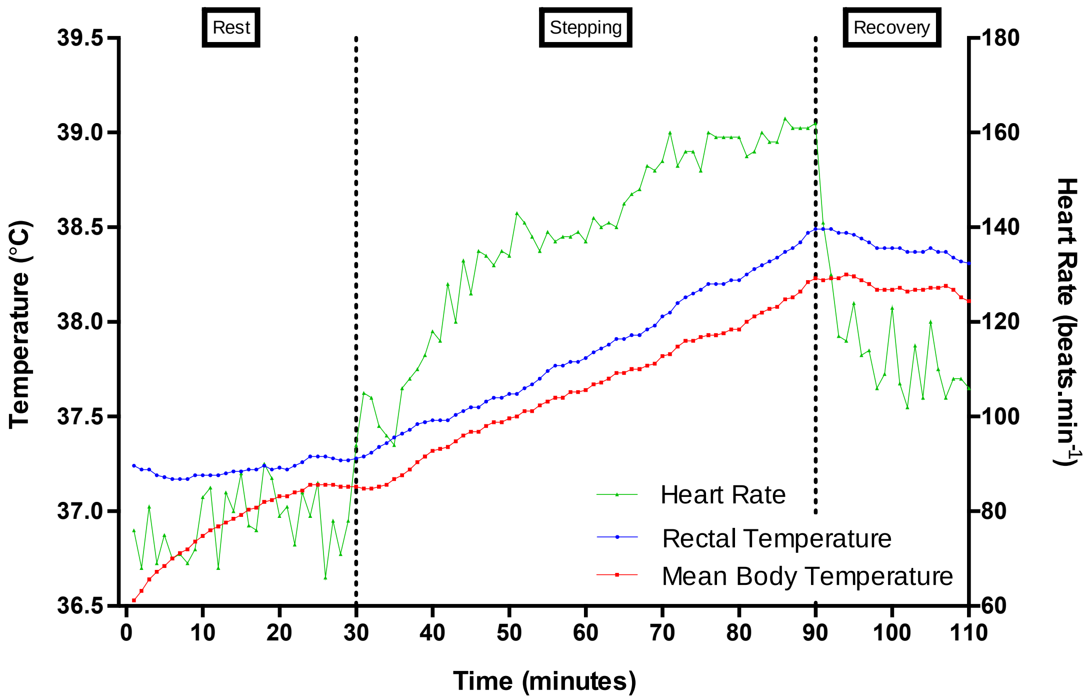

Figure 73: Mean rectal temperature, mean body temperature and heart rate during rest, stepping and recovery in 40.5 °C and 20 % rh whilst wearing chemical protective equipment without the hood or respirator.

Figure 74 illustrates the when the skin thermistor was secured using either a Tegaderm™ (blue trace) or Transpore™ (red trace) dressing. The figure also illustrates T_{cheek} as estimated by infrared thermography using the thermal imaging camera (green trace).

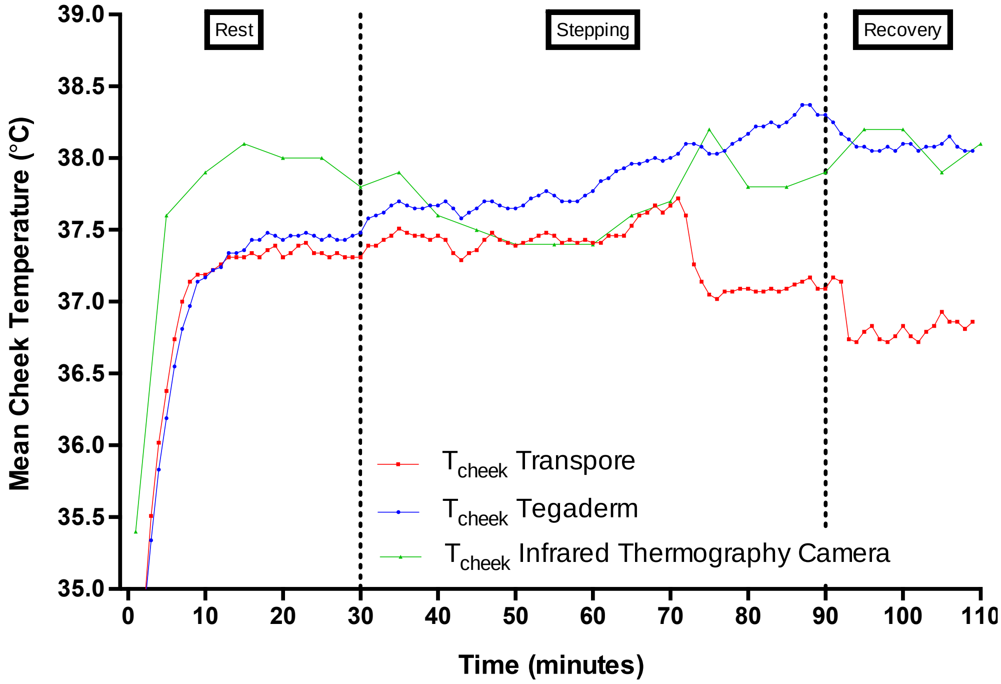

Figure 74: Mean cheek temperature during rest, stepping and recovery in 40.5 °C and 20 % rh whilst wearing chemical protective equipment without the hood or respirator, as measured by skin thermistors secured using different tapes or by infrared thermography.

Discussion: Surface skin thermistors are mounted onto a stainless steel disc and covered by epoxy resin for protection. The temperature of the skin surface either adds or extracts heat from the skin thermistor through the highly thermally conductive stainless steel disc. This induces a change in the electrical resistance of the thermistor that is transmitted to the SharkTooth telemetry system for quantification and representation of skin surface temperature[15]. T_{cheek} from the thermistor covered with Tegaderm™ was more often higher than T_{cheek} from the thermistor covered with Transpore™ suggesting that Tegaderm™ might be restricting evaporative cooling at the site of the thermistor, particularly when considering that T_{cheek} estimated with infrared thermography was also more often lower than T_{cheek} from the thermistor covered with Tegaderm™. However, attaching the thermistor with Transpore™ also showed a limitation of not remaining secured to the skin throughout the protocol, as noted from 70 minutes and 92 minutes (Figure 74) when the tape came away from the skin and had to be re-secured. The drop in T_{cheek} at these points was most likely indicative of sweat evaporation from the thermistor.

[15] SharkTooth Product Manual, MIE Medical Research Ltd, Doc 152-01.

Detecting the infrared radiation emitted from the skin's surface creates the image formed by the thermal imaging camera when directed at human skin[16]. As radiation is dependent on an object's surface temperature, it is possible for the camera to estimate the T_{sk} taking into account the emissivity of the object. That being the quantity of infrared radiation, compared to a perfect blackbody object, emitted from the skin at the same temperature[4]. This is expressed as a ratio with zero being a completely reflective body (shiny mirror) and one being a completely black body. The human skin has an emissivity of 0.97 to 0.98 and is therefore considered a blackbody radiator[4] (Hardy & Muschenheim, 1934; Togawa, 1989). Water has an emissivity of 0.96[4]. Therefore directing the infrared camera at dry skin compared to wet (sweat soaked) skin (Figure 75) with differing emissivity levels will distort accurate calculation of T_{sk}. For example, changing the emissivity from 0.97 to 0.96 could alter the measured temperature by 0.2 °C. Bernard *et al.* (2013) also explored this concept with topical administration of treatments (oils, gels and disinfectants).

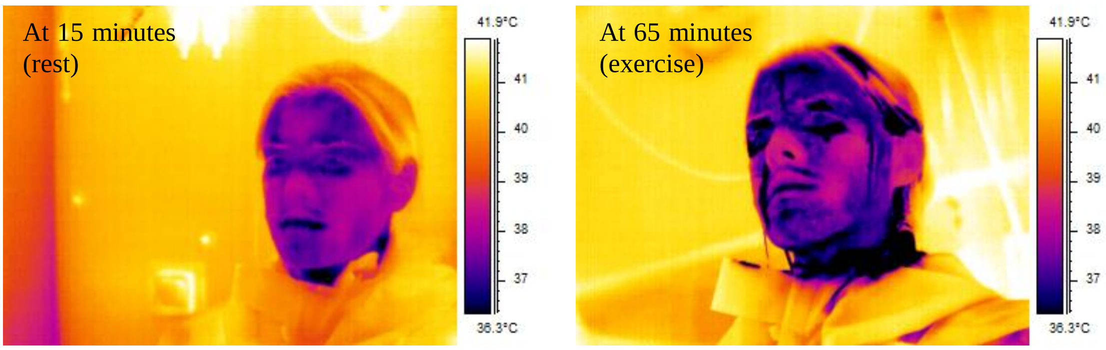

Figure 75: Infrared thermography shown when the face is warm and mostly dry (left panel) compared to when the face is hot and sweat soaked (right panel).

Infrared thermography combines radiation emitted from the skin as well as the surroundings to produce an image displaying heat spectrums[4]. Both the infrared radiation emitted from the skin and the surroundings in the measurement path are subject to attenuation by passing through the atmosphere on route to the camera lens[4]. Although debatable, the measured distance from the camera lens between image stills can also introduce a bias into estimations of temperature if the distance is not identical between each image still. In this experiment although an effort was made to resume to the exact position and posture at each five minute mark during the protocol when the image still was taken, Figure 76 illustrates that this was not always achieved. Nonetheless, the greatest variability in accuracy most likely stems from the thermal imaging camera as the official

[16] FLIR User's Manual A3 and A6 Series (2011). ThermaCAM™ Researcher Professional (2009). Version 2.9.

operating guide states that there is a ± 2 % or ± 2 °C accuracy across the full range of the camera (-20 °C to +120 °C). A ± 2 % accuracy could result in a difference of 0.8 °C at a temperature of 40 °C, yet as the guidelines state the accuracy can be as low as ± 2 °C then this is the predicted accuracy rather than 0.8 °C. It would only be above 100 °C that the accuracy of ± 2 % would be relevant *e.g.* at 105 °C, ± 2 % accuracy equates to ± 2.1 °C.

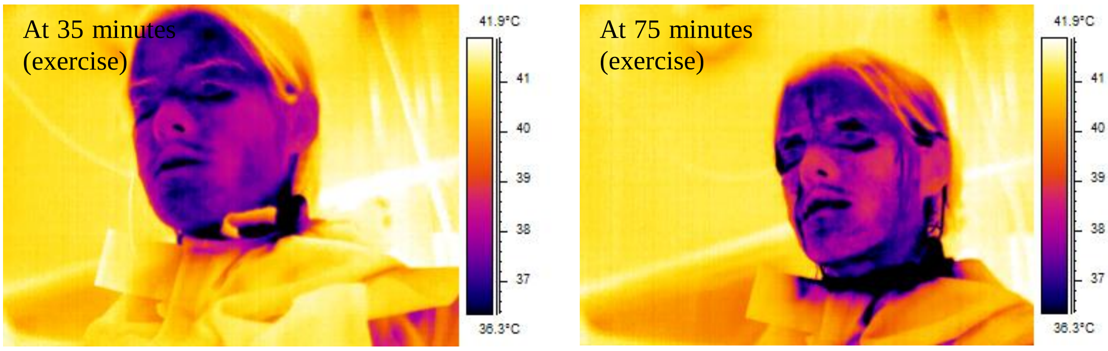

Figure 76: Image stills taken by infrared thermography highlighting the differing distances from the camera lens between stills.

Conclusions: There are limitations to each method used to measure T_{sk}. Securing skin surface thermistors with porous Transpore^{TM} tape, while allowing for some evaporative cooling (thereby resulting in a lower T_{cheek} compared to covering the thermistor with Tegaderm^{TM}), introduces the severe limitation of detaching from the skin, causing large fluctuations to T_{sk}. Furthermore securing skin surface thermistors with waterproof Tegaderm^{TM} tape, whilst rarely detaching from the skin during the experiment, insulates and restricts evaporative cooling thereby artificially raising T_{sk}. Measuring T_{sk} using infrared thermography might yield inaccurate T_{sk} recordings due to the altered emissivity of wet *vs*. dry skin. Furthermore, using infrared thermography does not allow for detection of T_{sk} under clothing, unlike securing thermistors with tape.

The balance between accuracy and precision should also be considered when determining which measurement technique should be used. Accuracy considers how close a value measures to a known standard or value whereas precision refers to how close two or more measures are to one another. The accuracy of the thermal imaging camera as stated by the manufacturers was either ± 2 °C or ± 2 % whereas the accuracy of the skin thermistors was 0.2 °C (General Methods: Section 3.4.3.1) with a precision stated by the manufacturers of 0.01 °C.

Poor agreement between infrared and conductive devices for measuring T_{sk} has previously been reported (Bach *et al*., 2015) and this experiment confirmed that whilst accurate T_{sk} might be difficult to precisely obtain, it was at least clear that in all three conditions, T_{sk} was shown to be heating during stepping and by no means cooling. It is concluded that accurate T_{sk} measurement procedures are lacking of a gold standard method with no limitations. In the absence of such a method, we conclude that for the purpose of our studies, securing a surface skin thermistor with a Tegaderm™ tape, while acknowledging its limitations, is superior to other methods available to our laboratory. Further methods of attaching skin surface thermistors should be investigated such as securing thermistors with collodion adhesive glue.

Appendix 9: Handling of Errors

Evaluation of all individual temperature plots revealed that occasionally skin thermistors, sweat capsules or laser Doppler probes became unattached from the skin during the experiment or the equipment malfunctioned (Table XVII).

Table XVII: Record of errors.

Participant	**Site**	**Time of Detachment**	**Condition**
		First Study	
P2	Arm (T_{sk})	90 minutes	SO
P4	Calf (T_{sk})	112 minutes	SOGA
P7	Calf (T_{sk})	101 minutes	S
P9	Arm (T_{sk})	86 minutes	S
		Second Study	
P1	Calf (T_{sk})	92 minutes	N_R
P4	Calf (T_{sk})	136 minutes	N_{OB}
P8	Calf (T_{sk})	93 and 116 minutes	N_{OB} and N_{BAL}
		Third Study	
P3	Thigh (sweat capsule)	0 minutes	NRHF
P3	Thigh (sweat capsule)	0 minutes	N2GF2
P5	Thigh (T_{sk})	91 minutes	NRHF2
		Fourth Study	
P1	T_{oe}	30 minutes	n/a
P1	Thigh (sweat capsule)	30 minutes	n/a
P3	Chest (sweat capsule)	56 minutes	n/a
P8	Chest (laser probe)	65 minutes	n/a
		Appendix 10: Comparison of Suits	
P3	Arm (T_{sk})	139 minutes	FP_C
P8	Thigh (T_{sk})	152 minutes	RP_P
P10	Thigh (T_{sk})	152 minutes	RP_C
P11	Calf (T_{sk})	171 minutes	RP_P

The reasons for thermistor, capsule or laser probe detachment could have been due to initial inadequate placement, sweating and / or movement. As T_{sk}, LSR or SkBF data were not always linear, no attempt could be made to predict the data using the rate of rise from the point where the thermistor, capsule or probe became detached. Therefore in an attempt to predict the calf temperature (T_{calf}) the average difference between the T_{thigh} and T_{calf} during each period (work and rest) was calculated. Missing T_{calf} data were then predicted by either adding or subtracting the difference from T_{thigh}. As the thigh is the closest site of temperature measurement to the calf, it was likely that both sites displayed similar temperature profiles and thus one could possibly be used to predict the other. T_{thigh} and T_{calf} might also have shown similar temperature profiles because both are lower limbs and are weighted equally in the $\overline{T}_{sk}$ equation (Ramanathan, 1964):

$$\overline{T}_{sk} = 0.3\ (T_{chest} + T_{arm}) + 0.2\ (T_{thigh} + T_{calf})$$

Using the average difference between T_{calf} and T_{thigh} per period to predict the missing T_{calf} would be acceptable if no differences in the relationship between T_{calf} and T_{thigh} were expected between conditions. However with the removal of the overboots in particular, a change in T_{calf} could occur, altering the relationship between T_{thigh} and T_{calf}. Therefore it was decided that for the conditions where T_{calf} was missing, T_{calf} would be removed from the $\overline{T}_{sk}$ equation and to add a double weight to T_{thigh} in the equation. The adjusted $\overline{T}_{sk}$ equation was as follows:

$$\overline{T}_{sk} = 0.3\ (T_{chest} + T_{arm}) + 0.4\ (T_{thigh})$$

In the same manner, if for example the arm, chest or thigh thermistor became detached, the formula was adjusted to double weight the corresponding skin site according to the $\overline{T}_{sk}$ equation. For example, if the arm thermistor became unattached then T_{chest} would be double weighted in the formula for all conditions for that participant. An example of the consequences to $\overline{T}_{sk}$ and $\overline{T}_{b}$ of applying this outlier method is shown in Figure 77 where the T_{calf} is removed and a double weighting to T_{thigh} was given in a participant whereby all skin thermistors remained attached. By checking the method outcomes on a known $\overline{T}_{sk}$ and $\overline{T}_{b}$, it can be considered whether the method severely under- or overestimated the $\overline{T}_{sk}$ and $\overline{T}_{b}$ or whether the method was appropriate.

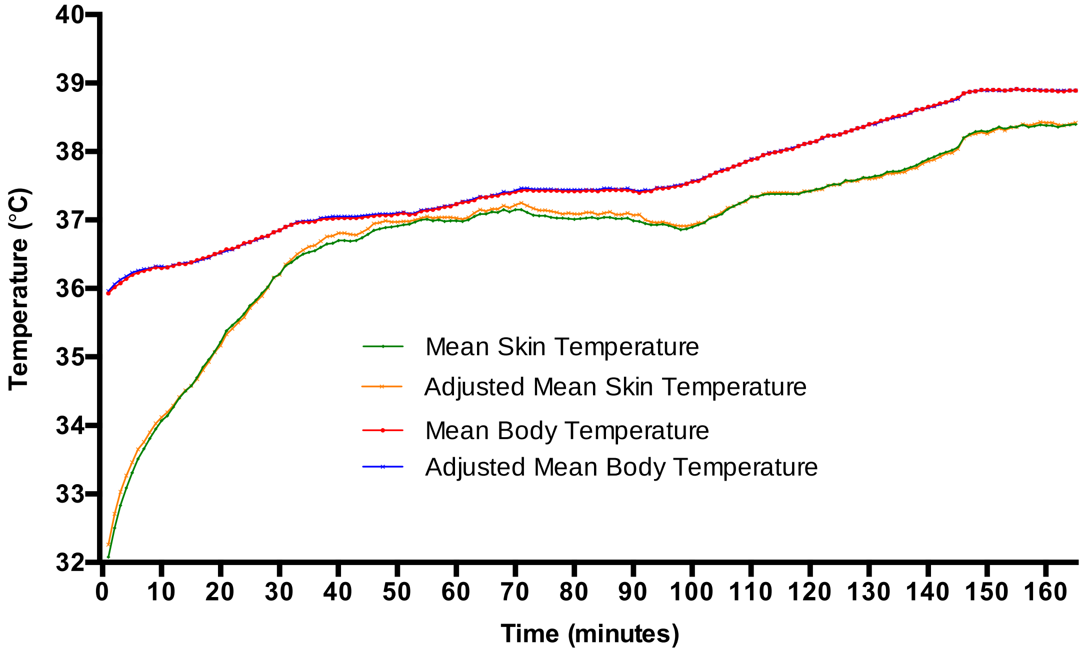

Figure 77: An example of the consequences of applying the selected outlier method to a set of data where all skin thermistors actually remained attached to the participant.

The results indicated that as the adjusted $\overline{T}_{sk}$ and $\overline{T}_{b}$ were close to the original and actual $\overline{T}_{sk}$ and $\overline{T}_{b}$, this method of dealing with outliers was appropriate. Indeed Teichner (1958) argued that the medial thigh temperature alone corresponded to a prediction of $\overline{T}_{sk}$ using a 10-point mean weighted T_{sk} equation. The thigh muscle is particularly heat stable as it is the muscle with the largest mass in the body and, when the individual is clothed, the upper legs are an area of low convection (Ramanathan, 1964). Therefore the approach to handling outliers adopted in this experiment was deemed acceptable when $\overline{T}_{sk}$ was still calculated based on three skin sites in the case where a thermistor became detached. Furthermore, the work of Olesen (1984) concluded that as little as two to four skin sites could be used for estimation of $\overline{T}_{sk}$ in a warm environment provided that intra-site variability was presumed to be low. When a sweat capsule or laser Doppler probe became detached or the rectal or oesophageal probe malfunctioned, no attempt was made to predict the trajectory of the missing data as the response was known to fluctuate due to external factors such as exercise, posture, individual variations *etc*. Therefore in these instances, the data simply were not included in the analysis.

Appendix 10: Thermoregulatory Strain in a Prototype, Lightweight CBRN Ensemble in Comparison to a Common CBRN Ensemble

Abstract

A lightweight prototype CBRN protective suit and gloves ensemble has been developed. Manikin test results showed that the suit and gloves had a lower vapour resistance compared to the common ensemble (Havenith *et al*., 2013). This is of interest to the warfighter who is deployed to hot areas, where any restriction to the evaporation of sweat imposes a thermoregulatory burden and places the warfighter at increasing risk of developing heat illness. The aim of this study was to quantify the reduction to the physiological and perceptual thermoregulatory strain when wearing the prototype suit and gloves compared to a common CBRN ensemble in the exercising and recovering human placed in a chamber set to hot, desert-like conditions.

The study was a five-condition, repeated measures design with male volunteers (n = 12) who stepped to a height of 22.5 cm, at a light intensity ($\dot{V}O_2$ of 14.1 mL.kg^{-1}.min^{-1}), interspersed with 20-minute recovery periods (final recovery period lasting 30 minutes) in a hot and dry environmental chamber set to 40.5 °C and 20 % rh for a maximum of 180 minutes. There were three work periods each that increased in the duration of time spent stepping (Work 1 lasting 20 minutes with participants stepping for 50 % of the time, Work 2 lasting 20 minutes with participants stepping for 75 % of the time and Work 3 lasting 60 minutes, or until reaching a stopping criteria [General Methods: Section 3.4.4], with participants stepping continuously). The clothing ensembles were assessed in full protective (FP) and relaxed protective (RP) dress states. A FP state, as would be adopted during times of CBRN attack, involved wearing the fully encapsulating protective ensemble (suit, respirator, butyl gloves and overboots) whereas a RP state, as would be adopted in times of a CBRN threat, involved wearing the protective suit and carrying the masses of the ancillary items (respirator, gloves and overboots) at the area from which they were removed. The conditions were as follows: wearing a common suit and common ancillary items (respirator, butyl gloves and overboots) in a FP state (FP_C), wearing the prototype suit and common ancillary items in a FP state (FP_P), wearing a common suit in a RP state (RP_C), wearing the prototype suit in RP state (RP_P), wearing the common suit in a FP state with common ancillary items except for the prototype gloves (FP_{PG}) in place of the butyl gloves. A value of $p < 0.05$ was considered statistically significant.

Replacing the common suit with a prototype suit in a FP state improved the rate of sweat evaporation by 16.7 %, extended predicted TT from a T_{re} of 37.5 °C to a T_{re} of 40 °C by 38.3 % and reduced PSI by 20 % by 20 minutes into Work 3. Perceptually, participants also reported a lowered RPE, felt less hot, less uncomfortable and less wet at some points in the protocol. Wearing the prototype suit compared to a common CBRN suit in a RP state improved the rate of sweat evaporation by 9.9 %, attenuated the rate of rise of T_{re} by 25.4 % during continuous work and lowered $\overline{T}_b$ by 0.14 °C. Participants also felt less uncomfortable and less wet at the end of the protocol. Replacing the butyl gloves with the prototype gloves lowered T_{finger} throughout the entire protocol until the last point measured during Work 3, lowered T_{re} by 0.23 °C, $\overline{T}_b$ by 0.12 °C, and reduced PSI by 17 % at the final point measured during Work 3. Participants also felt less hot and less uncomfortable at the end of the protocol.

Wearing the prototype suit and gloves significantly lowered physiological and perceptual thermoregulatory strain in a hot and dry environment during exercise and recovery compared to wearing a common suit and butyl gloves and should therefore be considered for use by the military when warfighters are deployed to these areas. Although even just replacing only the butyl gloves for the prototype gloves would reduce thermoregulatory strain.

Executive Summary

<u>Introduction</u>

The warfighter is required to don CBRN IPE (suit, respirator, butyl gloves and overboots) during periods of CBRN threat and attack. Some areas of operations, in the Middle East, experience average daytime air temperatures of 40.5 °C with rh of 20 %. The CBRN ancillary items (respirator, butyl gloves and overboots) are MVIP and therefore protect against contaminating agents but also limit moisture vapour passing through the material which induces a saturated microclimate underneath the items, inhibiting further evaporation (the body's main mechanism for cooling). A common CBRN suit has a low air permeability and protects against contaminating agents (although not to the same extent as MVIP materials) but does allow some water vapour to pass through and therefore inhibits evaporative cooling less than MVIP materials. Both the CBRN ancillary items and the suit impose a thermal burden upon the warfighter primarily by restricting evaporative cooling, particularly when exercising in a hot, desert environment where other minor heat loss rates (conduction, convection and radiation) are either greatly reduced or become a source of heat gain.

A new low evaporative burden prototype suit manufactured to a standardized design from Zorflex® has been developed. Zorflex® is a lightweight outer textile that provides a high level of protection from contaminating agents whilst maintaining a high degree of air and moisture permeability. Manikin tests wearing the suits (common and prototype) in a FP and RP state identified a reduced vapour resistance by 19 % when the prototype suit was worn compared to the common suit (Havenith *et al*., 2013). Dstl have also shown that industry developed prototype gloves can offer the same level of protection against contaminating agents as the butyl gloves but which are more air permeable (Zorflex® material with leather patches) as shown by a 9.1 % reduction to vapour resistance during manikin tests (Havenith *et al*., 2013). While manikin studies are a widely used method for estimation of clothing heat and vapour resistances, human studies provide final confirmation that the advantages identified in physical tests on manikins, remain in humans who possess complex thermoregulatory systems governed by the hypothalamus.

The aims of this study were to identify and quantify any reduction in physiological and perceptual thermoregulatory strain associated with wearing the prototype suit compared to the common suit during a FP and RP state when exercising in hot, desert-like conditions; as well as to quantify the impact that the prototype gloves have on reducing thermoregulatory strain compared to butyl gloves.

Methods

The study was a five-condition, repeated measures design with male volunteers (n = 12) who stepped lightly ($\dot{V}O_2$ of 14.1 $mL.kg^{-1}.min^{-1}$) to a height of 22.5 cm, interspersed with 20-minute recovery periods for a maximum of 180 minutes (Table XVIII).

Table XVIII: The experimental protocol to allow for calculations of rates of heating and cooling as well as to optimise the detection of differences between conditions.

Section	Time (minutes)	Percentage of time working	Workload
Baseline	0-10	0 %	Seated Rest
Work 1	10-30	50 %	Cycles of 2 minutes work + 2 minutes seated recovery
Recovery 1	30-50	0 %	20 minutes seated recovery
Work 2	50-70	75 %	Cycles of 3 minutes work + 1 minute seated recovery
Recovery 2	70-90	0 %	20 minutes seated recovery
Work 3	90-150	100 %	Continuous exercise
Recovery 3	150-180	0 %	Seated Recovery

Experiments took place in an environmental chamber set to hot, dry environmental conditions (40.5 °C and 20 % rh). The experimental conditions were as follows: wearing a common suit and common ancillary items (respirator, butyl gloves and overboots) in a FP state (FP_C), wearing the prototype suit and common ancillary items in a FP state (FP_P), wearing a common suit in a RP state (RP_C), wearing the prototype suit in RP state (RP_P), wearing the common suit in a FP state with common ancillary items except with the prototype gloves (FP_{PG}) in place of the butyl gloves. During the RP state, the masses of the items not worn were still carried at the area from which they were removed, because in reality, the warfighter would still carry the protective items even when the threat of attack was not great enough for the items to be worn. Likewise BA, in the form of a soft armour liner (BAL), was worn in all conditions as, in reality, the warfighter would always wear BA regardless if a CBRN threat existed or not. The weight difference between the butyl gloves and the prototype gloves, as well as between the common and prototype suit, were not matched between conditions as any improvements seen during FP_{PG}, or FP_P, might either be due to the gloves, or suit, being lighter or having a lower vapour resistance and thus imposing less of a thermal burden. Statistical analyses are as those presented in General Methods: Section 3.4.5. A value of $p < 0.05$ was considered statistically significant for all results presented.

Results

Wearing the prototype, compared to a common CBRN suit in a FP state reduced both physiological and perceptual thermoregulatory strain. The rate of sweat evaporation was improved by 16.7 %, predicted TT from a T_{re} of 37.5 °C to a T_{re} of 40 °C was extended by 38.3 % and PSI was reduced by 20 % at the last point measured during continuous work. Participants also reported a lower RPE 20 minutes into the continuous work period and reported feeling “just comfortable” and “warm” compared to “uncomfortable” and “hot” at the end of the protocol when the prototype suit was worn in place of the common suit, with a lower perceived skin wettedness.

During a RP state, wearing the prototype suit reduced both physiological and perceptual thermoregulatory strain compared to when wearing the common suit. The rate of sweat evaporation was improved by 9.9 % with the rate of rise of T_{re} being attenuated by 25.4 % during continuous stepping and $\overline{T}_b$ lowered by 0.14 °C at the final point measured during Work 3. Perceptually, at the end of the protocol participants reported feeling “warm” and “just uncomfortable” during RP_C compared to only “slightly warm” and “just comfortable” as well as less wet during RP_P.

Replacing the butyl gloves with prototype gloves resulted in three more participants completing the protocol, a lowered T_{finger} throughout the protocol until 20 minutes into Work 3, a reduced T_{re} by 0.23 °C and $\overline{T}_b$ by 0.12 °C by 20 minutes into Work 3, with PSI being reduced by 17 %. Participants also perceived an improved thermal state feeling "warm" and "just uncomfortable" during FP_{PG} compared to "hot" and "uncomfortable" during FP_C at the end of the protocol.

Conclusions

The prototype suit reduced physiological and perceptual thermoregulatory strain during a FP state and RP state compared to when wearing the common suit. Replacing the butyl gloves with the prototype gloves improved physiological and perceptual thermal responses. It is therefore recommended that the prototype suit and gloves be considered for use by the military as wearing these items lowered the thermal burden imposed upon the warfighter compared when wearing a common CBRN suit and butyl gloves.

Full Study Report

Background

Dstl requested an investigation to quantify the thermal burden imposed by prototype CBRN clothing compared to common CBRN protective clothing in exercising humans. Due to the lowered evaporative resistance imposed by the prototype suit and gloves, reduced thermal measures (heat and vapour resistance) were observed in manikin studies (Havenith *et al*., 2013). However up until this point, no studies comparing the thermal burden imposed by the prototype suit and gloves compared to the common suit and butyl gloves have been conducted on humans. The aim of this investigation was to determine whether the improvements to the ensemble characteristics of reduced heat and vapour resistances found in physical tests on manikins would translate to human physiology and perceptual measures.

Introduction

The warfighter is required to don CBRN IPE (suit, respirator, butyl gloves and overboots) during periods of CBRN threat or attack. In one current area of operation, the Middle East region, experiences average daytime air temperatures of 40.5 °C with 20 % rh (Def Stan 00-35, 1999[17]). Peak temperatures can reach 44 °C in the early afternoon with humidity as

[17] Def Stan 00-35 is the MoD Defence Standard produced by the Meteorological Office sand provides climatic information worldwide.

low as 14 %. CBRN IPE is designed to be fully encapsulating with the ancillary items (respirator, butyl gloves and overboots) being MVIP to protect against contaminating agents but at the cost of limiting sweat evaporation. The suit has low air permeability, offering a lowered degree of protection from contaminating agents but allowing some sweat to evaporate.

As discussed in the main body of this thesis, wearing the CBRN IPE ensemble in hot conditions places a thermoregulatory strain upon the individual due to its insulative and moisture-vapour restrictive properties. A new low evaporative burden prototype suit manufactured to a standardized design from Zorflex®[18] has been developed. Zorflex® is a carbon fabric laminated to a lightweight outer textile that provides a high level of protection whilst maintaining a high degree of air and moisture permeability (Table XIX). Although not currently durable enough for general service use by the military, Zorflex® garments would impose less of an evaporative restriction than the common clothing. Data from a manikin test in a FP state comparing the common suit when wearing the ancillary items, to the prototype suit when wearing the ancillary items, is shown in Table XIX (Havenith *et al*., 2013).

A FP dressed state is adopted in times of a CBRN attack and involves wearing the common or prototype suit (with the hood up), respirator, gloves (with inner cotton liners for the butyl gloves) and overboots, BA, undershorts, t-shirt combat boots and socks. A RP dress state is adopted when a threat is perceived but no attack has been confirmed and involves wearing the common or prototype suit (with the hood down), BA, combat boots, undershorts, t-shirt and socks.

[18] Zorflex® activated carbon cloth. Chemviron Carbon, The European Operation of Calgon carbon Corporation, Pennsylvania, USA

Table XIX: Manikin data showing the changes in heat and vapour resistance and vapour permeability index when a prototype CBRN suit and gloves were worn compared to a common CBRN suit and gloves in full protective and relaxed protective dress states.

State of Dress	**Heat Resistance ($m^2.K.W^{-1}$)**		**Vapour Resistance ($m^2.Pa.W^{-1}$)**		**Vapour Permeability Index (nd)**	
	Common	**Prototype**	**Common**	**Prototype**	**Common**	**Prototype**
Full Protection (suit + BA + butyl gloves + overboots)	0.204	0.173	46.3	37.5	0.27	0.28
Full Protection using prototype gloves	-	0.176	-	34.1	-	0.31
Relaxed Protection (without BA, without overboots) but using prototype gloves	0.188	0.157	31.5	26.5	0.36	0.36

Note that these data were representative of the whole manikin body with the exclusion of the head (body surface area of 1.66 m² and are presented per m^2).

During a FP state, compared to wearing the common suit, wearing the prototype suit reduced heat resistance by 15.2 %, vapour resistance by 19.0 % and slightly increased the vapour permeability index by 3.7 %. Comparisons were also made when a RP dress state was adopted. A 16.5 % reduction in heat resistance and a 15.9 % reduction in vapour resistance were found between the common and prototype suits in a RP state whilst wearing the prototype gloves. Personal communication with Dr Mike Dennis at the Physical Sciences Department at Dstl stated that industry developed prototype gloves can offer the same level of protection against CBRN agents as butyl gloves can but which are more air permeable (Zorflex® material with leather patches). Results from manikin testing of the prototype gloves in place of the butyl gloves during a FP state whilst wearing the prototype suit show a further reduction of 9.1 % in vapour resistance with an increased vapour permeability index of 10.7 % with only a small (1.7 %) increase in overall heat resistance in manikin measurements excluding the head values (Table XIX). The prototype gloves therefore potentially offer an increased evaporative capacity and subsequent improved measures of localized thermal comfort owing to less sweat saturating the hands due to the lowered vapour resistance. However, the improved evaporative efficiency of the gloves should be considerable to influence whole body thermoregulatory measures as in previous human studies (Chapters 4 and 5 of this thesis), whole body thermoregulatory strain was reduced when materials covering the hands were made 100 % MVP.

Hand cooling by immersion in cold water (10 °C to 30 °C) after exercise in the heat whilst wearing protective clothing has been a research area of interest because of the effect that convective and conductive hand cooling has on lowering T_c (Livingstone *et al*., 1989; Allsopp & Poole, 1991; House *et al*., 1997). However in the current experiment, covering the hands with a air permeable prototype glove (compared to the MVIP butyl glove), in a dry environment (20 % rh) would encourage evaporative cooling and the benefits of evaporative cooling at local areas of the body on reducing whole body thermoregulatory strain has been previously demonstrated in this thesis (Chapters 4 and 5). It is noted that liquid sweat from the skin might also be absorbed by the glove material and could evaporate from the glove surface or evaporate within the glove thickness (Kerslake, 1972) thus drawing heat for evaporation from the material rather than the skin. However any evaporation of sweat from the glove would allow for the maintenance of a vapour transfer gradient between the skin and the material, promoting further evaporative cooling. Whether the thermoregulatory benefits of improving the MVP of the gloves, resulting in an improved rate of evaporative cooling will translate into benefits of a similar magnitude in human participants as in the manikin tests, will be investigated in the current study. The limitations of manikins have been discussed in the main body of this thesis.

Research Aims

The aims of this study were to:

1. Quantify any reduction in thermoregulatory strain associated with wearing the prototype suit compared to the common suit during a FP and RP state when exercising in hot, desert-like conditions.

2. To quantify any reduction to thermoregulatory strain when replacing butyl gloves with air permeable prototype gloves during exercise in hot, desert-like conditions.

Hypotheses

The general null hypothesis (H_0) was as follows:

$\boldsymbol{H_{01}}$: The thermoregulatory strain experienced when exercising at a light intensity in hot, desert-like conditions would not be decreased when wearing the prototype suit compared to when wearing the common suit.

Various experimental hypotheses (H_a) will be tested as stated below.

***H*a**: The thermoregulatory strain experienced when exercising at a light intensity in hot, desert-like conditions would:

> ***H*a1**: Be decreased by approximately 15 % to 20 % when wearing the prototype suit compared to the common suit in a FP state (FP_C *vs*. FP_P).
>
> ***H*a2**: Be decreased by approximately 15 % when wearing the prototype suit compared to the common suit in a RP state (RP_C *vs*. RP_P).
>
> ***H*a3**: Be decreased by approximately 10 % when wearing the prototype gloves compared to the butyl gloves in a FP state (FP_C *vs*. FP_{PG}).

Method

Confidentiality and Ethics

MoDREC granted ethical approval for this study on the 1st June 2014 (515/MODREC/14). All procedures are also in compliance with the University of Portsmouth Department of Sport and Exercise Science Schedule of Approved Procedures[19] and the Declaration of Helsinki[20].

Research Design

Several pilot studies were conducted to develop the experimental design. The aims of the pilot studies were to identify a thermal stress that would maximally differentiate between conditions and thus would not overwhelm participants, but would challenge them sufficiently, on one single condition (Appendix 4; Table XVIII).

Twelve fit and free from injury male participants from the University of Portsmouth's staff and student population volunteered for this study. Mean (standard deviation) anthropometric characteristics were age: 24.0 (2.9) years, height: 180.0 (4.9) cm, weight: 76.49 (11.79) kg and body fat: 16.54 (4.37) %. The study was a five-condition, repeated measures design with participants exercising lightly (average $\dot{V}O_2$ of approximately 14.1 $mL.kg^{-1}.min^{-1}$). Exercise was interspersed with 20-minute recovery periods (Table XVIII), and took place in a hot, dry environment set to 40.5 °C, 20 % rh (actual mean [SD]: 40.28

[19] University of Portsmouth, Schedule of Approved Procedures, Department of Sport and Exercise Science, November 2012.

[20] World Medical Association (WMA) Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects. 64th WMA General Assembly, Fortaleza, Brazil, October 2013.

[0.49] °C [dry bulb] and 23.39 [0.62] °C [wet bulb] equating to 26.9 % rh) for a maximum of 180 minutes, with the final recovery period lasting 30 minutes. There were no significant differences in environmental parameters between conditions ($p > 0.05$).

The conditions were as follows:

- FP_C - wearing the common suit in a FP state
- FP_P - wearing the prototype suit in a FP state
- FP_{PG} - wearing the common suit in a FP state with the prototype gloves
- RP_C – wearing the common suit in a RP state
- RP_P - wearing the prototype suit in RP state

The conditions were not necessarily undertaken in this order but were counter-balanced to avoid any order effects (Appendix 1).

Alterations to protective equipment (wearing the BAL in place of BA, removing the absorbent carbon contents from the filter canisters) and differences from the manikin studies (wearing the hood up when the respirator was not worn, lowered rigidity of the soft armour liner and not wearing the neck collar) and are as those mentioned in Chapter 4: Section 4.4.2 and 4.4.3 respectively.

During the RP states (RP_C and RP_P), the masses of items not worn (respirator, butyl gloves and overboots) were still carried during these tests. This is because the warfighter would realistically still carry (although not wear) the ancillary items when assuming a RP state when under the threat of a CBRN attack. When the items were not worn, the weights were added to the body site from where they had been removed, although realistically, the warfighter would carry the ancillary items in a rucksack during a RP state and therefore the weight of these items would, in reality, be added to the torso. If the weights were added to the front chest pockets of the torso (as there are no pockets at the back) then this might have induced leverage on the back supporting muscles additionally, this would have reduced the surface area available for heat exchange at the torso possibly underestimating the potentially reduced thermal burden of wearing the prototype suit. Thus it was decided to secure the weights at the area from where the items had been removed. The metabolic heat production associated with wearing the ancillary items therefore remained equal between RP and FP states, with the only difference during a RP state of a greater percentage of body surface area not covered by MVIP materials. Any weight difference between the common and prototype suits as well as between the butyl and prototype gloves were not matched between conditions. A lighter weight suit or gloves could result in a lower thermal burden due to the reduced metabolic heat production associated with carrying a lighter load and would therefore be of benefit to the warfighter. Therefore, any physiological and thermal benefits that could be attributed to the lighter weight of the prototype suit and gloves were of importance to Dstl and were incorporated into the study design.

A) B)

Figure 78: Two participants resting in the environmental chamber. A) The difference between the FP_P (left participant) and RP_P conditions (right participant). B) The difference between RP_C (left participant) and FP_P (right participant).

Figure 79: Four participants exercising resting in in the environmental chamber. The conditions shown from far left are FP_P, RP_C, FP_{PG} and RP_C.

Experimental Protocol

The environmental chamber preparation, participant preparation and instrumentation, experimental protocol (including end-points) and statistical analyses were identical to that of the first and second studies presented in this thesis (General Methods: Section 3.4).

Except that the final recovery period (Recovery 3) was extended to 30 minutes instead of 20 minutes to allow for more accurate calculations of rates of change.

Data are illustrated to the last point in each condition where n = 12 and were statistically analyzed every 10 minutes from 0 minutes until 110 minutes only, that being the maximum time where n = 12 for all conditions. Direct comparisons at discrete time intervals during Recovery 3 could not be made without introducing a bias into the results as participants spent varying durations exercising in the chamber before reaching Recovery 3. When data were linear during Recovery 3 the hourly rate of change was calculated based upon the rate of fall from 10 minutes into Recovery 3 onwards. When data were not linear during Recovery 3, the mean change in measurements were calculated for data from the last 20 minutes of Recovery 3 (rΔ).

Results

<u>Oxygen Uptake</u>

There were no significant differences in the mean $\dot{V}O_2$ between any of the conditions except during Work 1 when $\dot{V}O_2$ was increased by 0.65 $mL.kg^{-1}.min^{-1}$ ($p < 0.01$) when the prototype gloves were worn (FP_{PG}) compared to wearing the butyl gloves (FP_C).

<u>Tolerance Time</u>

The maximum amount of time that a participant could be present in the environmental chamber (180 minutes) was dictated by the experimental protocol. Not all participants remained in the chamber for the maximum amount of time (Table XX) as some participants reached stopping criteria that were put in place to lessen the risk of heat illness (General Methods: Section 3.4.4).

Table XX: Experimental protocol completion information with reasons that participants did not finish the experimental protocol (n = 12).

Participant	Condition				
	FP_C	FP_{PG}	FP_P	RP_C	RP_P
1	T_{re} (21 min)^	T_{re} (24 min)	T_{re} (30 min)	T_{re} (35 min)	T_{re} (50 min)
2	T_{re} (55 min)	HR (53 min)	✓	✓	✓
3	T_{re} (43 min)	✓	✓	✓	✓
4	✓	✓	✓	✓	✓
5	✓	✓	✓	✓	✓
6	HR (39 min)	HR (55 min)	HR (50 min)	✓	✓
7	T_{re} (23 min)	T_{re} (41 min)	T_{re} (31 min)	T_{re} (35 min)	✓
8	T_{re} (50 min)	✓	✓	✓	✓
9	HR (22 min)	HR (26 min)	HR (30 min)	HR (47 min)	HR (41 min)
10	Fatigue (32 min)	T_{re} (40 min)	✓	✓	✓
11	✓	✓	✓	✓	✓
12	T_{re} (44 min)	T_{re} (31 min)	T_{re} (50 min)	✓	✓
Completion	**25 %**	**42 %**	**58 %**	**75 %**	**83 %**

Note: TT are presented for early cessation of exercise during Work 3. A tick indicates that the participant completed the full 60-minutes of stepping during Work 3.

^This means that 21 minutes of stepping was completed during the continuous stepping period when the participant's T_{re} reached the experimental end-point of 39.0 °C.

Table XXI shows the number of participants completing each condition with the mean actual and predicted TT data also displayed.

Table XXI: The number of participants completing the final work period with the mean (SEM) actual and predicted tolerance time during stepping and recovering in 40.5 °C and 20 % rh air (n = 12). *p < 0.05, **p < 0.01 *vs*. FP_C.

	FP_C	FP_{PG}	FP_P	RP_C	RP_P
Number of participants completing Work 3	2	5	7	9	10
TT (minutes)	42.4 (4.4)	47.5 (4.1)	50.9 (3.8)*	54.8 (2.9)	57.6 (1.7)
Predicted TT to a T_{re} of 40 °C (minutes)	170.2 (6.0)	188.1 (9.6)	204.1 (9.8)**	218.9 (11.8)	302.8 (44.2)
Predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C (minutes)	65.8 (3.5)	77.5 (5.2)	91.2 (6.2)**	101.8 (7.6)	162.3 (29.5)
Predicted TT from a T_{re} of 37.5 °C to a T_{re} of 40.0 °C (minutes)	82.1 (4.3)	96.3 (6.5)	113.5 (7.7)**	127.2 (9.4)	202.1 (36.7)

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Five more participants completed the protocol when the prototype suit was worn compared to the common suit in a FP state, whilst TT during Work 3 was significantly extended by 8.5 minutes (20.0 %, $p < 0.05$). Predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C was extended by 25.4 minutes (38.6 %, $p < 0.01$). Predicted TT from a T_{re} of 37.5 °C to a T_{re} of 40 °C was extended by 31.4 minutes (38.3 %, $p < 0.01$), whereas predicted protocol TT to a T_{re} of 40.0 °C was significantly extended by 33.9 minutes (19.9 %, $p < 0.01$) in FP_P compared to FP_C.

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

During a RP state, while 1 more participant completed the full stepping hour in Work 3, there were no significant differences in TT or predicted TT to a T_{re} of 40 °C between the suits.

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

Replacing butyl gloves with prototype gloves did not significantly extend TT or predicted TT to a T_{re} of 40 °C but did result in 3 more participants completing the final hour of stepping in Work 3.

Rectal Temperature

The ΔT_{re} is illustrated in Figure 80. All data presented on a timeline are shown until the point at which n = 12 in each condition. Comparisons were made between all conditions from 0 minutes until 110 minutes (where n = 12 for all conditions). The rate of change of T_{re} is illustrated in Figure 81 including comparisons during Recovery 3.

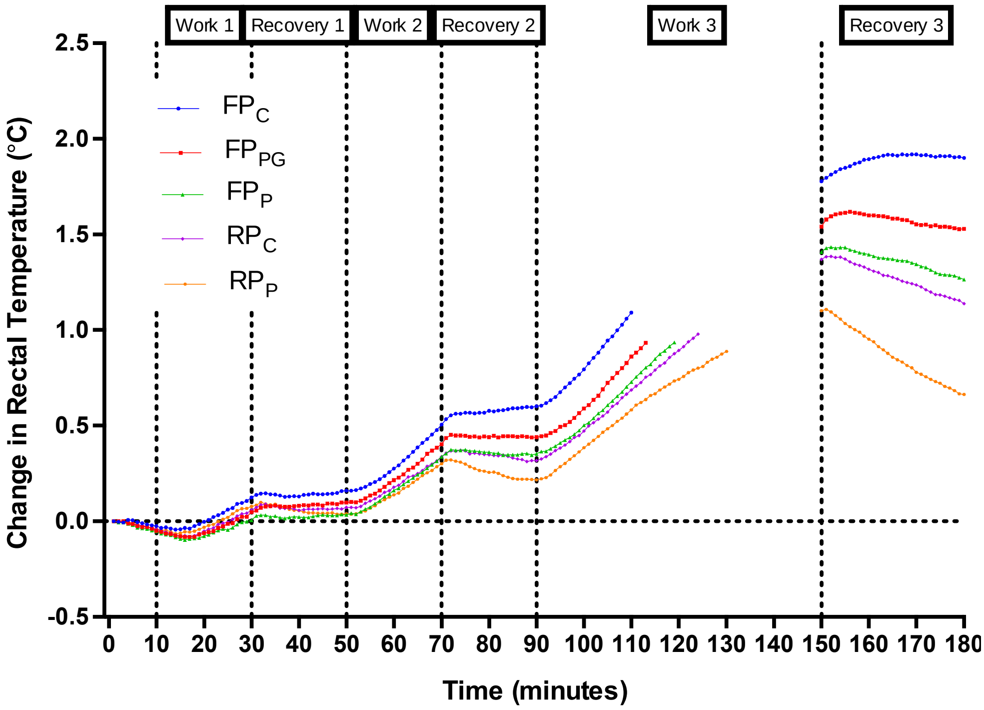

Figure 80: Mean change in rectal temperature from baseline whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12).

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Compared to FP_C, wearing the prototype suit in a FP state (FP_P) resulted in a significantly lowered ΔT_{re} from 20 minutes until 110 minutes with a maximum difference between conditions of 0.36 °C (33.0 %) at 110 minutes ($p < 0.0001$).

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

In a RP state, wearing the prototype suit significantly lowered ΔT_{re} from 80 minutes until 110 minutes compared to RP_C by a maximum of 0.10 °C (14.5 %) at 110 minutes ($p < 0.05$).

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

Replacing only the butyl gloves with the prototype gloves (FP_{PG}) resulted in a lowered ΔT_{re} at 30 minutes and then from 70 minutes until 110 minutes with a maximum difference between conditions of 0.23 °C (21.1 %) at 110 minutes ($p < 0.0001$).

Linear data from the final 10 minutes in each period, and final 20 minutes during Recovery 3, were used for calculation of the rate of change of T_{re} (Figure 81). For calculation of rate of change of T_{re} during Work 3, data were obtained from 10 minutes into the work period onwards and were adjusted for individual TT.

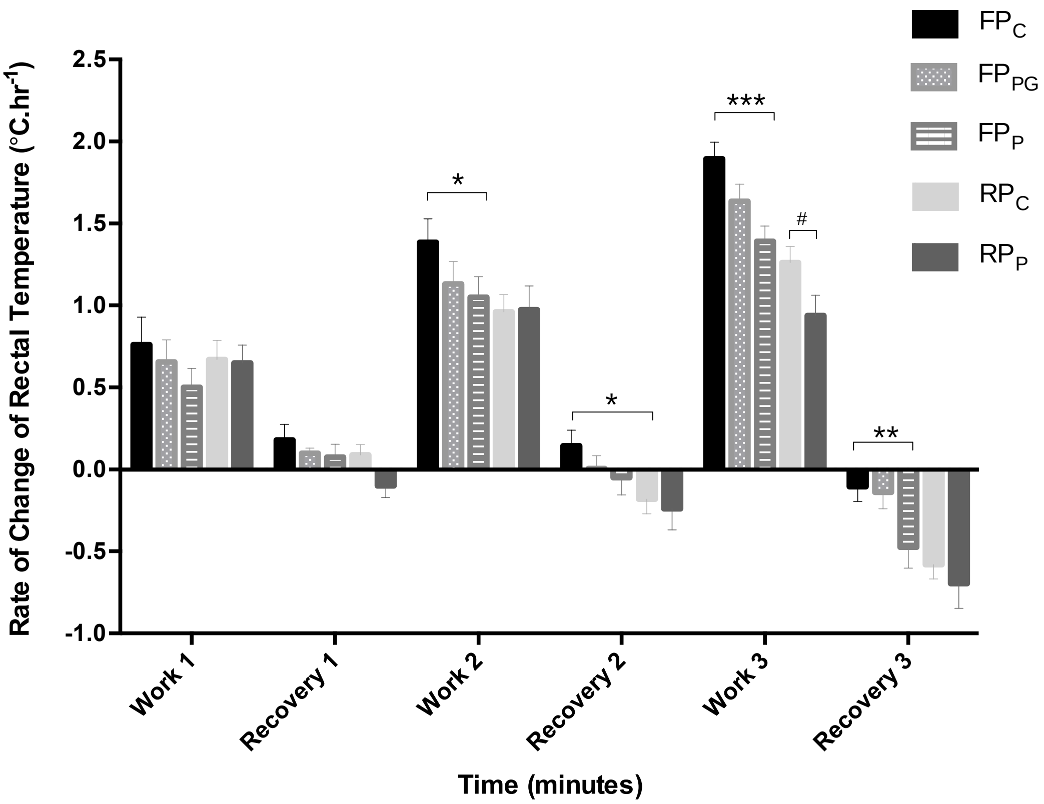

Figure 81: Mean (SEM) rate of change of rectal temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ *vs*. FP_C; $^{\#}p < 0.05$ *vs*. RP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

In a FP state, wearing the prototype suit compared to the common suit resulted in a significant attenuation in the rate of rise of T_{re} by 0.34 °C.hr^{-1} (24.5 %) during Work 2 ($p < 0.05$) and by 0.50 °C.hr^{-1} (26.4 %) during Work 3 ($p < 0.001$). The rate of T_{re} cooling during Recovery 3 was significantly augmented by 0.37 °C.hr^{-1} ($p < 0.01$).

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

In a RP state, wearing the prototype suit compared to the common suit significantly attenuated the rate of rise of T_{re} by 0.32 °C.hr^{-1} (25.4 %) during Work 3 ($p < 0.05$).

Mean Body Temperature

The $\overline{T}_b$ for each condition throughout the protocol is illustrated in Figure 82. Comparisons were made between all conditions from 0 minutes until 110 minutes (where n = 12 for all conditions), however as participants were in the chamber for varying durations during Work 3 (Table XXI) and $\overline{T}_{sk}$ (a component of the $\overline{T}_b$ equation) was not linear, comparisons of the mean $\Delta\overline{T}_b$ during Recovery 3 ($r\Delta\overline{T}_b$) were calculated from the last 20 minutes of Recovery 3.

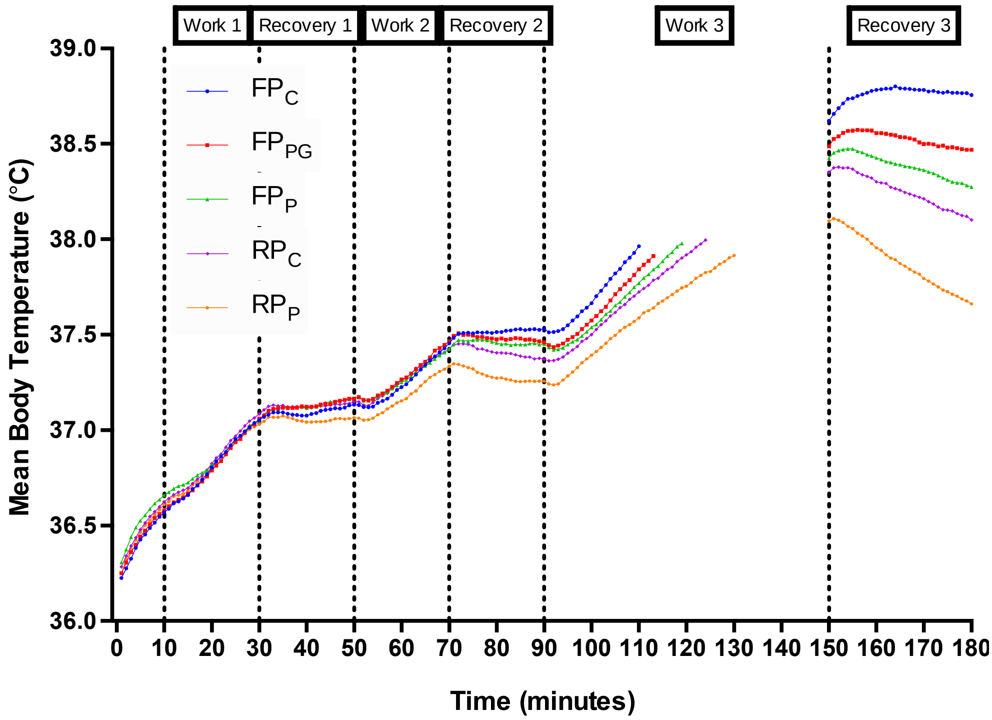

Figure 82: Average mean body temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12).

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

$\overline{T}_b$ was lower during FP_P compared to FP_C from 90 minutes until 110 minutes by 0.19 °C ($p < 0.001$). The mean $r\Delta\overline{T}_b$ during Recovery 3 when the prototype suit compared to the common suit was worn in a FP state was significantly improved by 0.06 °C ($p < 0.05$).

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

During a RP state, wearing the prototype suit significantly lowered $\overline{T}_b$ from 50 minutes until 110 minutes by a maximum of 0.14 °C ($p < 0.0001$) at 110 minutes.

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

$\overline{T}_b$ was lower during FP_{PG} compared to FP_C from 100 minutes until 110 minutes by 0.12 °C ($p < 0.01$).

Sweat Production and Evaporation

The mean whole body rate of sweat production, rate of sweat evaporation and the sweat evaporation / production ratio are illustrated in Figure 83.

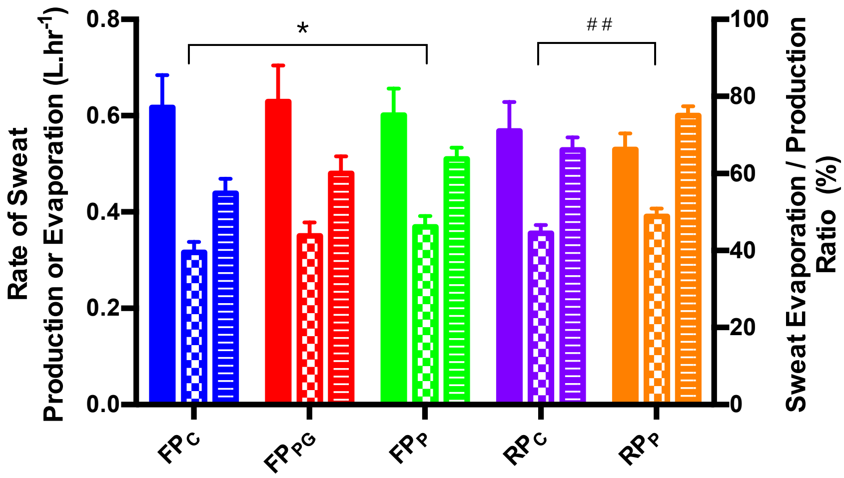

Figure 83: Mean (SEM) whole body rate of sweat production (solid) and evaporation (checked) and the sweat evaporation / production ratio (stripes) whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$ *vs*. FP_C, $^{\#\#}p < 0.01$ *vs*. RP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Replacing the common suit with the prototype suit in a FP state resulted in 0.053 $L.hr^{-1}$ (16.7 %, $p < 0.05$) more sweat being evaporated.

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

During a RP state, replacing the common suit with the prototype suit resulted in 0.035 $L.hr^{-1}$ (9.9 %, $p < 0.01$) more sweat being evaporated.

The sweat evaporation / production ratio provides an indication of the efficiency for the sweat that is produced to be evaporated from the body. There were no significant differences in the sweat evaporation / production ratio between FP_C *vs*. FP_P, RP_C *vs*. RP_P and FP_C *vs*. FP_{PG}.

Local Skin Temperature: Finger

T_{finger} during each condition throughout the protocol is illustrated Figure 84.

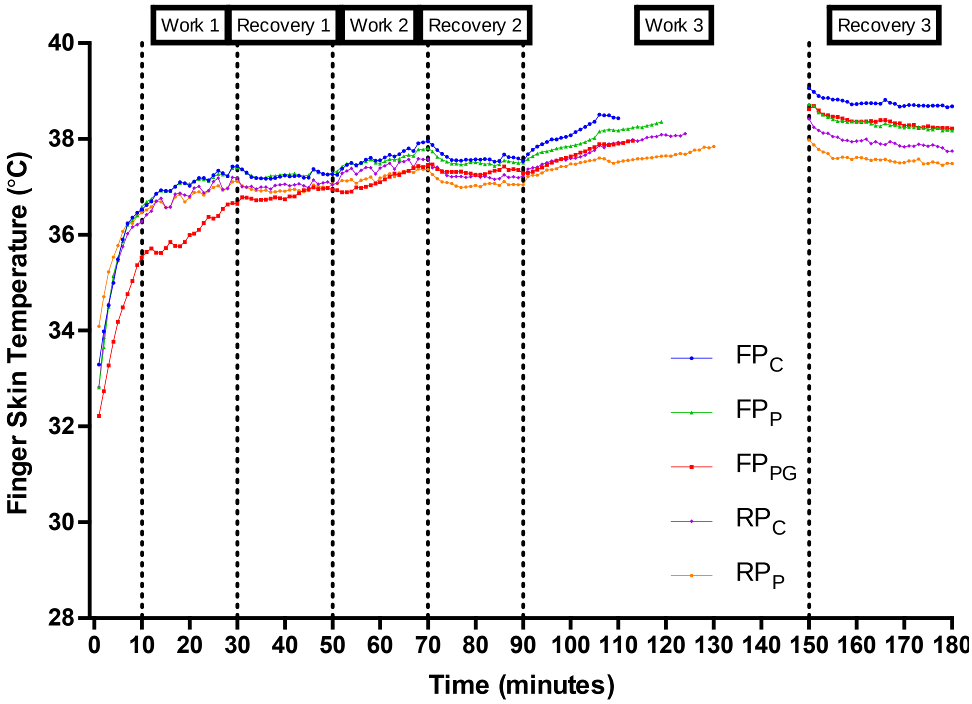

Figure 84: Mean finger temperature whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12).

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

FP_P resulted in a lower T_{finger} compared to FP_C at 110 minutes by 0.25 °C ($p < 0.05$). The mean $r\Delta T_{finger}$ during Recovery 3 when the prototype suit compared to the common suit was worn in a FP state was significantly reduced by 0.14 °C ($p < 0.05$).

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

RP_P resulted in a lower T_{finger} compared to RP_C at 110 minutes by 0.41 °C ($p < 0.0001$).

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

Throughout the entire protocol until 110 minutes, with the exception of at 90 minutes, replacing the butyl gloves with the prototype gloves significantly lowered T_{finger}. This was by a maximum of 1.03 °C ($p < 0.0001$) at 20 minutes.

Heart Rate

The mean heart rate during each condition is shown in Figure 85.

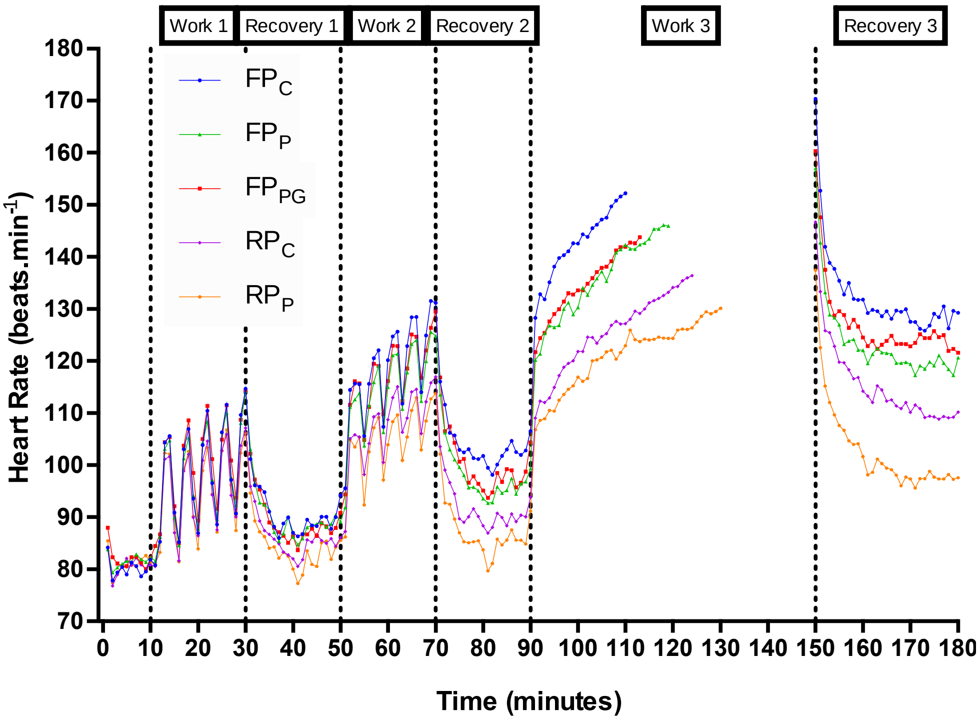

Figure 85: Mean heart rate whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12).

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Heart rate was significantly lower when wearing FP_P compared to FP_C from 70 minutes until 110 minutes. The maximum difference between conditions was by 12 beats.min^{-1} (8 %, $p < 0.0001$) at 100 minutes.

FP_C *vs.* FP_{PG}

Heart rate was significantly lower during FP_{PG} compared to FP_C from 80 minutes until 110 minutes with the exception of 90 minutes. The maximum difference was by 10 beats.min^{-1} (7 %, $p < 0.0001$) at 110 minutes.

Physiological Strain Index

The mean PSI during each condition is shown in Figure 86.

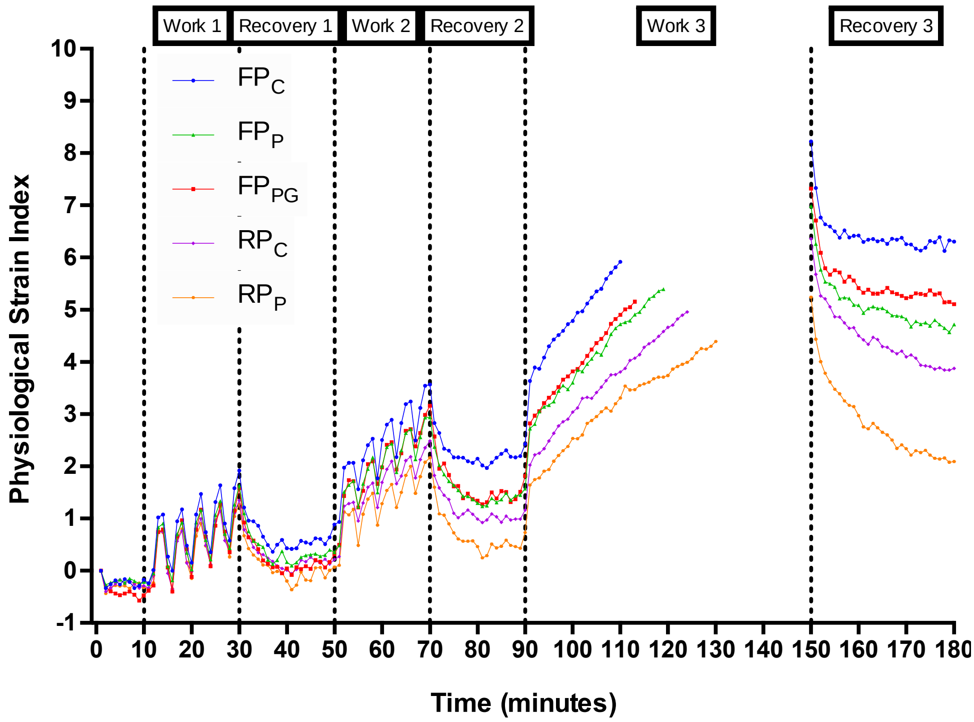

Figure 86: Mean physiological strain index whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12).

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

From 50 minutes until 110 minutes, the PSI was significantly lower during FP_P compared to FP_C. The greatest reduction to the PSI between these conditions was by 1.19 (20 %, $p < 0.0001$) at 110 minutes.

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

From 60 minutes until 110 minutes, with the exception of at 70 minutes, the PSI was significantly lower during RP_P compared to RP_C. The greatest reduction to the PSI between these conditions was by 0.53 (54 %, $p < 0.001$) at 80 minutes (Recovery 2) and by 0.50 (13.1 %, $p < 0.01$) at 110 minutes (Work 3).

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

From 40 minutes until 110 minutes, the PSI was significantly lower during FP_{PG} compared to FP_C. The greatest reduction to the PSI between these conditions was by 1.01 (17 %, $p < 0.0001$) at 110 minutes.

Perceptual Measures: Rating of Perceived Exertion

One measure of RPE per work period was taken, except during Work 3 where RPE was taken three times throughout the one-hour stepping period every 20 minutes. For all perceptual measures, data were truncated after the first measure was taken 20 minutes into Work 3 (that is at 110 minutes into the protocol) as in each condition at least one participant had stopped stepping by 40 minutes into Work 3 when the second perceptual measure was taken.

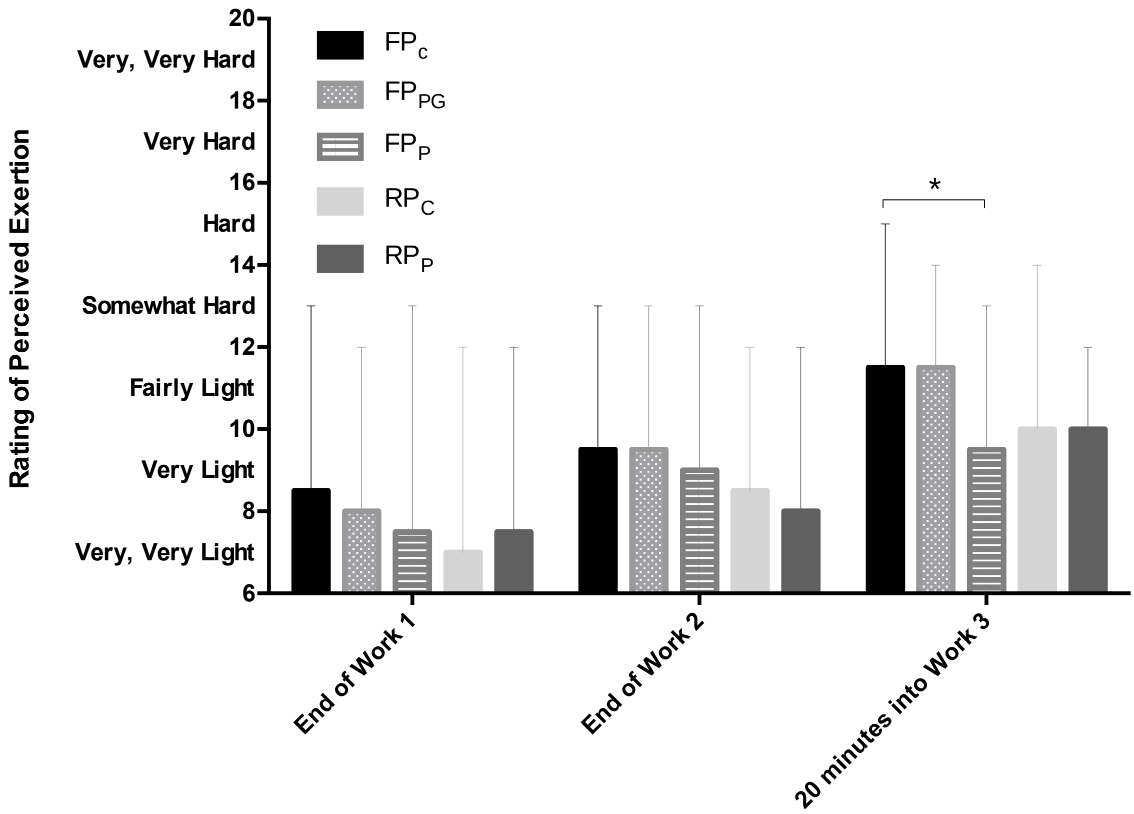

Figure 87: Median (range) rating of perceived exertion whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). *$p < 0.05$ *vs*. FP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

RPE, 20 minutes into Work 3, was lower during FP_P compared to FP_C (11.0 (8) *vs*. 9.0 (6), $p < 0.05$). RPE was reported as “fairly light” during FP_C compared to “very light” during FP_P.

Perceptual Measures: Thermal Sensation

Figure 88 illustrates participants' reporting of whole body thermal sensation.

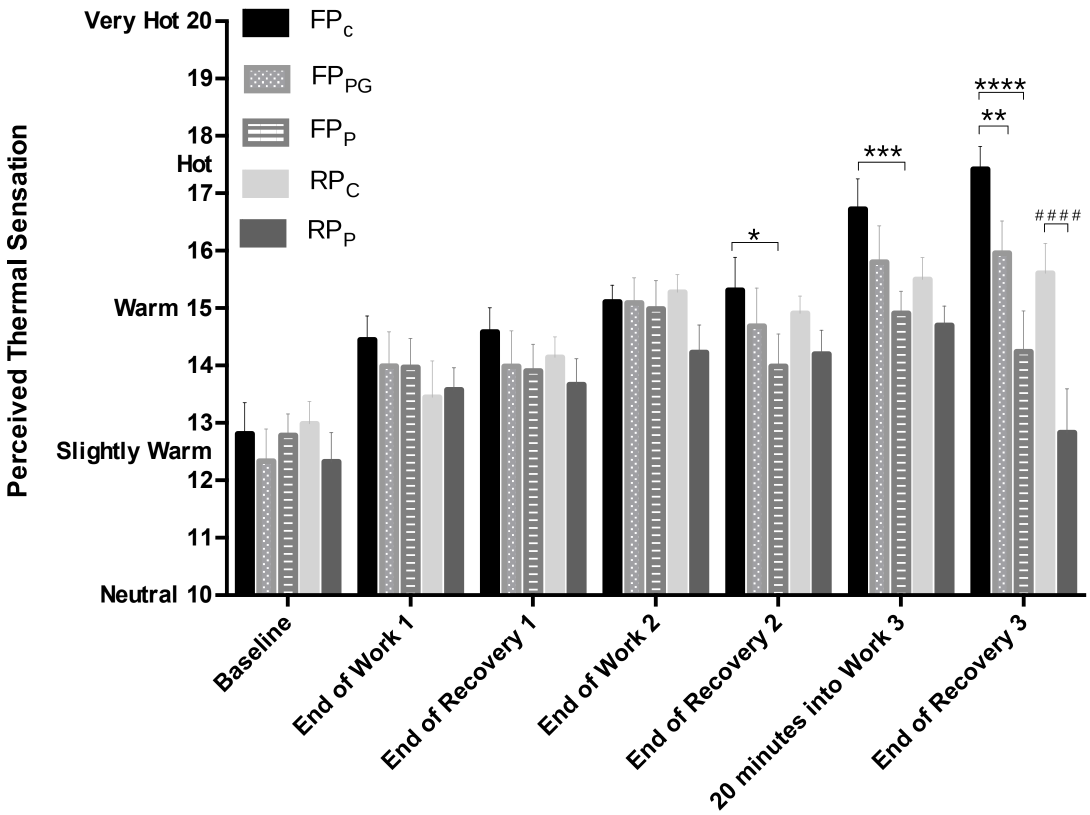

Figure 88: Mean (SEM) perceived thermal sensation whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{****}p < 0.0001$ *vs*. FP_C; $^{####}$ $p < 0.0001$ *vs*. RP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

From the end of Recovery 2 until the end of the protocol, participants reported feeling less hot during FP_P compared to FP_C. The greatest difference was at the end of Recovery 3 (14.24 (0.71) *vs*. 17.42 (0.40), $p < 0.0001$) when most participants reported FP_C as being "hot" whereas participants only reported feeling "warm" during FP_P.

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

Only at the end of Recovery 3 did participants report RP_P as feeling less hot than RP_C (12.83 (0.76) *vs*. 15.61 (0.52), $p < 0.0001$). This equated to participants reporting feeling "warm" during RP_C compared to only "slightly warm" during RP_P.

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

Participants reported feeling less hot when wearing the prototype gloves compared to the butyl gloves at the end of Recovery 3 only (15.96 (0.56) *vs*. 17.42 (0.40), $p < 0.01$). This equated to participants feeling “warm” during FP_{PG} compared to “hot” during FP_C.

Perceptual Measures: Thermal Comfort

Figure 89 illustrates participants’ reporting of whole body thermal comfort.

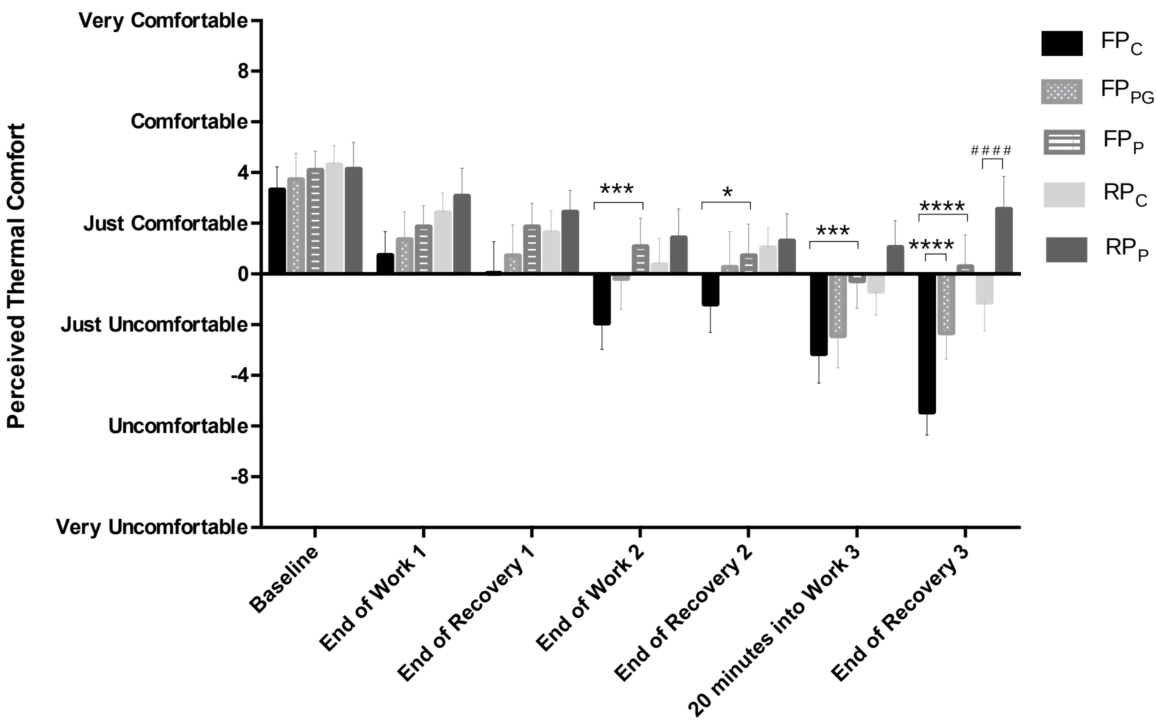

Figure 89: Mean (SEM) perceived thermal comfort whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^{*}p < 0.05$, $^{***}p < 0.001$, $^{****}p < 0.0001$ *vs*. FP_C; $^{####}p < 0.0001$ *vs*. RP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Replacing the common suit with the prototype suit during a FP state resulted in participants feeling less uncomfortably hot from the end of Work 2 (1.08 (1.12) *vs*. 1.93 (1.04), $p < 0.001$) until the end of the protocol (0.28 (1.26) *vs*. -5.44 (0.91), $p < 0.0001$). The maximum reduction to thermal discomfort between conditions was perceived at the end of Recovery 3 when participants reported feeling “uncomfortable” in FP_C compared to “just comfortable” in FP_P.

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

It was only at the end of the final recovery period that changing the common suit to the prototype suit in a RP state reduced perceived thermal discomfort (2.56 (1.29) *vs*. -1.11 (1.13), $p < 0.0001$). Participants reported feeling "just comfortable" during RP_P compared to "just uncomfortable" during RP_C.

Effect of the Prototype Gloves in a Full Protective Dress State (FP_C vs. FP_{PG})

Wearing the prototype gloves significantly reduced perceptions of thermal discomfort at the end of Recovery 3 only (-2.32 (1.04) vs. -5.44 (0.91), $p < 0.0001$). The difference equated to FP_C being perceived as "uncomfortable" at the end of Recovery 3 with FP_{PG} being perceived as "just uncomfortable".

Perceptual Measures: Skin Wettedness

Figure 90 illustrates participants' reporting of whole body skin wettedness.

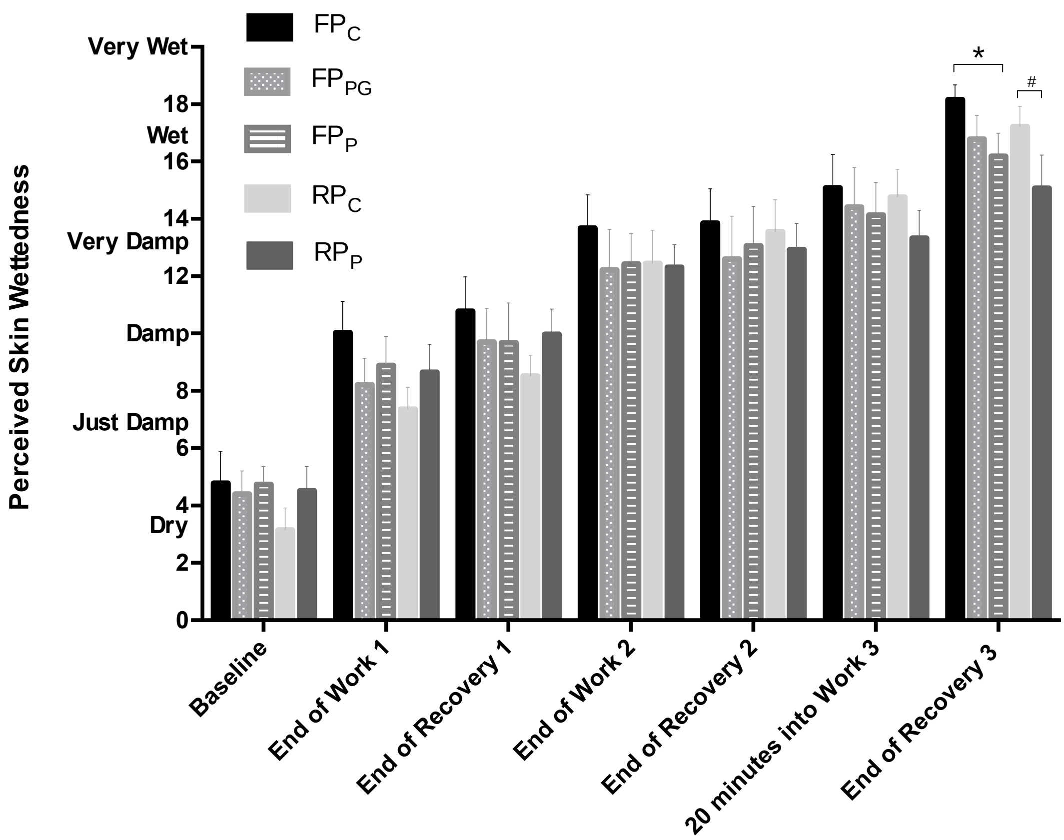

Figure 90: Mean (SEM) perceived skin wettedness whilst stepping and recovering in 40.5 °C and 20 % rh air (n = 12). $^*p < 0.05$ *vs*. FP_C; $^\#p < 0.05$ *vs*. RP_C.

Effect of the Prototype Suit in a Full Protective Dress State (FP_C vs. FP_P)

Participants perceived higher skin wettedness at the end of Recovery 3 when wearing the common suit in a FP state compared to the prototype suit in a FP state (18.16 (0.51) *vs*. 16.18 (0.81), $p < 0.05$).

Effect of the Prototype Suit in a Relaxed Protective Dress State (RP_C vs. RP_P)

It was also only at the end of Recovery 3 that participants perceived higher skin wettedness when wearing the common suit in a RP state compared to the prototype suit (17.22 (0.17) *vs*. 15.08 (1.15), $p < 0.05$).

Discussion

The aim of this experiment was to quantify the reduction to thermoregulatory strain when wearing a lightweight prototype suit compared to a common CBRN suit during a FP and RP state, as well as to quantify the reduction to thermoregulatory strain when wearing air permeable prototype gloves compared to the butyl gloves during a FP state. Thermoregulatory strain was measured in human participants during periods of exercise and recovery in an environmental chamber set to hot, desert-like conditions. Overall, the results indicated that the prototype suit reduced both physiological and perceptual thermoregulatory strain compared to when wearing the common suit during both a FP and RP state. Replacing the butyl gloves with the prototype gloves also reduced both the physiological and perceptual thermoregulatory strain placed upon participants throughout the protocol.

Thermoregulatory Benefits of the Prototype Suit in a FP State

The first hypothesis stated that thermoregulatory strain would be decreased by approximately 15 % to 20 % when wearing the prototype suit compared to the common suit in a FP state and during the current study it was found that the whole body rate of sweat evaporation was enhanced by 16.7 %. Improving the rate of sweat evaporation, the main mechanism of metabolic heat dissipation during exercise in a hot environment (Åstrand & Rodahl, 1977), decreases the heat load placed upon the body. The lowered heat load when wearing the prototype suit significantly attenuated the rate of rise of T_{re} during the final work period by 0.50 $°C.hr^{-1}$, which equated to a 38.6 % (25.4 minutes) or 38.3 % (31.4 minutes) extension to predicted TT when starting from a T_{re} of 37.5 °C until a critical T_{re} of 39.5 °C or 40.0 °C respectively. Therefore, if a warfighter walked at a speed of 1.1 $m.s^{-1}$ at a 0 % gradient (McLellan *et al.*, 1992) then an improved TT of 25.4 minutes or 31.4 minutes equates to a further 1.68 km (to a T_{re} of 39.5 °C, with 8 % not making this based on reaching a maximum heart rate prior to predicted T_{re} reaching 39.5 °C) or 2.08 km (to a T_{re} of 40.0 °C, with 17 % not making this based on reaching a maximum heart rate) walked before there is an increased risk of heat stroke causing serious systemic dysfunction (Knochel & Reed, 1994). This prediction assumed a constant work rate however in reality the patrolling warfighter might, where possible, stop exercising and recover. Therefore, the rate of decline of T_{re} between suits was important. The rate of T_{re} cooling during Recovery 3 when the prototype suit was worn was 0.48 $°C.hr^{-1}$ and 0.11 $°C.hr^{-1}$ when wearing the common suit in a FP state. It could then be calculated that to cool by 0.5 °C it would take a little over one hour (62.5 minutes) when fully encapsulated wearing the prototype suit compared to about 4.5 hours (272.7 minutes) in the common suit.

$\overline{T}_b$ was lower during the final work and recovery periods when wearing the prototype suit (FP_P) compared to the common suit (FP_C) and thus the cardiac demand to dissipate heat was also lowered. The lowered thermal burden was manifested as a reduced heart rate with a 20 % reduction to PSI at the last point measured during the final work period, at which point participants also felt less hot, less thermally uncomfortable and reported a lower RPE. $\dot{V}O_2$ was not significantly different between the two conditions, suggesting that the lowered thermoregulatory strain observed when wearing the prototype suit was not because the suit was lighter, which would have result in a lowered $\dot{V}O_2$, but rather because the evaporative burden of the suit is lower. This assertion was supported by 0.053 $L.hr^{-1}$ (16.7 %) more sweat being evaporated during FP_P compared to FP_C, which equates to 36 W more cooling assuming 100 % efficiency and 2.43 $kJ.mL^{-1}$ heat loss.

Overall, wearing the prototype suit in a FP state improved both physiological and perceptual responses that resulted in a 16.7 % improved rate of sweat evaporation, an extended predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C or 40 °C by 38.6 % or 38.3 % respectively, with a reduced PSI of 20 %. Therefore the first null hypothesis was rejected and the experimental hypothesis that thermoregulatory strain experienced when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 15 % to 20 % when wearing the prototype suit compared to the common suit in a FP dress state was accepted.

Thermoregulatory Benefits of the Prototype Suit in a RP State

The second hypothesis stated that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 15 % when wearing the prototype suit compared to the common suit in a RP state. While there were no significant differences to TT between wearing either suit in a RP state, the rate of rise of T_{re} was attenuated during the final work period by 25.4 % (0.32 °C.hr^{-1}), with $\Delta\overline{T}_b$ lowered by 0.14 °C during this period. The thermal benefits of wearing the prototype suit in a RP state compared to the common suit might be attributed to the enhanced rate of whole body sweat evaporation of 9.9 % (0.035 L.hr^{-1}). This was a lesser improvement in sweat evaporation than seen in a FP state (16.7 %, 0.053 L.hr^{-1}). The manikin tests (Table XIX) also showed that the difference in vapour resistance between either suit was lower in a RP (15.9 %) compared to a FP (19.0 %) state (Havenith *et al*., 2013), although to a lesser extent than identified in the human tests. In a FP state, vapour transport was reduced as additional clothing was worn (Havenith *et al*., 1999), this increased the evaporative resistance, amplifying any differences in vapour resistance between the common and prototype suits. Additionally, during the human studies, as the thermal load was lower during a RP state (mean T_{re} at 110 minutes during RP_C: 37.9 °C, mean rate of sweat production during RP_C: 0.57 L.hr^{-1}) compared to a FP state (mean T_{re} at 110 minutes during FP_C: 38.2 °C, mean rate of sweat production during FP_C: 0.62 L.hr^{-1}), there might have been less of a thermal load over which to demonstrate an improvement.

Although there were no significant differences in heart rate during RP_C compared to RP_P, the significantly lowered thermoregulatory strain (T_{re} and $\overline{T}_b$) when wearing the prototype suit in a RP state was manifested in the PSI. The PSI was reduced by 13.1 % at 110 minutes (20 minutes into Work 3) when the prototype suit was worn in a RP state, although participants did not report feeling any less hot, wet or uncomfortable at this point. It was only at the end of Recovery 3 that participants reported feeling “warm”, “just uncomfortable” and perceived a higher skin wettedness during RP_C compared to only “slightly warm”, “just comfortable” and less wet during RP_P. The $\overline{T}_b$ at the end of Recovery 3 was 38.1 °C during RP_C and 37.7 °C during RP_P, thus the perception of thermal state appeared proportional to the actual thermal state and it was interesting that the threshold between feeling just thermally comfortable and just thermally uncomfortable lay between a $\overline{T}_b$ of 38.1 °C and 37.7 °C during recovery when wearing protective clothing.

Overall, during a RP state, wearing the prototype suit improved both physiological and perceptual responses. The rate of sweat evaporation was improved by 9.9 % with an attenuated rate of rise of T_{re} during the final work period by 25.4 % with a lower $\Delta\overline{T}_b$. Therefore the second null hypothesis was rejected and the experimental hypothesis that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 15 % when wearing the prototype suit compared to the common suit in a RP state was accepted.

Thermoregulatory Benefits of the Prototype Gloves

During FP_{PG}, the weight difference between the prototype gloves (size 8: 0.104 kg) and the butyl gloves with cotton glove liners (size 8: 0.168 kg) was not matched. Therefore, any improvements seen during FP_{PG} might, in addition to the reduced evaporative burden identified in the physical manikin tests (Table XIX), have been due to the gloves being lighter and thus imposing less of a thermal burden due to a slightly lowered metabolic heat production associated with carrying less weight. $\dot{V}O_2$ was higher during Work 1 when wearing the prototype gloves (FP_{PG}) compared to the butyl gloves (FP_C). As this result was only seen during the first work period (and not during any subsequent work periods) when Douglas bag measures were only taken for a 1-minute duration, because the participant only stepped for 2 minutes at a time, it could be that the participant had not yet reached a steady state of exercise, thereby introducing bias into the results. Although, as this protocol was identical for all conditions, this was unlikely to have accounted for the result. A further point to consider is that the method required that the Douglas bag valve should be opened and closed mid-inspiration (to allow for the measurement of a full breath), but this was not always achievable given the tube attachment to the respirator obstructing visual confirmation of inspiration. Whatever the reason, the direction of error would in this case underestimate the improvements when wearing the prototype gloves.

The third hypothesis stated that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 10 % when wearing the prototype gloves compared to the butyl gloves in a FP state. An improved MVP of the gloves, as identified by the manikin tests (Table XIX), would allow for greater evaporation of sweat from the hands and, although no significant differences in the whole body rate of sweat evaporation were noted, a lowering T_{finger} could either represent evaporative cooling from the hands, or better insulation protecting T_{finger} from gaining heat from the environment. T_{finger} was significantly lowered throughout the entire protocol until 110 minutes compared to when the butyl gloves were worn (FP_C). There was also a lowered ΔT_{re} with a maximum difference of 0.23 °C and a lowered $\overline{T}_b$ by 0.12 °C at 110 minutes. The lowered thermoregulatory strain when the prototype gloves were worn also resulted in a lowered heart rate and a reduction to PSI by 17 % compared to FP_C. The thermoregulatory benefits of replacing the butyl gloves with prototype gloves were also detected perceptually at the end of Recovery 3 with participants reporting feeling less hot and less thermally uncomfortable compared to when the butyl gloves were worn.

Overall, while the prototype gloves did not result in an extended TT or improved rates of whole body sweat evaporation, three more participants completed the full protocol, T_{finger}, T_{re}, $\overline{T}_b$, heart rate and PSI were lowered, with participants reporting a reduced thermal sensation and reduced thermal discomfort by the end of the protocol. Therefore, the third null hypothesis was rejected and the experimental hypothesis was accepted that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 10 % when wearing the prototype gloves compared to the butyl gloves in a FP state.

Additional Thermoregulatory Considerations of the Prototype Gloves

Previous research conducted in our laboratory (first and second studies, Chapters 4 and 5) identified that wearing the respirator during the first 30 minutes of being placed in an extreme hot, desert-like environment might have provided a protective shield against convective and radiative heat gain, a protection that was not seen in T_{finger} when the butyl gloves were worn. The current study found that wearing the butyl gloves (FP_C and FP_P) did not protect against initial heat gain to the finger from the environment, in concurrence with previous research (first and second studies, Chapters 4 and 5). However, wearing the prototype gloves initially protected against heat gain compared to when no gloves were worn and the hand was completely exposed to the environment (RP_C and RP_P). Wearing the prototype gloves, that possess a reduced evaporative resistance compared to the butyl gloves (Havenith *et al.*, 2013), also allowed for a reduced T_{finger} throughout the entire protocol until 110 minutes compared to FP_C. Therefore, the prototype gloves appeared to both protect against initial heat gain and later, allowed for an improved vapour exchange between the skin and the environment.

The question arises therefore that in a hot and dry environment, whether wearing the prototype gloves would result in a greater thermoregulatory benefit than a hand completely exposed to the environment or covered by a theoretical 100 % MVP material, and whether this would have any whole body thermoregulatory consequences. Additional experiments would be required to test this hypothesis, as in this study the thermal load was lowered between FP_{PG} and RP_C, which could introduce a bias into the results if making a comparison directly between those conditions. Additional experiments should consider wearing the prototype gloves in a RP state compared to the completely exposed hand in a

RP state. Indeed it must be remembered that the prototype gloves were not heat-soaked in the environment before the start of the experiment, as would be the case in the practical setting, but rather were stored externally at a normal room temperature. This might have confounded the results, as the gloves would have initially acted as a heat sink, although the same protocol of donning equipment at room temperature was applied to the butyl gloves. Thus, further research is required to address these concerns.

A Comparison of the Thermal Burden of Wearing the Prototype Suit in a FP State Compared to the Common Suit in RP State

The predicted distances patrolled before reaching a critical T_{re} (40.0 °C) based upon the rate of rise of T_{re} during continuous exercise when fully protected and wearing the prototype suit (FP_P) was 7.5 km compared to 8.4 km when wearing the common suit and being unprotected (RP_C). Theoretically therefore, for a deficit of a further 0.9 km of patrolling before reaching a critical T_{re}, the warfighter could be fully protected when wearing the prototype suit compared to being unprotected and wearing the common suit. Additionally, participants also felt equally as thermally comfortable when wearing the common suit in a RP state as when wearing the prototype suit but worn in a FP state.

Conclusions

As the rate of sweat evaporation was improved by 16.7 % with predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C or 40 °C extended by 38.6 % or 38.3 % respectively and a reduced PSI of 20 % when wearing the prototype suit compared to the common suit in a FP dress state, the first null hypothesis was rejected and the experimental hypothesis was accepted that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 15 % to 20 % when wearing the prototype suit compared to the common suit in a FP state. While the rate of sweat evaporation was improved by 9.9 %, with the rate of rise of T_{re} being attenuated by 25.4 % and the $\Delta\overline{T}_b$ lowered by 0.14 °C when wearing the prototype suit compared to the common suit in a RP dress state, the second null hypothesis was rejected and the experimental hypothesis was accepted that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 15 % when wearing the prototype suit compared to the common suit in a RP state. Replacing the butyl gloves with the prototype gloves significantly lowered T_{re} by 0.23 °C and $\overline{T}_b$ by 0.12 °C while PSI was reduced by 17 % during FP_{PG} compared to FP_C, the third null hypothesis was rejected and the experimental hypothesis that thermoregulatory strain when exercising at a light intensity in hot, desert-like conditions would be decreased by approximately 10 % when wearing the prototype gloves compared to the butyl gloves in a FP state was accepted.

Recommendations

The prototype suit significantly lowered thermoregulatory strain in the exercising and recovering human compared to the common CBRN suit in both a FP and RP state and should therefore be considered for use by the military, with respect to reducing the thermal burden. Thermoregulatory strain was decreased when wearing the prototype gloves compared to the butyl gloves and therefore, from a thermal perspective, the prototype gloves should be considered for use by the military.

Limitations and Future Studies

- In retrospect it would have been advantageous to secure the weights of the items not worn during RP states to the MVIP torso BAL rather than at the area from where these items were removed as in reality, the warfighter would most likely carry these items in a rucksack.
- When predicting TT from the rate of rise of T_{re} during Work 3, the calculation assumed that the rate would remain constant and there would be no achievement of thermal balance, which in reality might not be the case as mentioned in the main body of this thesis.
- Future studies should investigate the potential benefits of wearing the prototype gloves in a RP state compared to completely exposing the hands to the hot and dry environment.

Appendix 11: Pilot Experiment for the Third Study

Aim: Previous research (first and second studies) identified that exposing only small surface areas such as the hands or face could reduce whole body thermoregulatory strain in a hot and dry environment. During the second study it was identified that a greater reduction to the thermal burden was evident when the hands were exposed compared to exposing other areas such as the face. The surface area of both hands is approximately 4.6 % of total body surface area (Yu *et al*., 2008) whereas the surface area of the face is only approximately 2.7 % of total body surface area (manikin Newton, Thermetrics, US). Therefore it was not surprising that a larger reduction to thermal strain was evident when exposing a surface area that was approximately 1.7 times greater. Furthermore, it has been suggested that thermosensitivity of various body areas might be more important to consider than merely surface area when assessing relative contributions to the whole body thermoregulatory response (Nadel *et al*., 1973; Crawshaw *et al*., 1975; Cotter & Taylor, 2005). As such, a pilot study was conducted to explore the thermoregulatory response of LSR primarily, when exposing areas that are of a more similar surface area, thus one hand or the face, whilst wearing CBRN equipment in a hot and dry environment.

Method: The Pinsent environmental chamber was set to air conditions of 40.5 °C and 20 % rh. The volunteer participant was weighed naked and then self-inserted a rectal thermistor to monitor T_{re}. The participant was then instrumented with a heart rate monitor and four skin thermistors (chest, arm, thigh and calf) for estimation of $\overline{T}_{sk}$ according to Ramanathan’s (1964) equation. Four sweat capsules were secured to the chest, back, forearm and thigh. The participant completed five conditions on separate days and was dressed either in full CBRN military protective equipment (CON), full CBRN equipment without the respirator (annotated as N1R) but with the suit hood up so as to only expose the face, or full CBRN equipment with one glove and cotton liner removed (annotated as N1G) to expose a single hand to the environment. CON and N1R were repeated (CON2 and N1R2) to assess the reliability between repeated measures. A dressed weight was then taken and the participant was escorted into the chamber and rested for 30 minutes after the participant stepped to a height of 22.5 cm at a light intensity of 12 steps.min^{-1} for the duration of one hour, with standard experimental end-points in place (General Methods: Section 3.4.4). The participant then ceased stepping and remained seated in the chamber for a further 30 minutes after which they were escorted from the chamber and dressed and naked weights were again obtained.

Results: T_{re} (Figure 91) heart rate (Figure 92) and $\overline{T}_{sk}$ (Figure 93) are illustrated below for the participant wearing either full CBRN equipment (CON and CON2), full CBRN equipment with one glove removed (N1G) or full CBRN equipment without the respirator (N1R and N1R2).

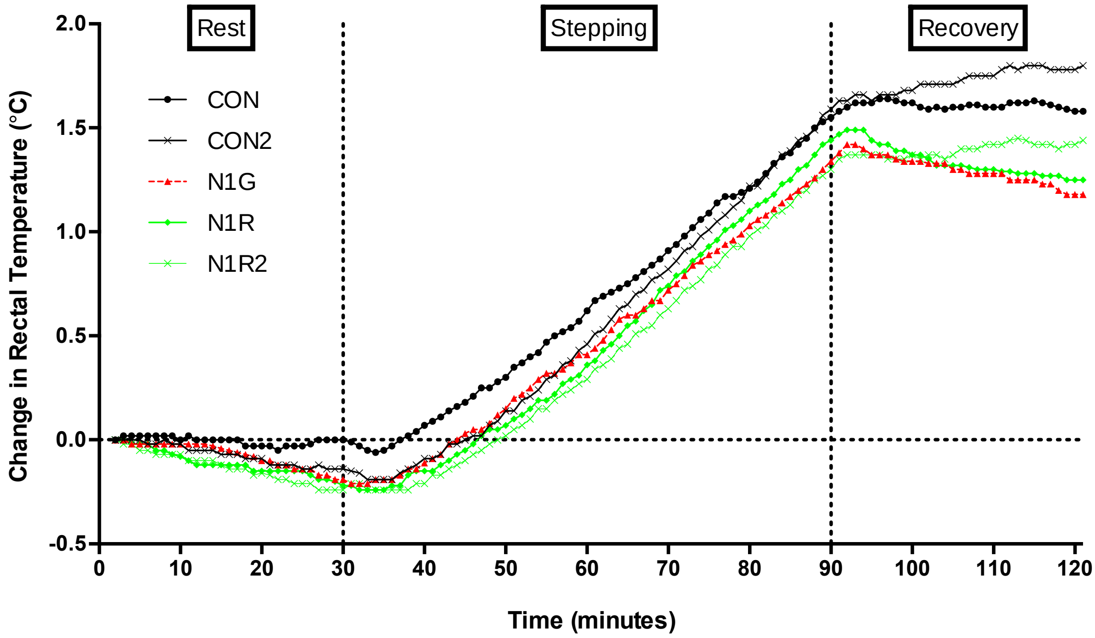

Figure 91: Individual change in rectal temperature whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

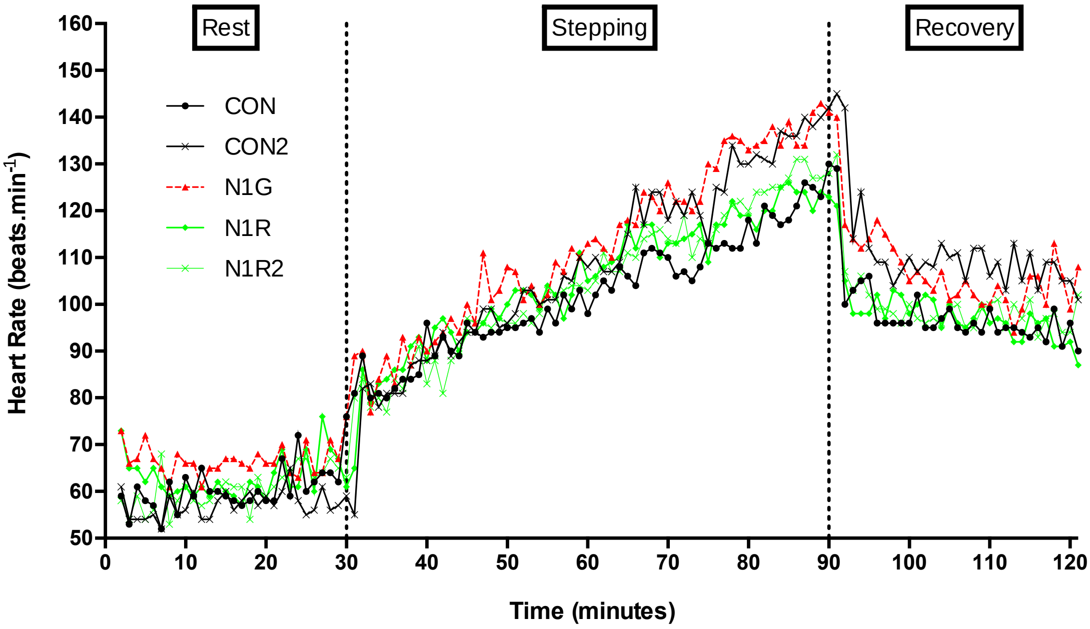

Figure 92: Individual heart rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

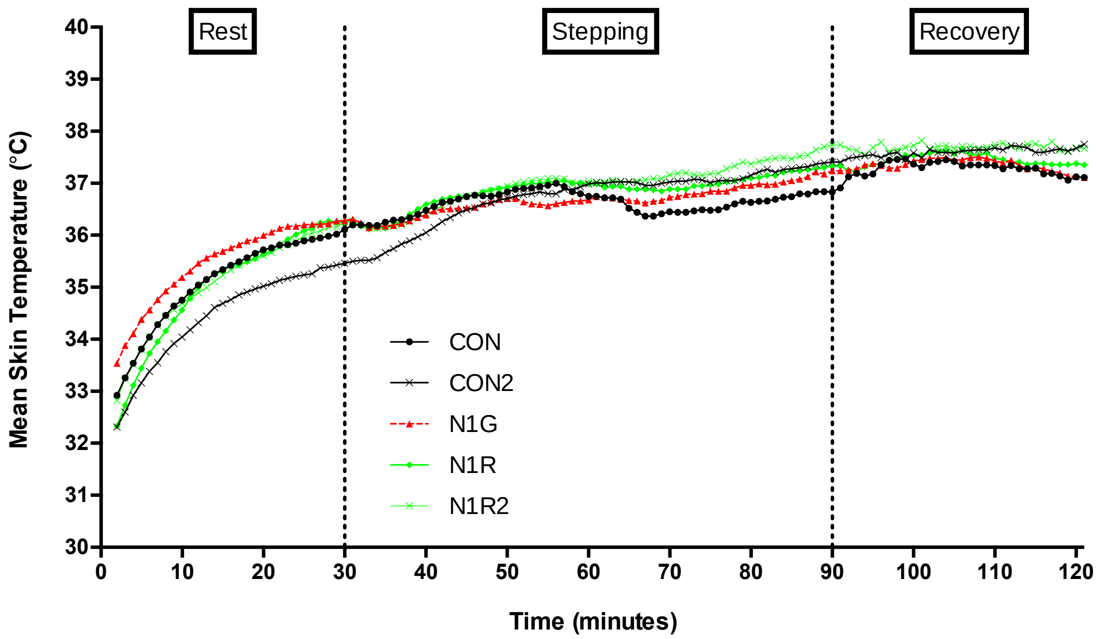

Figure 93: Individual mean skin temperature whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

Figures 94 to 97 below illustrate the rate of sweat production at the chest, back, forearm and thigh.

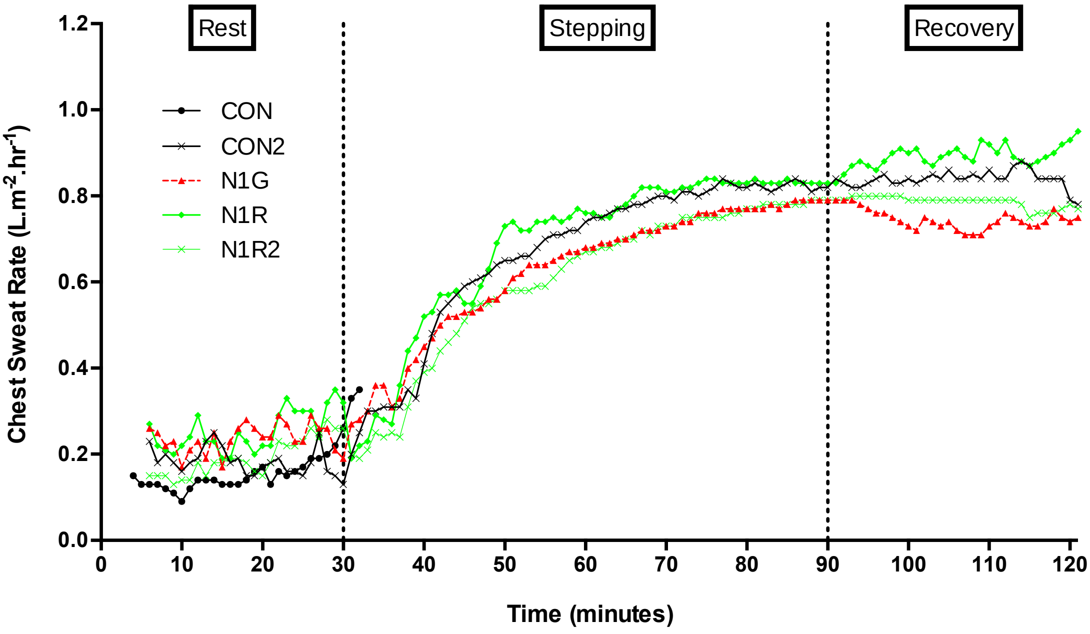

Figure 94: Individual chest sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

Note that the chest sweat capsule during CON became unattached from 32 minutes into the protocol.

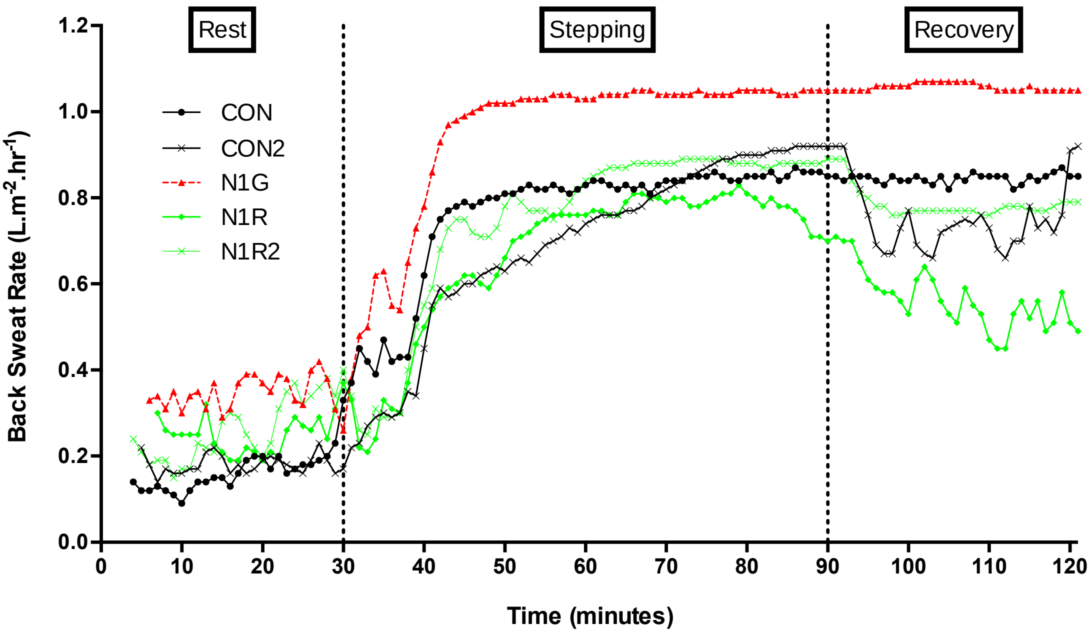

Figure 95: Individual back sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

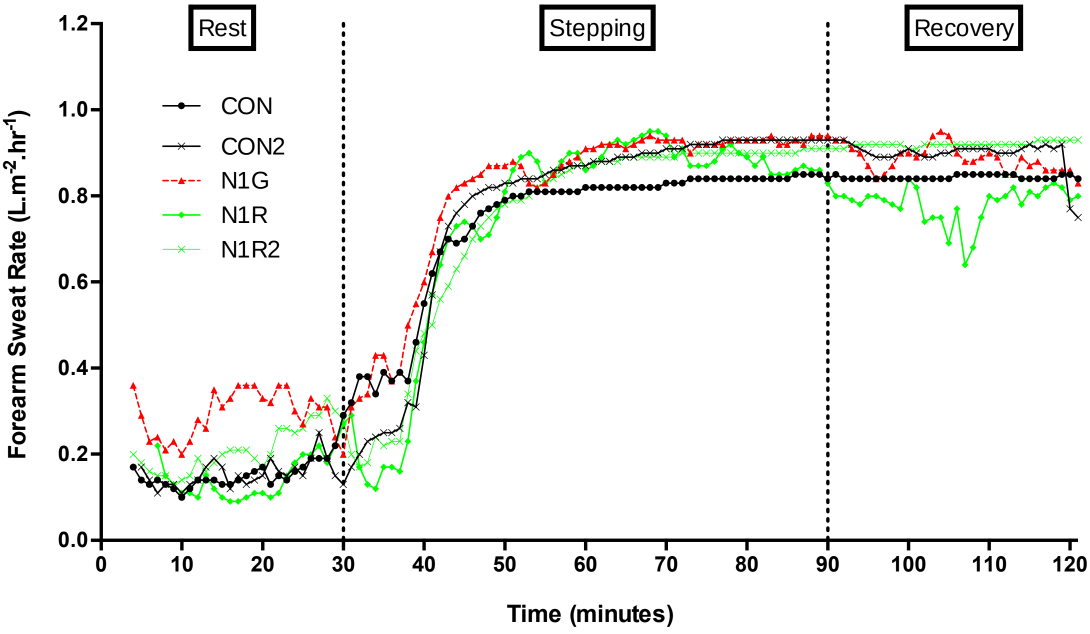

Figure 96: Individual forearm sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

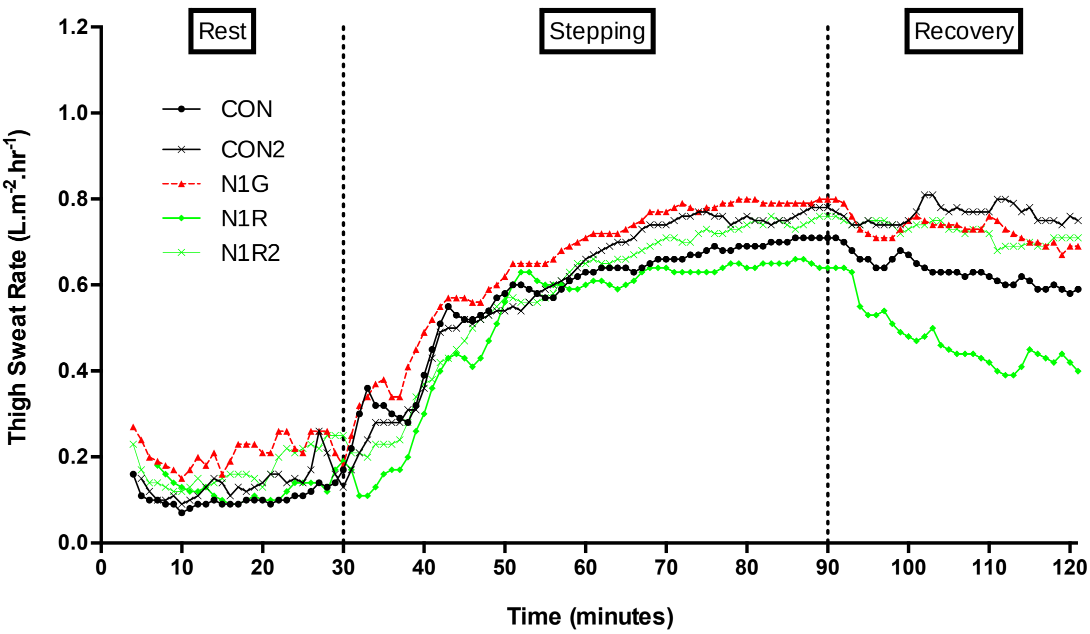

Figure 97: Individual thigh sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed (n = 1).

Discussion: Upon entering the chamber T_{re} decreased in all conditions, although to a lesser degree during CON. Initially this could be the result of cooler peripheral blood mixing with warmer central blood as blood is shifted from splanchnic to peripheral circulation during whole-body heating (Rowell *et al*., 1969; Crandall *et al*., 2008). The decrease in T_{re}

during the rest period could also be due to evaporative cooling within the microclimate. As exercise commenced, the generation of metabolic heat from the exercising muscles resulted in a rise in T_{re}. Wearing CBRN clothing that is insulative and restricts evaporative cooling places the individual into a state of uncompensable heat stress whereby the mechanisms employed to dissipate heat are ineffective to combat the rise in T_c (McLellan *et al*., 1992; Amos & Hansen, 1997). However, exposing either a hand or the face to the hot and dry environment most likely supported evaporative cooling from those areas (although not directly measured), slightly attenuating the rate of rise of T_{re} (Figure 91). During the recovery period, due to the exposure of either a hand or the face, cooling was evident (as indicated by a declining T_{re}) except during CON and CON2 when T_{re} appeared to plateau or increase. As the participant entered into the hot and dry environment from a thermoneutral environment there was initially a large increase in $\overline{T}_{sk}$ (Figure 93) as the gradient for heat exchange was large whereby the cooler body was gaining heat from the hotter environment. From approximately 15 minutes into the exercise period until the end of the protocol, $\overline{T}_{sk}$ increased only slightly over the 75 minutes but was not largely different between the conditions. This was due to the insulative and encapsulating properties of the CBRN clothing.

Addressing the aim of this study that was to explore LSR when exposing a hand or the face whilst exercising and recovering when wearing CBRN equipment in a hot and dry environment, small variations in LSR were observed between conditions with large variations in LSR between repeated conditions, although it must be remembered that this pilot study included data from only one participant. Nonetheless it was found for example that the variation in LSR at the chest between repeated measures (N1R and N1R2) appeared greater than the difference between exposing the face or a hand. Similarly, the variation in LSR at the thigh between repeated measures (CON and CON2, N1R and N1R2) appeared greater than the difference between exposing the face and covering the face with the respirator. Therefore with small differences between conditions, it would be difficult to distinguish the impact of exposing only a small surface area on LSR and therefore the driver for change needed to be increased so as to amplify the difference between conditions and lessen the difference between repeated measures.

Conclusion: Whilst T_{re} and $\overline{T}_{sk}$ responded as predicted, the small variation in LSR responses between conditions might not allow for significant differences to be observed when either exposing only the face or a hand. It was decided that by increasing the driver for change, a greater distinction between conditions could be obtained. This was accomplished by actively forcing evaporation by directing a fan at the exposed sites and was explored in Appendix 12.

Appendix 12: The Initial Experiment for the Third Study

Introduction: In an attempt to overcome the small variability between different conditions and the large variability between repeated conditions shown during the pilot study (Appendix 11), a fan was directed at either the face or a hand to increase the driver for change thereby maximizing the variation between conditions and possibly minimizing the variation between repeated measures. The aim of this initial experiment was to assess the contribution of exposing similar surface areas (either a hand or the face) on the thermoregulatory response of LSR and SkBF when a fan was directed at the exposed sites to assist in forced evaporation. This was investigated because it has been suggested that the thermosensitivity of various body areas might be more important than surface area when assessing contributions to the whole body thermoregulatory response (Nadel *et al*., 1973; Crawshaw *et al*., 1975; Cotter & Taylor, 2005).

Method: The study was granted a favourable ethical opinion by the Science Faculty Ethics Committee (SFEC) on the 19th of January 2015 (SFEC 2014-100). Five males volunteered for the study, which was a five condition, repeated measures design that required participants to lightly step to a height of 22.5 cm at a rate of 12 steps.min^{-1} for 60 minutes and recover for 30 minutes in a hot (40.5 °C) and dry (20 % rh) environment. The methodology was identical to Pilot Study 1 for the third study (Appendix 11) except for the addition of a fan (circulating ambient air at 120 m.min^{-1}) directed at either the uncovered face or a hand. The conditions were as follows:

CON: the participant was dressed in full CBRN equipment and no fan was used throughout the test

N1GF: the participant was dressed in full CBRN equipment with one glove and cotton liner removed (annotated as N1G) and a fan (annotated as F) was directed at the exposed hand throughout the test

N1RF - the participant was dressed in full CBRN equipment without the respirator (annotated as N1R) and a fan was directed at the exposed face throughout the test

The conditions that involved removing a piece of kit (N1GF and N1RF) were repeated (N1GF2 and N1RF2) to assess the agreement between the two conditions.

Results: T_{re} and $\overline{T}_{sk}$ are displayed below (Figures 98 and 99) along with LSR at the chest, back, forearm and thigh (Figures 100 to 103).

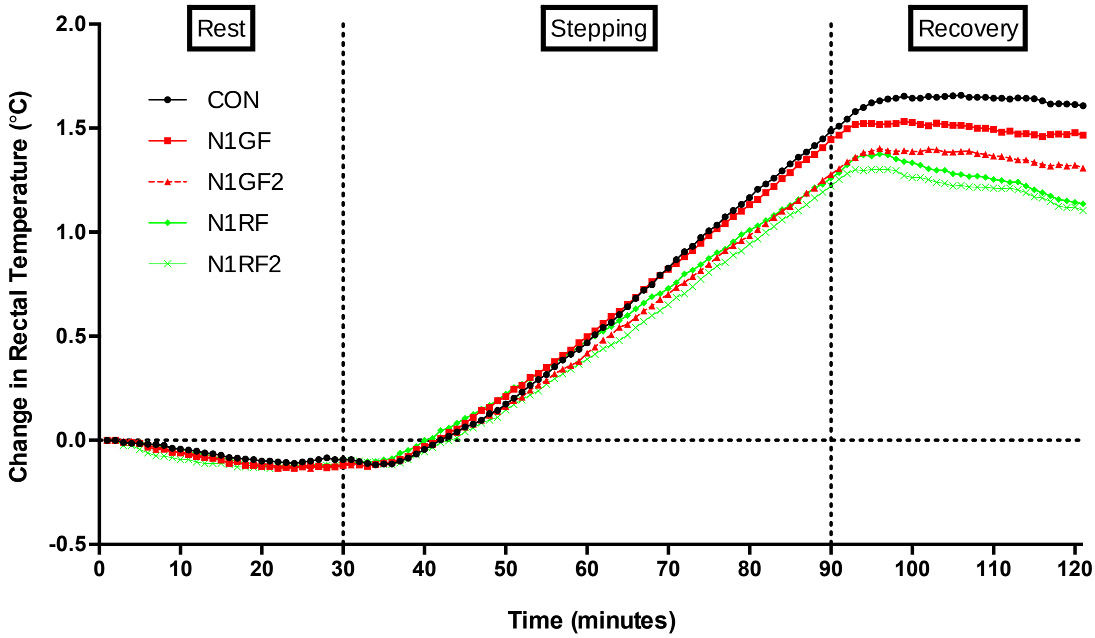

Figure 98: Mean change in rectal temperature whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

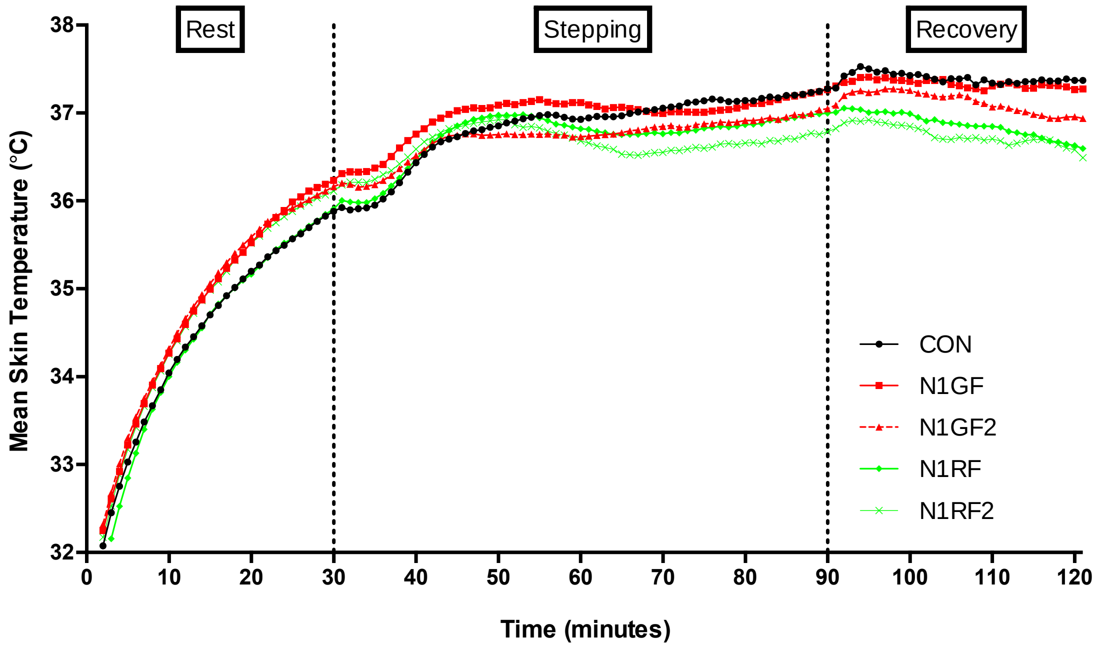

Figure 99: Mean skin temperature whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

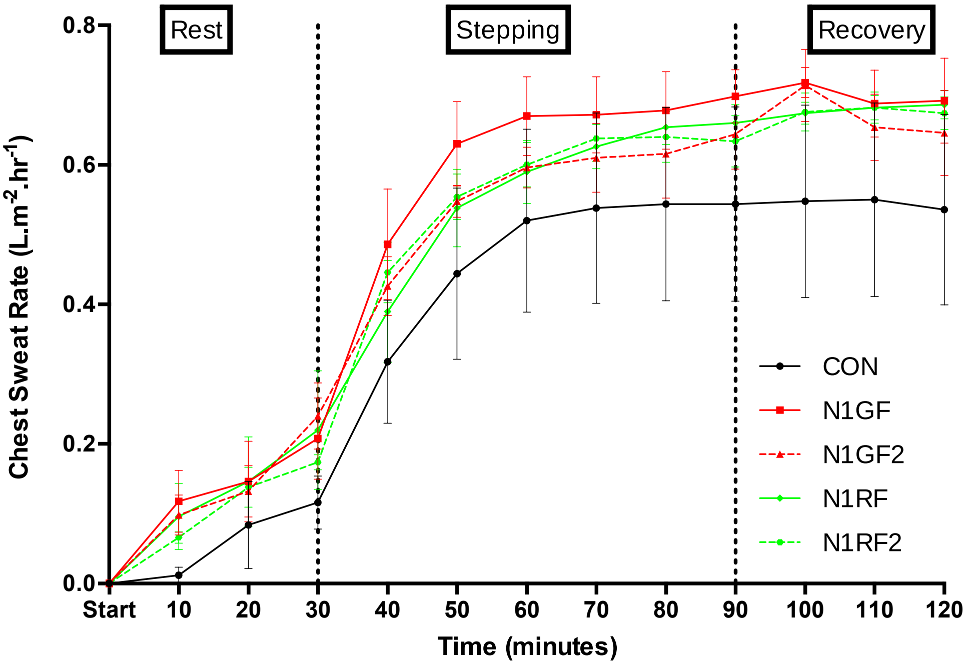

Figure 100: Mean chest sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

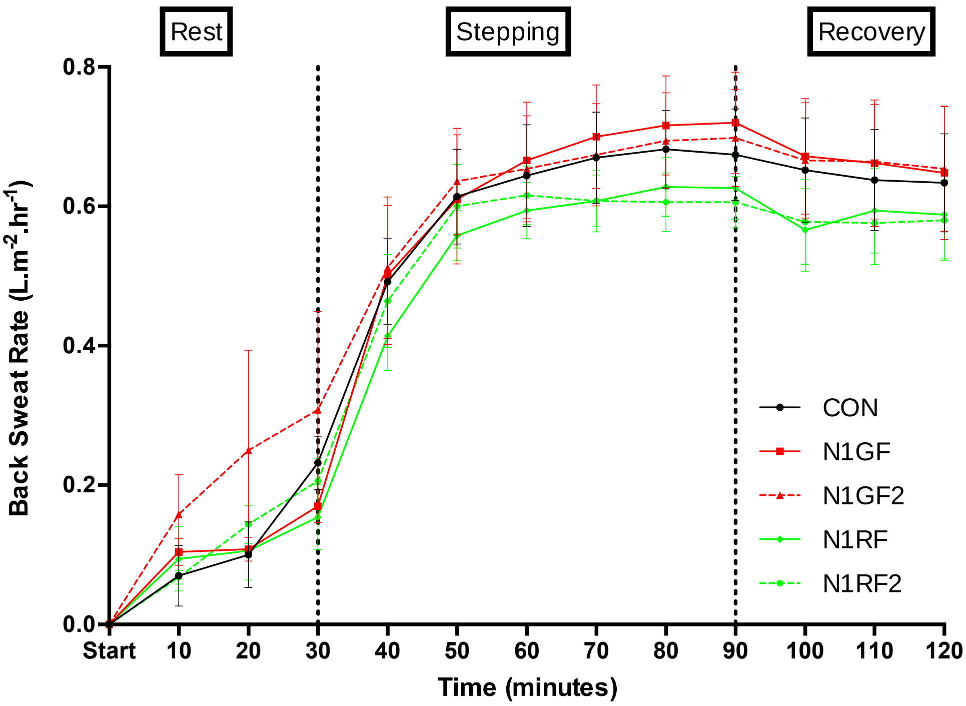

Figure 101: Mean back sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

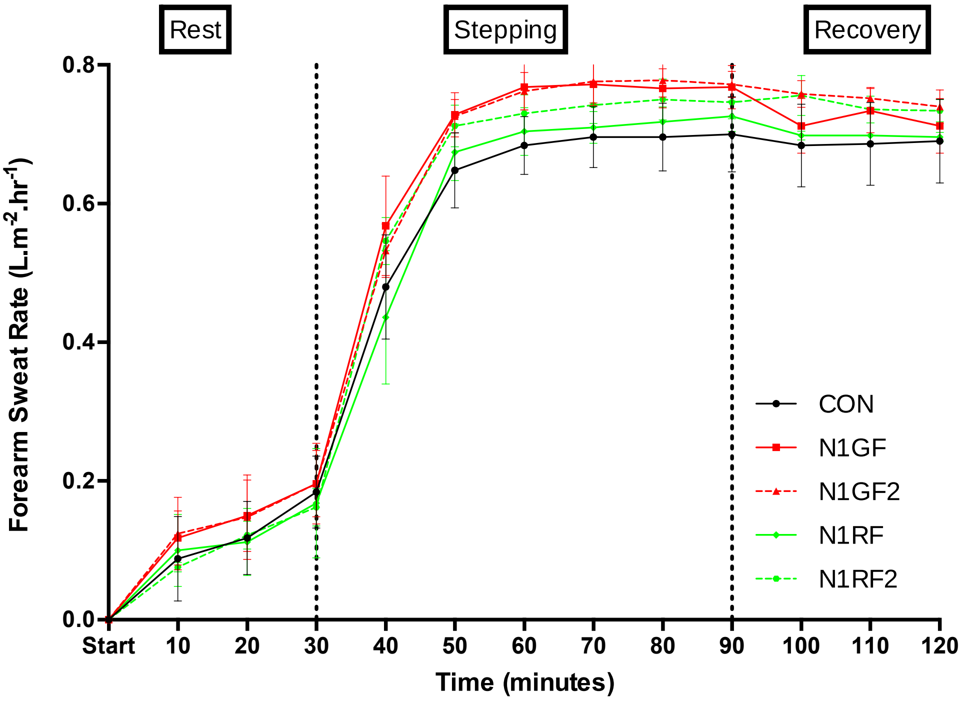

Figure 102: Mean forearm sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

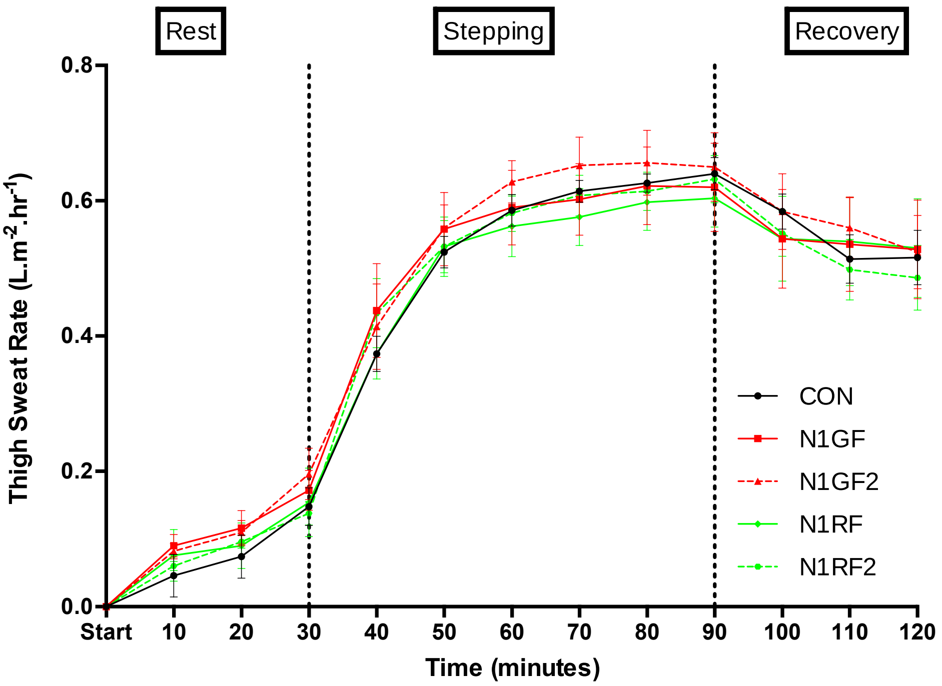

Figure 103: Mean thigh sweat rate whilst resting, stepping and recovering in 40.5 °C and 20 % rh air with full chemical, biological, radiological and nuclear individual protective equipment, and with either the respirator or one glove removed with a fan directed at the exposed site (n = 5).

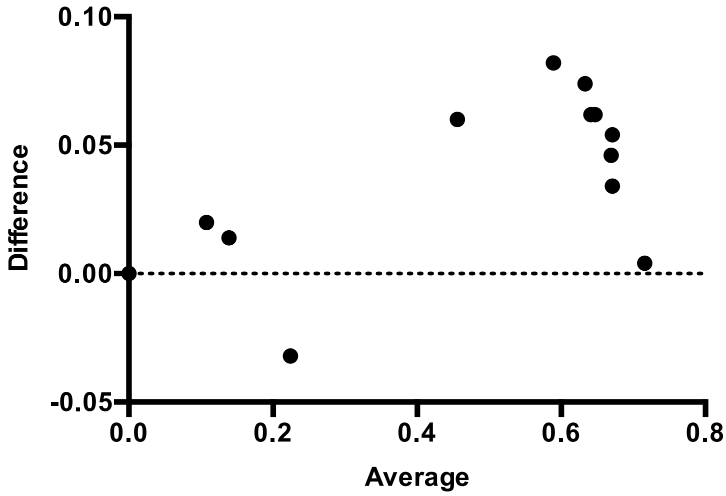

Figure 104: A Bland-Altman plot showing poor agreement of LSR at the chest between N1GF and N1GF2 with an average discrepancy between conditions (bias) of 0.04.

Discussion: Again, the variability between repeated conditions was high with the variability between different conditions being low. For example at the chest during stepping, the reliability of achieving similar results in repeated conditions (N1GF and N1GF2) as illustrated in Figure 104 where the bias between conditions was 0.04, was less than detecting the changes between different conditions (N1GF and N1RF). Additionally, at certain time points, LSR at the thigh was higher than CON during N1GF2 but lower than CON during N1GF even though the conditions were a repeat. Thus the variability within a repeated measure was high and the variability between different conditions was low. This might have been due to several factors such as a high variation observed within participants that fluctuated day-to-day, the high variability between participants, the equipment not being sensitive enough to detect any measurable differences or that the driver for change was still not large enough to elicit significant differences between conditions.

Conclusion: It was concluded that as there was poor agreement within a repeat condition, the driver for change again needed to be increased and this was accomplished by exposing a greater surface area between conditions. This was implemented into the main experimental procedure and involved the following conditions: a repeated condition exposing both hands (N2GF and N2GF2), a repeated condition exposing the whole head not just the face by removing the hood in addition to the respirator (NRHF and NRHF2) and a control condition (CON).

Appendix 13: Study 4 – Non-thermoregulatory Control of Sweating: Exercise

Aim: During the third study (Chapter 6) it was found that at the cessation of exercise, even though $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and the local T_{sk} at the chest, back, forearm and thigh were elevated post-exercise, LSR and SkBF declined at all those sites except LSR at the chest (Figure 48). Therefore it appeared that a non-thermal mechanism could be governing LSR and SkBF responses. At the cessation of exercise (stepping), participants recovered seated in the chamber and therefore there were two mechanisms that could have been responsible for regulating the thermoregulatory responses of LSR and SkBF: exercise and posture. The aim of this pilot study was to investigate the influence of exercise alone on the post-exercise decline in LSR and SkBF at most sites and therefore it was imperative that posture was unchanged between exercise and recovery periods.

Method: The Pinsent environmental chamber conditions were set to 35.0 °C and 20 % rh air. The volunteer participant (annotated as P1, male, 28 years, 182 cm, 91.59 kg) was instrumented with a heart rate monitor, a rectal thermistor and four skin surface thermistors to estimate $\overline{T}_{sk}$ (Ramanathan, 1964). Four sweat capsules were attached to the chest, back, forearm and thigh (General Methods: Section 3.4.2.8). The experiment involved only one laboratory visit whereby the participant cycled on a stationary bicycle at 120 W for 90 minutes with intermittent recovery periods (seated on the bicycle) lasting 5 minutes in duration. In this way the posture was unchanging between conditions, with only the onset or cessation of exercise changing. The participant was dressed in CBRN clothing without the respirator or gloves for the entire duration of the protocol. Water (250 mL) was given at 25 minute intervals at approximately 38 °C to avoid any influence on the sweat response that have been known to occur with no fluid intake (Nielsen, 1974; Fortney *et al.*, 1984) cooler fluids consumed (Lamarche *et al.*, 2015; Bain *et al.*, 2015).

A separate experiment was conducted on a different volunteer participant (annotated as P2, male, 28 years, 174 cm, 73.55 kg) that followed a slightly different methodology to clarify the results of the experiment with P1. The Pinsent environmental chamber conditions were set to 40.5 °C and 40 % rh air. These conditions were selected to induce mild hyperthermia with a reduced gradient for water vapour exchange in an attempt to minimize the extent of evaporation and subsequent whole body cooling that might affect LSR. P2 was instrumented in the exact way as P1. The experiment consisted of two conditions conducted on two separate days, Condition 1 (Exercise): 60 minutes of exercise (cycling on a stationary bicycle at 60 W), Condition 2 (Exercise + Rest): 30 minutes of cycling exercise on a stationary bicycle at 60 W followed by 30 minutes of recovery in a seated position on the bicycle. During exercise the participant was dressed in CBRN suit trousers, t-shirt, combat boots, socks, overboots and the respirator. Wearing full CBRN kit in a hot and humid environment and exercising induces a large thermal load on the body (McLellan & Ayogi, 1996). Wearing the kit but without the jacket and gloves still induced a thermal load but a lesser one than the fully encapsulating ensemble. During recovery, the participant donned the jacket and gloves (particularly due to their insulative and vapour restrictive properties) in an attempt to maintain a homogenous $\overline{T}_b$ between conditions (Exercise and Exercise + Rest), and thus allowed for the continued rise in $\overline{T}_b$ even after exercise was stopped in the Exercise + Rest condition that might otherwise have fallen post-exercise. The jacket and gloves were placed in the chamber before the start of the experiment to ensure they were sufficiently heat soaked before being donned. Ensuring that the $\overline{T}_b$ continued to rise post-exercise, allowed for direct comparison between conditions (Exercise *vs*. Exercise + Rest). Water (250 mL) at 38 °C was given at 20 minutes and 40 minutes into the protocol.

Results: The results from P1 are presented in Figure 105, with the results from P2 presented in Figures 106 and 107 below.

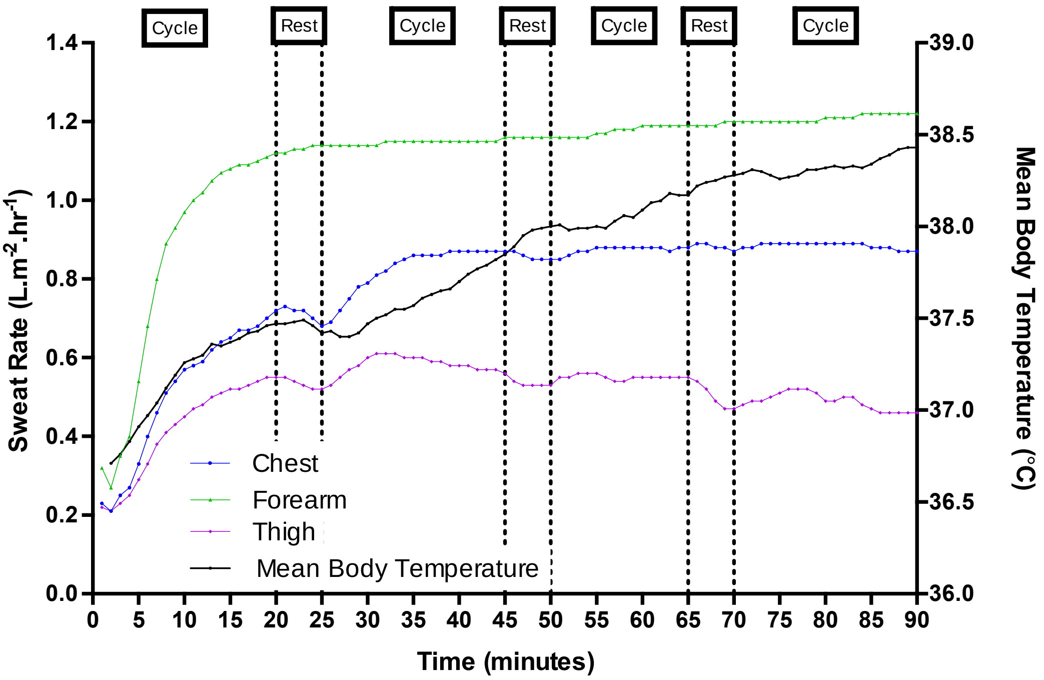

Figure 105: Mean body temperature and sweat rate at three sites during cycling and recovery in 35.0 °C and 20 % rh air whilst wearing CBRN clothing without the respirator or gloves (n = 1, P1).

Note that data is missing from the back due to sweat capsule detachment during the test.

Note that the Q-Sweat^{TM} is calibrated up to 1000 $nL.cm^{-2}.min^{-1}$ that equates to 0.76 $L.m^{-2}.hr^{-1}$ and therefore recordings above this value should be interpreted with caution.

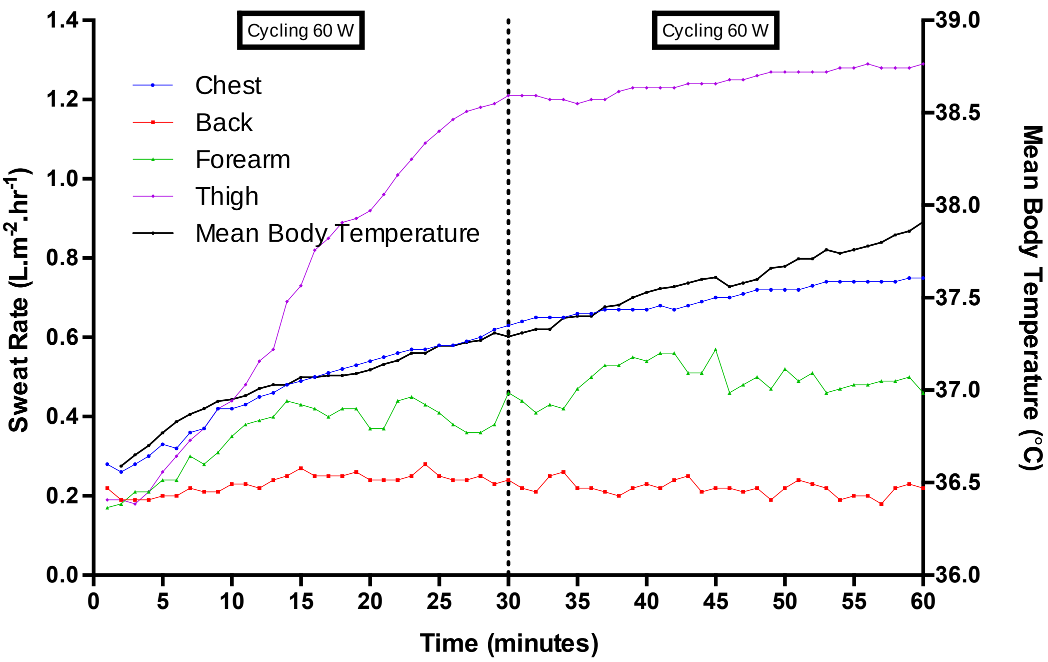

Figure 106: Mean body temperature and sweat rate at four sites during cycling in 40.5 °C and 40 % rh air whilst wearing CBRN clothing without the jacket and gloves (n = 1, P2).

Note that the Q-Sweat^{TM} is calibrated up to 1000 $nL.cm^{-2}.min^{-1}$ that equates to 0.76 $L.m^{-2}.hr^{-1}$ and therefore recordings above this value should be interpreted with caution.

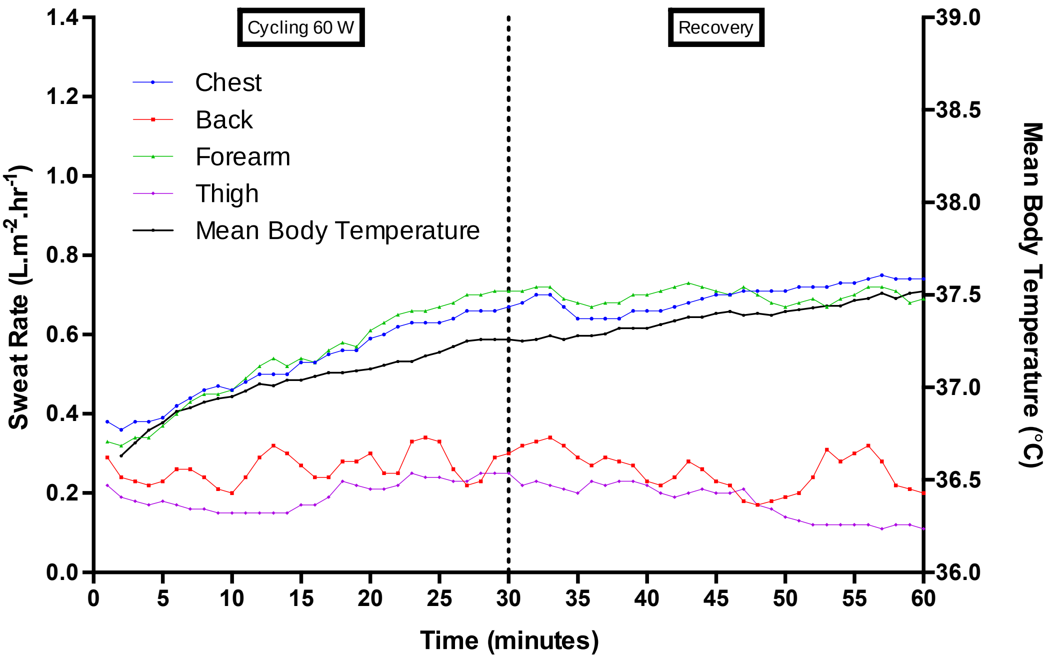

Figure 107: Mean body temperature and sweat rate at four sites during cycling and recovery in 40.5 °C and 40 % rh air whilst wearing varying combinations of CBRN clothing (n = 1, P2).

Discussion: It was difficult to interpret the influence of exercise alone on the sweat responses obtained for the experiment with P1 as $\overline{T}_b$ was not stable during the recovery periods and therefore would have exerted an influence on the LSR pattern of response. However, it appeared that during the second and third rest periods, when $\overline{T}_b$ was rising, as opposed to the first rest period when $\overline{T}_b$ declined, there were minimal changes to LSR at the forearm and chest, with some changes at the thigh. This suggests possible activation of metabo- and mechanoreceptors during exercise might play a role, albeit a minimal role, in modulating the sweating response as proposed by others (Kondo *et al.*, 1997; Shibasaki *et al.*, 2003a). Moreover, the position of the thigh during the recovery periods was not exactly matched to the position of the thigh during exercise and therefore the influence from a slight postural change could not be excluded even though the feet always remained on the pedals. Thus, the results from the experiment with P1 showed that the onset or cessation of exercise did not appear to greatly modulate LSR particularly at the chest and forearm when $\overline{T}_b$ was rising during recovery.

Regarding the results obtained from the experiment conducted with P2 in a hotter and less dry environment; although donning the CBRN jacket and gloves did not allow $\overline{T}_b$ to be identical between the two conditions (Exercise and Exercise + Rest), $\overline{T}_b$ during Exercise + Rest was still increasing post-exercise, as was the case during Exercise, and therefore the thermal driver for the sweating response was still present as no cooling was taking place. During Exercise the sweat response at all four sites continued to rise or plateau throughout the protocol, whereas during Exercise + Rest where posture was unchanging, the sweat response either continued to rise or plateaued with the exception of the sweat response at the thigh, which appeared to reduce slightly.

Conclusion: These data suggest that whilst exercise exerts some influence on modulating the sweating response, the response observed was not as apparent compared to the results from the third study (Chapter 6, Figure 48) in which LSR and SkBF declined at the chest, back, forearm and thigh except LSR at the chest post-exercise when both posture and activity were altered. Therefore the role of posture in modulating the sweating response was further investigated in Appendix 14.

Appendix 14: Study 4 – Non-thermoregulatory Control of Sweating: Posture

Aim: The role of exercise in regulating the sweating response was investigated in Appendix 13 and it was found that whilst exercise exerted some influence on modulating LSR, the response was not as measurable as the results from the third study (Chapter 6, Figure 48) in which LSR and SkBF declined at the chest, back, forearm and thigh except LSR at the chest post-exercise whilst $\overline{T}_b$, T_{re}, $\overline{T}_{sk}$, and the local T_{sk} remained elevated when both posture and activity were altered. The aim of this pilot study was to investigate the influence of posture alone on the post-exercise decline in LSR and SkBF at most sites.

Method: The Pinsent environmental chamber conditions were set to 40.0 °C and 40 % rh air. The participant (annotated as P1, male, 28 years, 174 cm, 73.55 kg) was instrumented with a heart rate monitor, a rectal thermistor and four skin surface thermistors to estimate $\overline{T}_{sk}$ (Ramanathan, 1964). Four sweat capsules were attached to the chest, back, forearm and thigh. The experiment consisted of three conditions. The first two conditions were as follows; Condition 1 (Ex): 60 minutes of exercise (stepping to a height of 22.5 cm at a rate of 12 steps.min^{-1}), Condition 2 (Stand): 30 minutes of stepping followed by 30 minutes of recovery in a standing posture. In this way the posture was largely unchanging between conditions, with only the onset or cessation of exercise changing. Condition 3 (Sit) involved 30 minutes of stepping followed by 30 minutes of recovery in an upright-seated posture on a stool with the back unsupported. During exercise the participant was dressed in CBRN suit trousers, t-shirt, combat boots, socks, overboots and the respirator. During recovery (30 minutes into either Stand or Sit conditions), the participant also wore the jacket and gloves that had been placed in the chamber before the start of the experiment to ensure they were sufficiently heat soaked before being donned. Ensuring that the $\overline{T}_b$ continued to rise post-exercise by donning the jacket and gloves, allowed for comparison between conditions (Ex *vs*. Stand *vs*. Sit) as no cooling was occurring in any condition. Water (250 mL) at 38 °C was given at 20 minutes and 40 minutes into the protocol.

Results: The results from Experiment 1a on P1 are presented in the figures below. A software crash, with no back up files, occurred during the Stand (red trace) condition at 27 minutes and was resolved by 37 minutes. The experiment was not repeated, as we were confident the $\overline{T}_b$ trace continued at the same rate of rise between 27 and 37 minutes (between stepping and standing). Retrospectively, this response was observed in future studies with P1 (Figures 111 and 113).

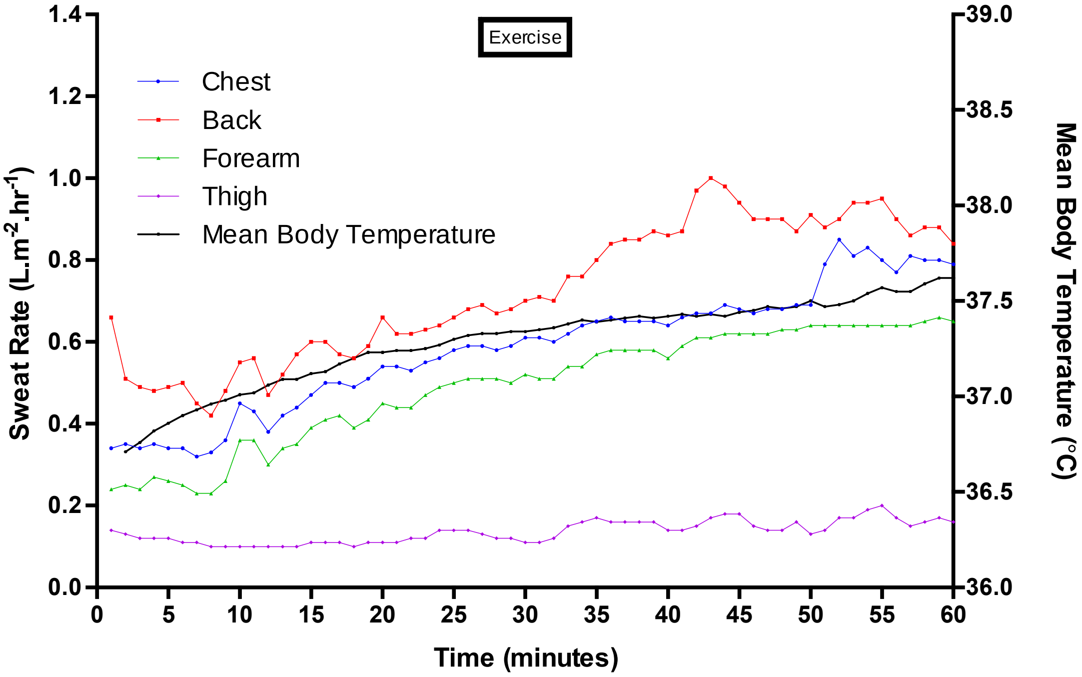

Figure 108: Local sweat rate at the chest, back, forearm and thigh during exercise in 40.0 °C and 40 % rh air whilst wearing varying combinations of chemical protective clothing (n = 1, P1).

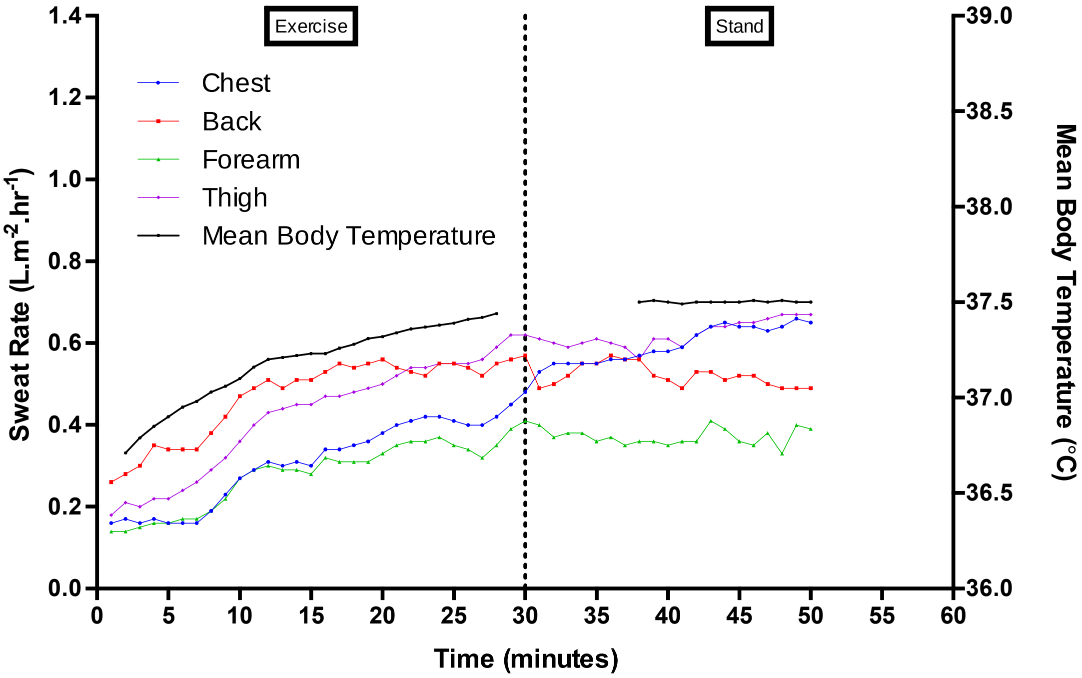

Figure 109: Local sweat rate at the chest, back, forearm and thigh during exercise and standing recovery in 40.0 °C and 40 % rh air whilst wearing varying combinations of chemical protective clothing (n = 1, P1).

Note that data are not available from 50 minutes onwards due to P1 being unable to complete the protocol (volitional withdrawal).

Note that mean body temperature data are missing from 28 minutes until 36 minutes due to a software crash.

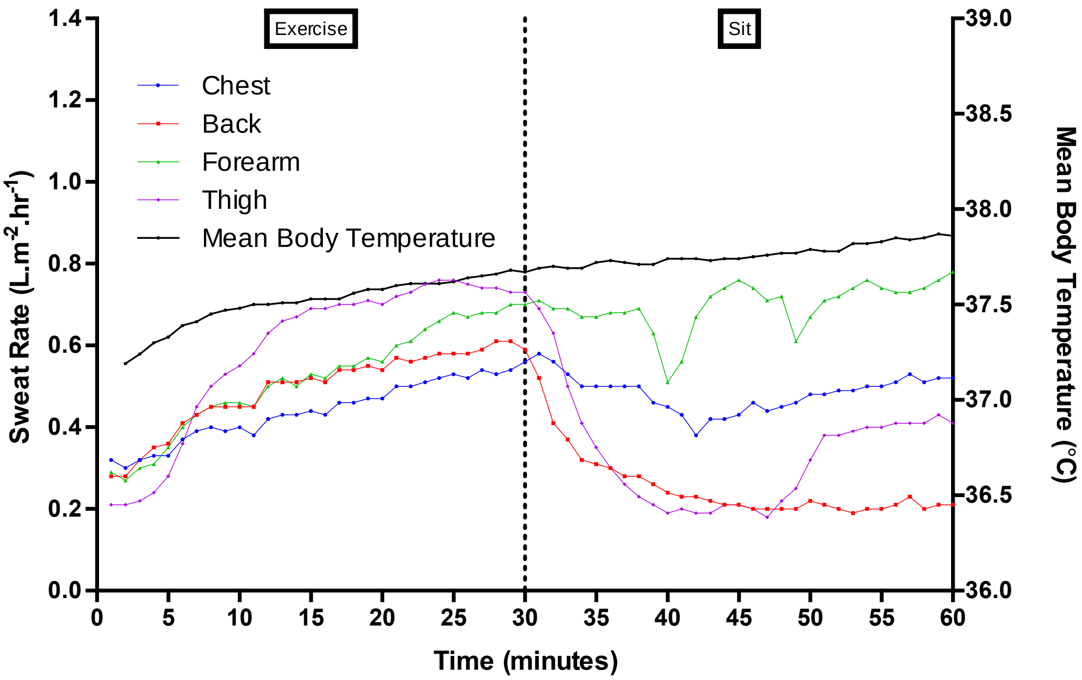

Figure 110: Local sweat rate at the chest, back, forearm and thigh during exercise and seated recovery in 40.0 °C and 40 % rh air whilst wearing varying combinations of chemical protective clothing (n = 1, P1).

Discussion: The results indicate that in all three conditions, $\overline{T}_b$ did not decline from 30 minutes until the end of the protocol. This was due to the environmental conditions providing a heat stimulus, lowering of the gradient for vapour exchange as well as due to donning extra CBRN clothing (jacket and gloves) post-exercise at 30 minutes. Therefore any noticeable changes in LSR at 30 minutes into the protocol was most likely due to the intervention, that being either the change in exercise and / or posture. Figure 108 highlights that with the continuation of exercise; there was a concurrent continuation of sweat production at all four sites measured (chest, back, forearm and thigh). Figure 109 highlights that at the cessation of exercise, whilst posture was largely unchanged from exercise (Stand), LSR appeared to plateau at most sites whereas when exercise was ceased and the posture was altered (Sit), there was a decrease in LSR at the thigh and back with LSR largely unchanging at the forearm and chest (Figure 110). The results of this experiment suggested that LSR could be modulated by both exercise and posture yet appeared influenced more by the change in posture.

Aim: After performing the three separate conditions (Ex, Stand and Sit), it was decided that combining all postures into one protocol would improve the reliability of the measures particularly in minimizing the unintentional error of capsule placement or tightness and day-to-day participant variations in T_c, hydration status and thermoregulatory responses.

Therefore a second experiment was conducted on the same participant (P1) that combined multiple posture changes in one protocol.

Method: The Pinsent environmental chamber was set to the same air conditions (40.0 °C and 40 % rh). The volunteer participant (male, 28 years, 174 cm, 73.55 kg) came into the laboratory on only one occasion and was instrumented in the exact way as the first experiment. To minimize the influence of evaporative cooling post-exercise, the participant wore the CBRN suit (hood down), t-shirt, combat boots, socks, overboots and gloves. The participant was escorted into the chamber and began to exercise (stepping to a height of 22.5 cm at a rate of 12 steps.min^{-1}) for 30 minutes to raise T_{re} and initiate a high rate of sweat production from all the four sites measured (chest, back, forearm and thigh). The participant then stood for 5 minutes post-exercise after which the participant then exercised again for a further 15 minutes. The participant then sat down on a stool with the back unsupported for 5 minutes after which exercise was resumed to elevate LSR that took approximately 7 minutes. For the final 5 minutes of the protocol the participant lay down on a medical bed in a supine position. The protocol was designed so as to maximize the number of postural changes possible before the participant became greatly hyperthermic and would have to be removed from the chamber. Postures were interspersed with exercise periods to ensure a high rate of sweat production was present throughout the protocol thereby maximizing the sweating response during posture manipulations. Water (250 mL) at 38 °C was given at 20 minute intervals.

Results: $\overline{T}_b$ and LSR results are presented in the figure below.

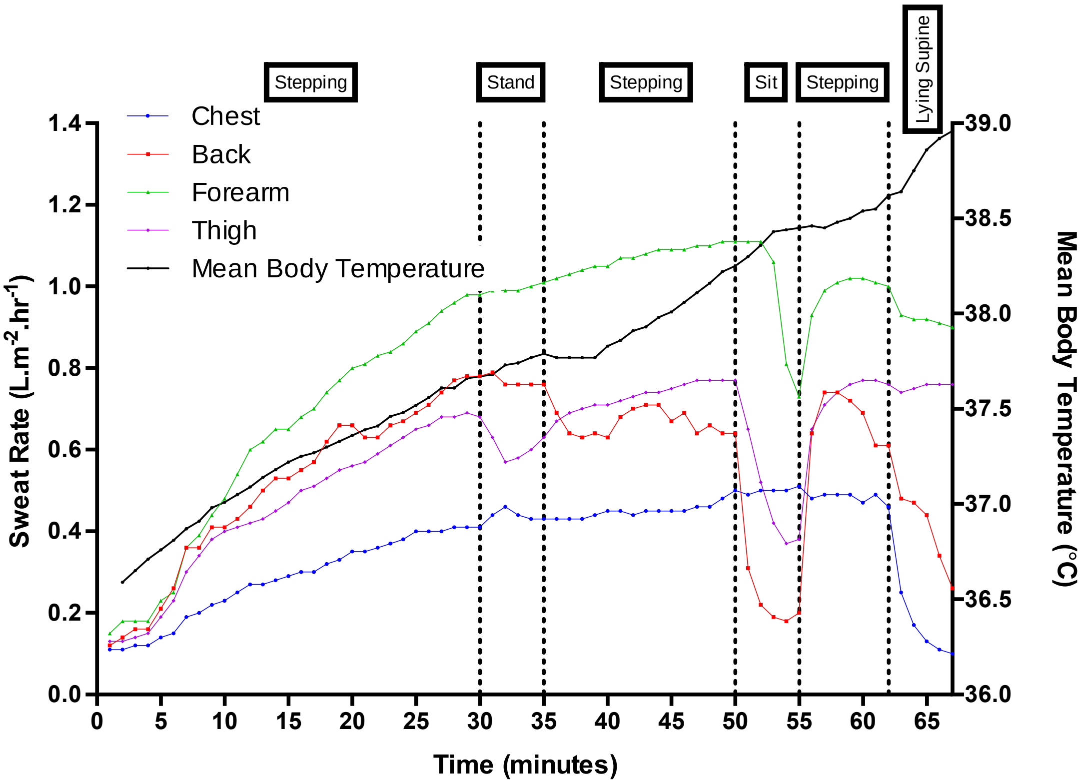

Figure 111: Mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery in various postures in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P1).

Figure 112: The participant standing post-exercise dressed in military chemical protective clothing without the respirator and hood.

Discussion: Figure 111 illustrates that throughout the entire protocol, the participant did not cool even when exercise was ceased, and therefore any change to the pattern of the sweating response was most likely a result of either activity or posture manipulation, or indeed an increased $\overline{T}_b$. During exercise LSR increased except for a slightly different sweat response pattern between 35 and 50 minutes at the back where LSR decreased and then remained largely unchanged. This response was most likely due to sweat capsule movement as a result of not being secured tightly enough. Nonetheless, it was noticed that there appeared to be a sweat reflex such that within minutes of a postural change (sitting or lying supine), LSR was reduced at most sites. Interestingly, during sitting regional differences in LSR were identified such that the sweat rate at all sites decreased except the chest where LSR remained unchanged, mimicking the results from the third study (Chapter 6, Figure 48). Furthermore, LSR at the torso appeared to be reduced more than the forearm or thigh during the supine posture.

Aim: As the second experiment interspersed postural changes with exercise periods to ensure a high rate of sweat production was present throughout the protocol, it was still not entirely clear the contribution of exercise *vs*. posture to the sweating response. Therefore a third experiment was conducted which involved the same participant (P1) completing a protocol whereby a series of postural manipulations were interspersed with only two exercise periods.

Method: The Pinsent environmental chamber was set to the same air conditions (40.0 °C and 40 % rh) as the first and second experiments. The participant came into the laboratory on only one occasion and was instrumented in the exact way as the first and second experiments. The participant wore the CBRN suit (hood down), t-shirt, combat boots, socks, overboots and gloves. After instrumentation and donning of equipment, the participant was then escorted into the chamber and began to exercise (stepping to a height of 22.5 cm at a rate of 12 steps.min^{-1}) to significantly elevate LSR for 22 minutes. The duration of exercise and subsequent postures was not fixed before the test, but rather were undertaken on an *ad hoc* basis as a preliminary attempt to investigate the effect of posture on LSR. After exercise the participant then undertook a variety of posture manipulations for the next 18 minutes. These included standing (2 minutes), sitting (6 minutes), standing (5 minutes) and sitting (5 minutes). After the posture manipulations the participant then completed an isometric contraction for 1 minute. This involved the participant attempting to raise his legs as a force was applied from above to match the participant's force therefore permitting no movement to occur whilst muscle activation was present. After the isometric contraction the participant sat for 5 minutes while the LSR pattern was monitored, before exercising for a further 8 minutes to elevate LSR again. Post-exercise, another series of posture manipulations were undertaken which involved the following postures of varied durations depending on the speed of the observed sweat response: sitting on a medical bed with the torso supported in the tilt-up position (6 minutes), sitting with the back supported and the legs perpendicular (5 minutes), sitting with the back supported and the legs horizontal (4 minutes), sitting with the back supported and the legs perpendicular (3 minutes), lying down supine (5 minutes), lying supine with the legs elevated (3 minutes) and lying supine with the forearm raised and supported (5 minutes). Water (250 mL) at 38 °C was given at approximately 20 minute intervals.

Results: $\overline{T}_b$ and LSR results are presented in the figure below.

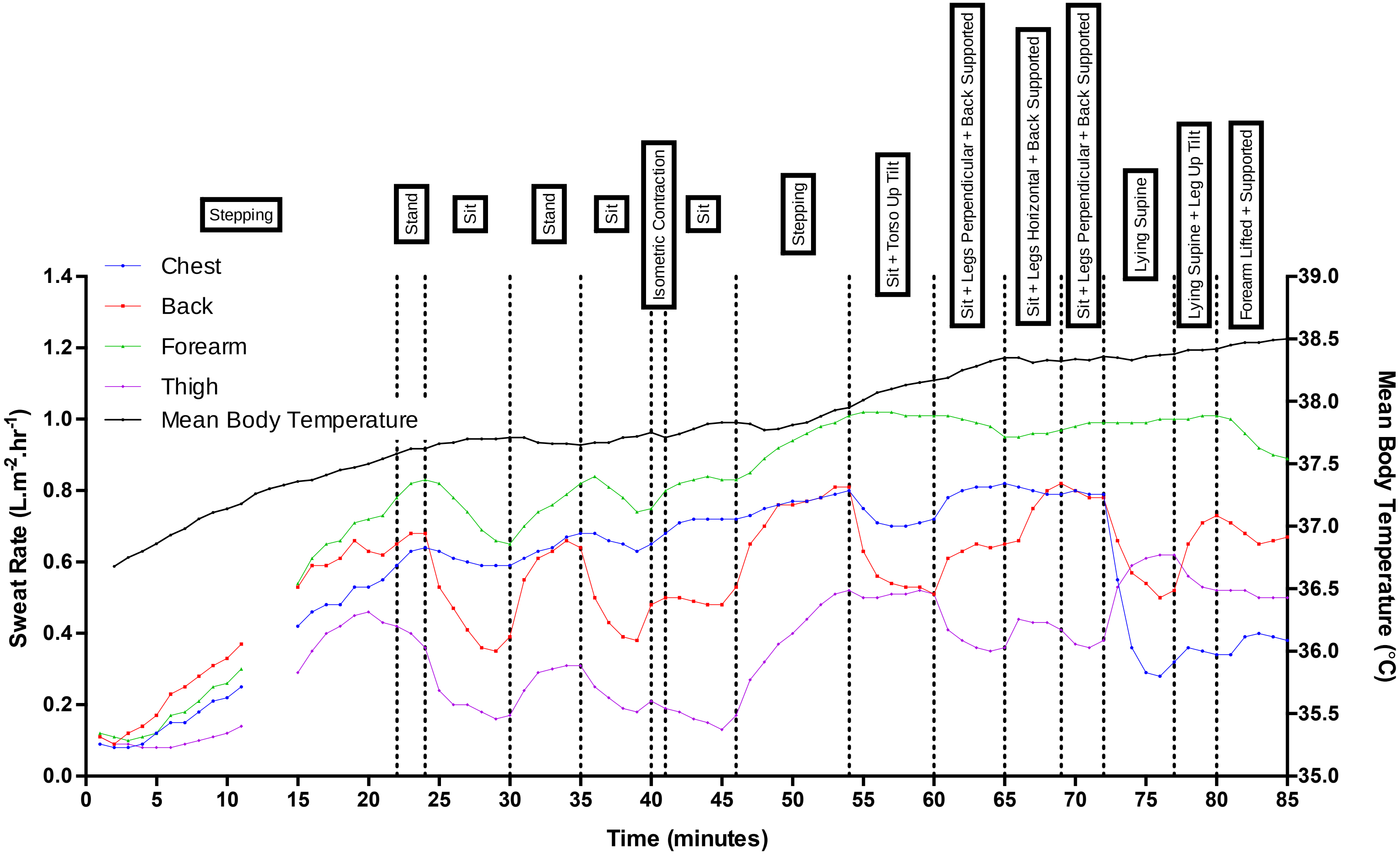

Figure 113: Mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P1).

Note that LSR data is missing from 12 to 15 minutes due to a software crash.

Discussion: Figure 113 illustrates that the participant did not cool throughout the entire protocol and therefore any reduction in the sweating response was not a product of a decreasing thermal status as the protocol progressed, but instead was most likely a product of exercise and / or postural manipulation. The sweat responses as illustrated in Figure 113 showed that posture exerted a larger influence on the sweating response and regional differences between sites were again identified. Adopting a standing posture “reset” LSR to a similar rate of sweat production that was observed during exercise. This was an important observation for future methodologies as a standing posture could be used to reset LSR without having to resume exercise, which also resets LSR but also increases the rate of rise of T_c, the standing method thereby allows for a greater amount of postural manipulations before participants develop a pronounced hyperthermia (T_{re} of 39.0 °C).

Kondo *et al*. (1999) showed that during IHG exercises in warm conditions when blood flow to the forearm was occluded at the end of the IHG exercise to stimulate only the muscle metaboreceptors, forearm sweat rate increased independently of T_{sk} and T_{oe}. The absence of occlusion after the isometric contraction in our experiment was a methodological limitation and should be present in future protocols involving isometric contractions to isolate the contribution of metaboreceptors on the sweating response. As the contraction in this experiment only lasted 1 minute, conclusions drawn from the results should be taken with caution, particularly as the test was conducted on only one participant, as was the case for most of the pilot work to this point. The data showed that LSR increased at all sites except the thigh (the muscle predominantly affected by the isometric contraction) where sweat rate first increased and then decreased approximately 30 seconds into the contraction. This result suggested that muscle activation in the absence of movement initially caused an elevated sweating response. As the amount of force was not directly measured although the participant was encouraged to continue a steady force production throughout the minute, it could not be confirmed that force production at the thigh did not decrease during the second half of the contraction, which might have been responsible for the decline in LSR at the thigh. Therefore although conclusive results were not possible, perhaps central drive and / or muscle metaboreceptor stimulation in response to the contraction caused an increased sweating response and that sweat rate at the thigh diminished half way through the contraction due to metabolite clearance and possible decreased force production. However without occlusion of blood flow and direct measurement of force production, this remained speculative.

The final activity of raising the forearm was an attempt to induce a response to the forearm LSR as the site appeared to be largely unaffected by any other posture from about 55 minutes into the protocol. The results highlighted that raising and supporting the forearm decreased forearm LSR. This again provided preliminary evidence that non-thermoregulatory components could modulate the sweat reflex. Furthermore, Ogawa *et al*. (1992) explored the rate of sweat production at the forearm when the limb was passively elevated and found that blood flow to the limb was reduced upon elevation. A reduced circulation to the limb resulted in hypoxia of forearm tissues and thereby decreased the release of transmitters at the neuroglandular junction causing a reduced sweat output at the forearm.

Aim: As the first three experiments were all conducted on one participant, it was important to assess whether similar LSR responses were observed in other participants when posture was manipulated. Therefore the fourth experiment involved measuring LSR responses of five participants during postural manipulations.

Method: Two of the participants were female. Although not measured, the self-reported fitness level of the participants varied from an average fitness to very fit. The Pinsent environmental chamber was set to the same air conditions (40.0 °C and 40 % rh) as the first three experiments. The participants came into the laboratory on only one occasion and were instrumented in the exact way as the participant in the first three studies. Three participants were also instrumented with aural thermistors (General Methods: Section 3.4.2.1), the results of which are discussed in Appendix 18. The participants wore the CBRN suit (hood down), t-shirt, combat boots, socks, overboots and gloves. After instrumentation and donning of equipment, the participants were escorted into the chamber and began to exercise (stepping to a height of 22.5 cm at a rate of 12 steps.min^{-1}) for 25 minutes to elevate LSR. Post-exercise posture was manipulated in a randomized order to ensure that different postures were adopted at differing stages of hyperthermia, which might (Kondo *et al*., 2002) or might not (Gagnon *et al*., 2008) affect the magnitude of the LSR response. The postures were: sitting on a stool with the back unsupported, lying down supine, lying down prone, lying on the left and right sides (Figure 114). All postures lasted 5 minutes in duration as in the previous experiments a response was observed within the first few minutes of a postural shift, and were interspersed with standing periods of 5 minutes to reset the sweat rate. Not all participants could complete the 5-minute standing periods due to feelings of syncope. This occurred particularly toward the end of the protocol when participants were progressively becoming hyperthermic. Before starting the experiment, one participant was instrumented with a beat-to-beat blood pressure monitor (General Methods: Section 3.4.2.10) to assess for hypotension during the standing periods (Figure 115). It was noted that finger blood pressure declined upon feelings of syncope. Water (250 mL) at 38 °C was given at 20 minute intervals.

A) B)

Figure 114: A participant adopting the prone (A) and lying down on the left side (B) postures whilst wearing chemical protective clothing without the respirator and hood in 40.0 °C and 40 % rh air.

Note that this participant did not wear the right glove due to placement of the blood pressure monitor.

Figure 115: A participant instrumented with a beat-to-beat blood pressure monitoring device on the right middle finger to detect hypotension during standing whilst wearing chemical protective clothing without the respirator and hood in an environmental chamber set to 40.0 °C and 40 % rh air.

Results: The results of the fourth experiment are presented in Figures 116 to 120.

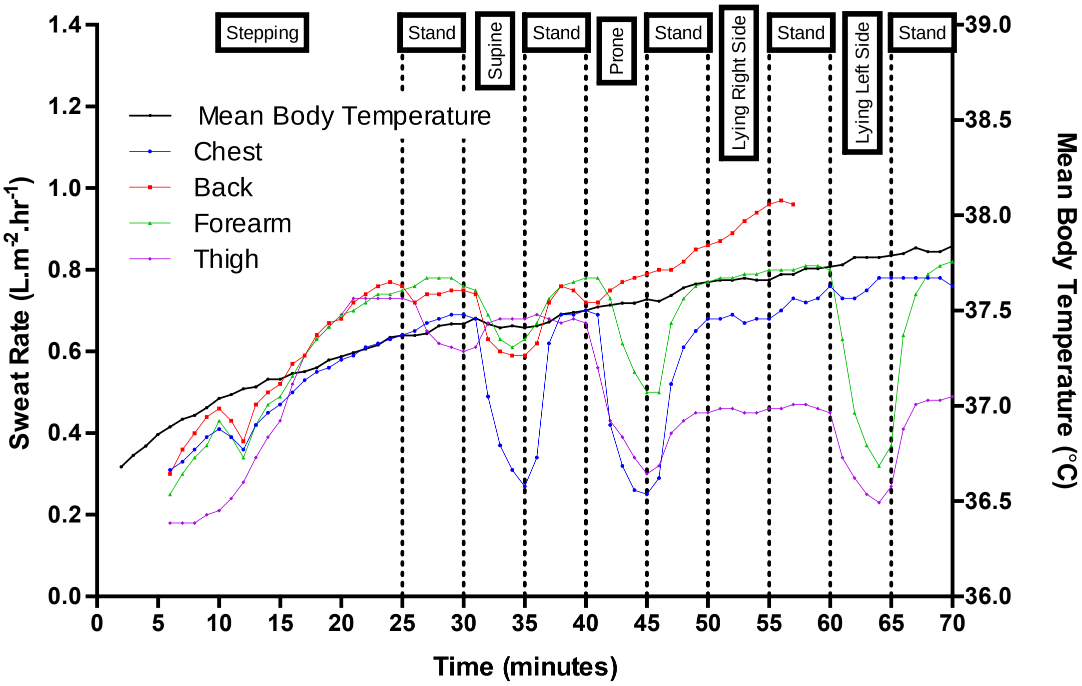

Figure 116: Individual mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P1).

Note that data is missing from the back from 58 minutes due to capsule detachment.

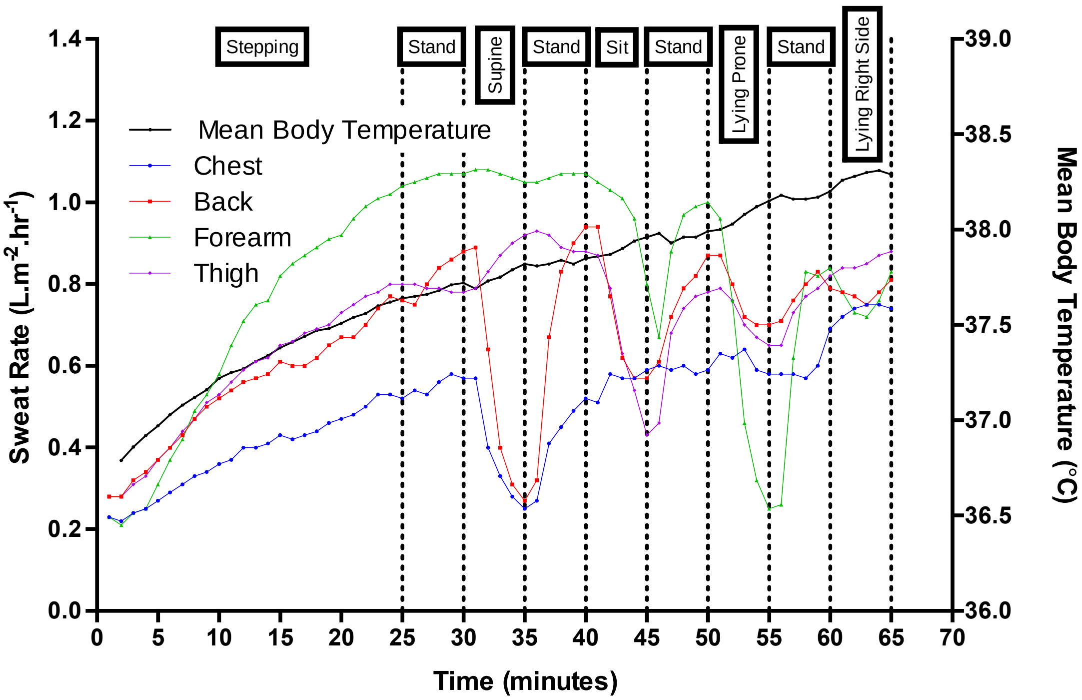

Figure 117: Individual mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P2).

Note that data is missing from 65 minutes due to a software crash.

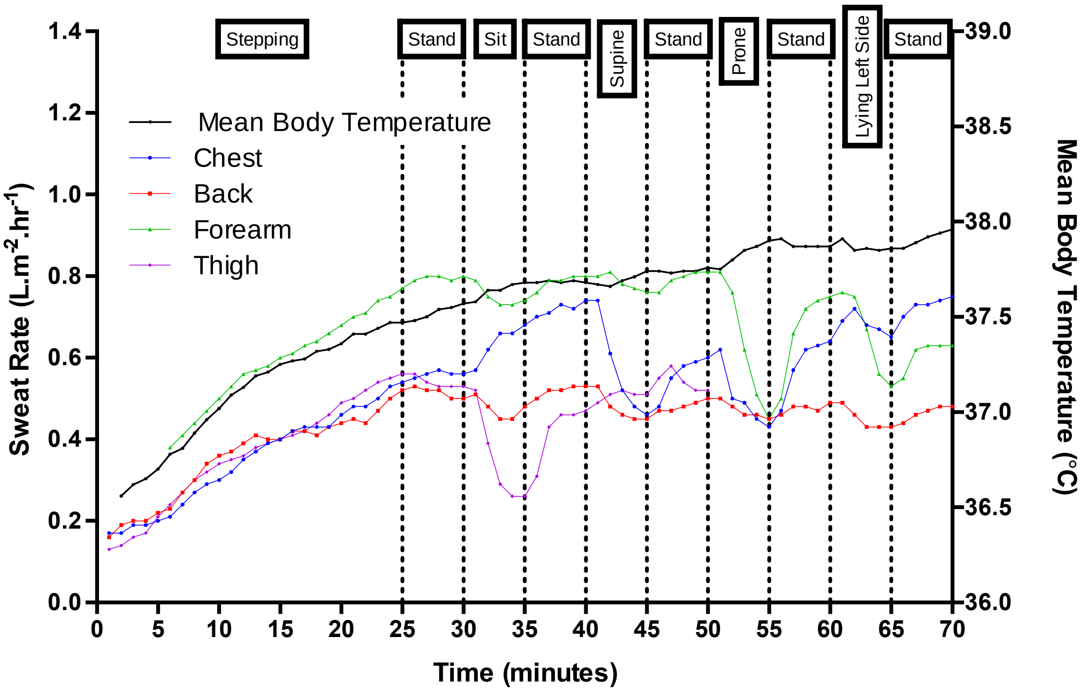

Figure 118: Individual mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P3).

Note that data is missing from the thigh from 50 minutes due to capsule detachment.

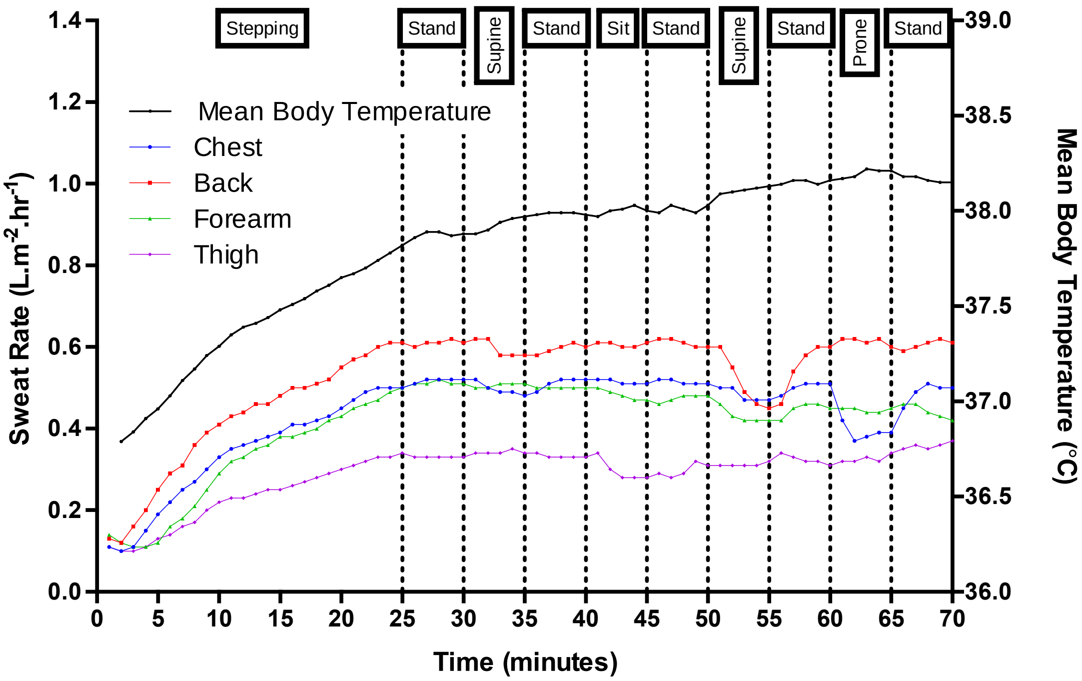

Figure 119: Individual mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P4, female).

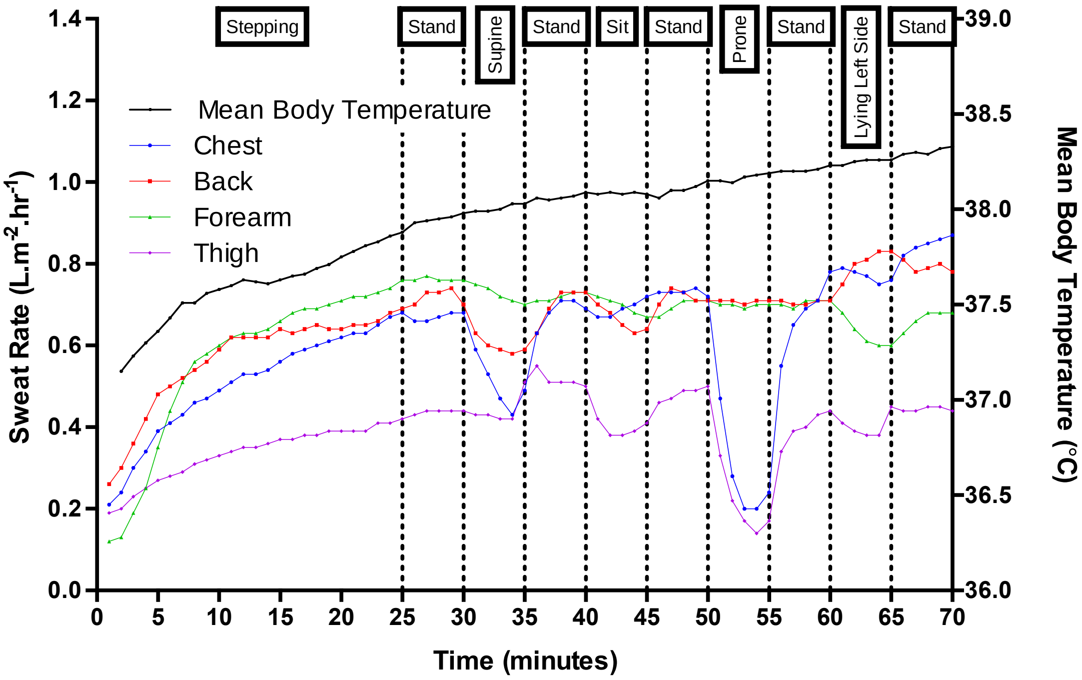

Figure 120: Individual mean body temperature and local sweat rate at the chest, back, forearm and thigh during exercise and recovery with various posture manipulations in 40.0 °C and 40 % rh air whilst wearing chemical protective clothing without the respirator and hood (n = 1, P5, female).

Discussion: In all participants $\overline{T}_b$ was higher at the end of the protocol compared to at the cessation of exercise and changed only slightly in response postural shifts. Therefore any rapid changes to the sweating response were most likely due to non-thermal factors. Similar sweat patterns were observed in all five participants, although the response was exaggerated in some participants, as have been observed in the previous experiments, such as a decline in back LSR during a supine posture, with a decline in LSR at all sites except the chest when sitting. Thus again it was highlighted that the non-thermal factor responsible for the changes to LSR was primarily postural rather than being mediated by the cessation of exercise. Moreover, the reflex appeared to be present in both male and female participants agreeing with similar conclusions on the absence of sex-related differences found by others (Gagnon *et al*., 2008).

Conclusions: The four experiments in this pilot study highlighted that posture regulated the sudomotor response more so than exercise. This was confirmed in multiple participants and was present in both males and females. The presence of regional variations in the sweating response required further investigation.

Appendix 15: Review of Literature on the Role of Skin Pressure in Reducing the Sweating Response

Inukai *et al*. (2005) investigated the effects of posture on sweating for minimally clothed participants in an environment set to 40 °C and 40 % rh air and found that altering posture by either sitting on one day or lying supine on a separate day significantly affected the rate of sweat production. When sitting, the rate of sweat production was increased at the forearm and chest compared when supine, whereas the rate of sweat production at the thigh was reduced during sitting compared to supine. The authors speculated as to possible mechanisms responsible for the heterogeneous sweat responses and suggested that the mechanism arose in the brain and / or spinal region in association with increased skin pressure. It appeared that when skin pressure was increased close to a sweat sampling area, sweat rate was reduced. For example sitting, the skin pressure was increased at the soles and buttocks and the back of the thigh, which the authors stated resulted in a decreased sweat rate at the thigh. Whilst there was an increased LSR at other areas not in the vicinity of the skin pressure site such as the forearm and chest. Similarly, LSR at the forearm and chest were reduced supine whereby skin pressure was primarily applied to the back of the chest and the back of the forearm.

It was important to note that Inukai *et al*. (2005) did not directly measure skin pressure at the sweat sampling site and therefore the assumptions remained speculative. It was interesting however that the results from the pilot study (Appendix 14) showed similar results to those obtained by Inukai *et al*. (2005) during sitting (reduced LSR at the thigh) and lying supine (reduced LSR at the chest). Inukai *et al*. (2005) suggested that the mechanism of action might be due to blood shift during a supine posture promoting venous return and stimulating cardiopulmonary baroreceptors or a possible involvement of the vestibular system following stimulation. This was suggested in conjunction with the studies conducted by Ogawa *et al*. (1993) who identified that a change in head posture could affect brain temperature due to vestibular stimulation.

Ogawa *et al*. (1992), when assessing the regulation of sweating in a weightless environment, stated that whilst posture might exert some influence in modulating the sudomotor response, areas subjected to increased or decreased skin pressure would primarily alter LSR. This was because during immersion when pressure on the skin was largely uniform and the effects of gravity on circulation were minimal, sweat responses were different to when sitting that applied pressure to the buttocks or during a 6° head-down tilt posture and pressure was applied to the scapular region. The results of the experiment were questionable however; as the sweat capsules during immersion were protected against the water by ventilation and therefore water pressure on the precise measured area was present *albeit* minimal. Kuno (1956) first investigated the application of skin pressure on the modulation of the sweat reflex in 1934 and found that sweating was increased on the upper body when lying on one side. Kuno (1956) termed this phenomenon hemi-hydrosis. The hemi-hydrotic effect was further explored by a number of investigators for example Ogata and Ichihashi (1935) who stated that the reflex was due to vasodilatation in response to body posture; Takagi and Sakurai (1950) who asserted that the effect was due to skin pressure, and Watkins (1956) who found that sweating responses changed sporadically and questioned the validity of the previous studies.

Further evidence of the skin pressure sweat reflex can be found in the work conducted by Kawase (1952). Data from their experiment resulted in the following assertion: pressure applied to the skin on one side of the body increases sweating on the contralateral side and attenuates sweating on the ipsilateral side. Kawase (1952) also stated that different body regions might possess different thresholds to provoke a sweat reflex, which could offer some insight to the regional variations in the sweating response identified in the pilot experiments (Appendix 14). Ogawa (1979) stated that sweat was inhibited regionally in response to applied skin pressure possibly due to the interaction of somatic afferent volleys with preganglionic neurons along the sympathetic chain. Okagawa *et al*. (2003) measured SkBF, sweating and SSNA when pressure was applied to the anterior superior iliac spine in a supine posture. The results indicated that the spinal reflex due to skin pressure affected the sudomotor nerve but not the vasoconstrictor nerve as the contralateral/ipsilateral ratio of sweating was increased following skin pressure whereas SkBF appeared to be unaffected by the pressure.

Appendix 16: Study 4 – Mechanical Tests on the Q-Sweat^{TM}

Pilot 1

Background: Regional variations in the LSR response to a change in posture and / or exercise were noticed during the third study (Chapter 6, Figure 48) and during the previous pilot studies conducted (Appendix 14) for example upon sitting, LSR at the back, forearm and thigh decreased but remained elevated at the chest. As many of the proposed mechanisms of non-thermal regulation of sweating would elicit a whole body systemic response rather than a local response (Shibasaki *et al.*, 2003a), it was questioned whether the regional variations in LSR found in the third study and during the pilot studies was a true physiological response or a mechanical artifact from the experimental design or measurements. Therefore a series of mechanical tests were conducted and are presented below, that authenticated the response time and validity of the equipment (Q-Sweat^{TM}) when changing the humidity or orientation such as could be present when changing posture or level of activity.

Aim: The aim of the first pilot experiment was to mechanically manipulate the sweat capsule to determine the response time of the Q-Sweat^{TM} to a changing humidity that was independent of any physiological mechanisms such as a declining $\overline{T}_b$ that could alter LSR.

Method: The mechanical experiment was conducted at an ambient temperature of approximately 24 °C. The Q-Sweat^{TM} was switched on 15 minutes before experimentation began in accordance with the manufacturer's instructions[21]. One sweat capsule was docked in a clean and dry docking chamber for 1 minute that was made dry by blowing compressed air at the chamber. The capsule was then transferred to a separate docking chamber for 24 minutes to which 5 µL of dH_2O had been added using a pipette (F123600, Pipetman Classis P20, Gilson, UK) (wet chamber) as per the manufacturer's calibration guidelines and service manual[22]. The capsule was then intermittently moved between the dry and wet docking chambers as per the timeline below:

[21] Q-Sweat Hardware User's Guide, Version 1.4. Quantitative Sweat Measurement System, Model 1.0. WR Medical Electronics Co. 2001-2007

[22] Q-Sweat Service Manual, Revised 5/19/15. WR Medical Electronics Co. 2015

Figure 121: Timeline of the movement of the sweat capsule between the dry and wet docking chambers.

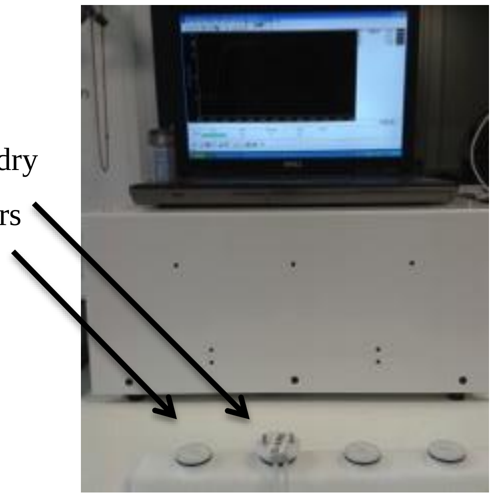

Figure 122: The set-up for assessing the response time of the Q-Sweat™ and sweat capsules.

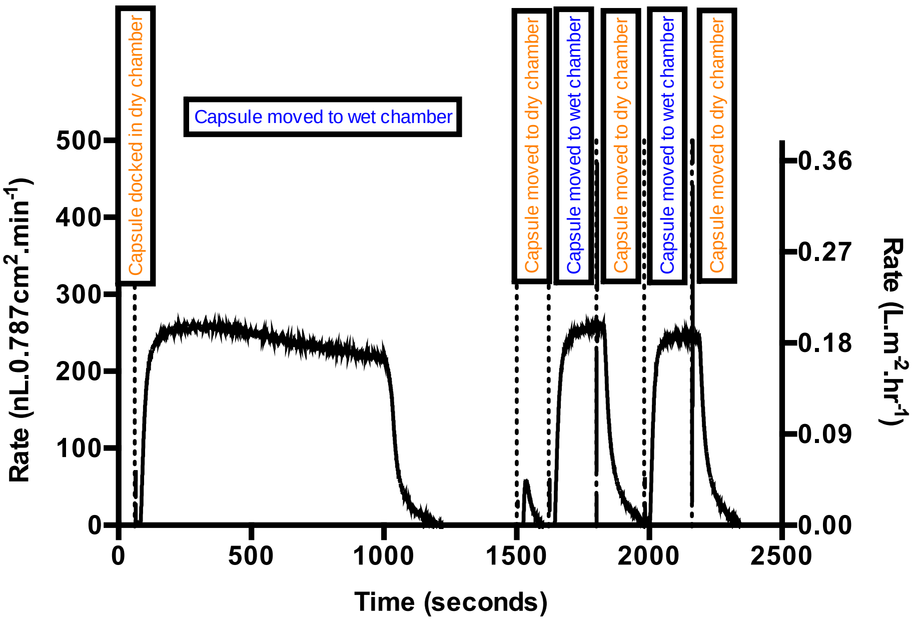

Figure 123: The entire test protocol showing the response time of a single sweat capsule placed over docking chambers set at either high (wet chamber) or low (dry chamber) humidity.

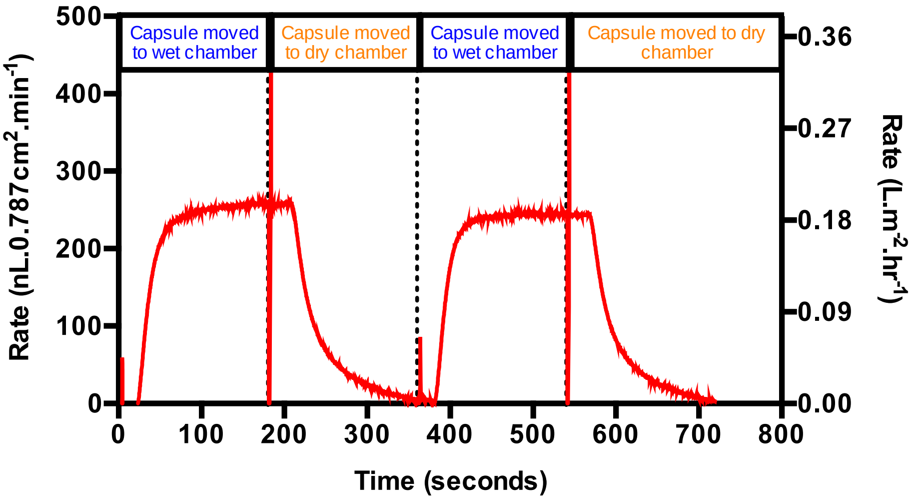

Figure 124: Response time of a single sweat capsule placed over docking chambers set at either high (wet chamber) or low (dry chamber) humidity.

Results: Figure 124 displayed the response time of the Q-Sweat™ when moved between the wet and dry docking chambers. It took approximately 20 minutes for the 5 µL of dH_2O to be completely evaporated by the Q-Sweat™ (Figure 123). The sharp decline observed at 1020 seconds was most likely caused by the dry air from the Q-Sweat™ being passed through the chamber at a set flow rate of 60 standard cubic centimeters per minute (SCCM) equating to 0.06 $L.min^{-1}$. Therefore, in a high humidity environment, the maximum amount of water vapour would be evaporated each time dry air was passed into the chamber. It is possible that when the 5 µL of dH_2O had evaporated completely, there was no water vapour left to evaporate when the next bolus of air was passed into the chamber thereby creating a sharp decline in the sweat rate trace (Figure 123). When moving from a dry to wet docking chamber the response time for the sweat capsule to detect a change in humidity was less than 1 minute, approximately 30 seconds (Figure 124). The same timing of response, approximately 30 seconds, was observed when moving the capsule from a wet to dry docking chamber (Figure 124).

Conclusion: Figure 124 shows that when the capsule was moved between dry and wet chambers and the response time was approximately 30 seconds. These results were more reflective of physiological responses compared to the Q-Sweat™ completely evaporating 5 µL of dH_2O immediately after being in a completely dry environment (Figure 123), particularly when recalling that the Q-Sweat™ provides a constant and dry airflow over the skin over which the capsule is placed. Therefore it is highly unlikely that under physiological conditions with the Q-Sweat™ continually passing dried air over the skin; that a volume of 5 µL of sweat could accumulate under the capsule, instead, sweat would be continually evaporated in the form of water vapour from the skin surface. Furthermore, the docking chamber had a volume that was greater, and therefore would take longer to evaporate water vapour, compared to the volume between the sweat capsule and the skin when secured to the participant. Therefore it was predicted that the response time observed in the above experiment might actually be an overestimated response as to that which would occur under physiological conditions.

To conclude, the mechanical test suggested that the sweat capsules displayed a quick response time to a changing humidity, approximately 30 seconds, and therefore the rapid decline in sweat rate observed upon a change in posture might reflect a true physiological response.

Pilot 2

Aim: The aim of the second pilot experiment was to mechanically manipulate the orientation of the sweat capsule to determine whether this alone affected the Q-Sweat™ measurement independent of any physiological mechanism.

Method: The mechanical experiments were conducted at an ambient temperature of approximately 24 °C. In accordance with the manufacturer's instructions[9], the Q-Sweat™ was switched on 15 minutes before the experiment began. One sweat capsule was docked in a chamber containing a sponge with 15 μL of dH_2O at a horizontal orientation (0°) for 5 minutes. The orientation of the capsule was then manipulated for a further 22 minutes as shown in the timeline below (Figure 125).

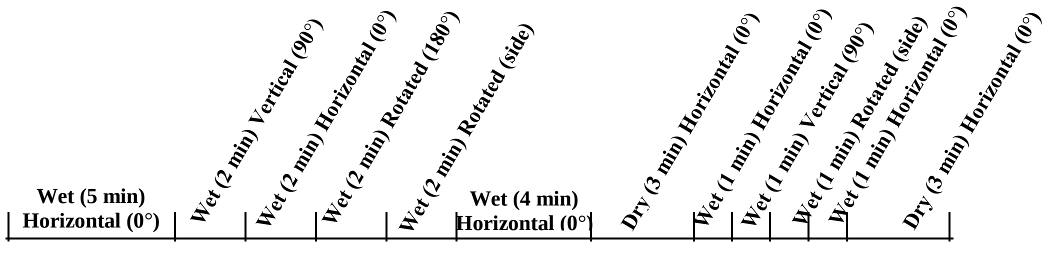

Figure 125: Timeline of the change in orientation of the sweat capsule.

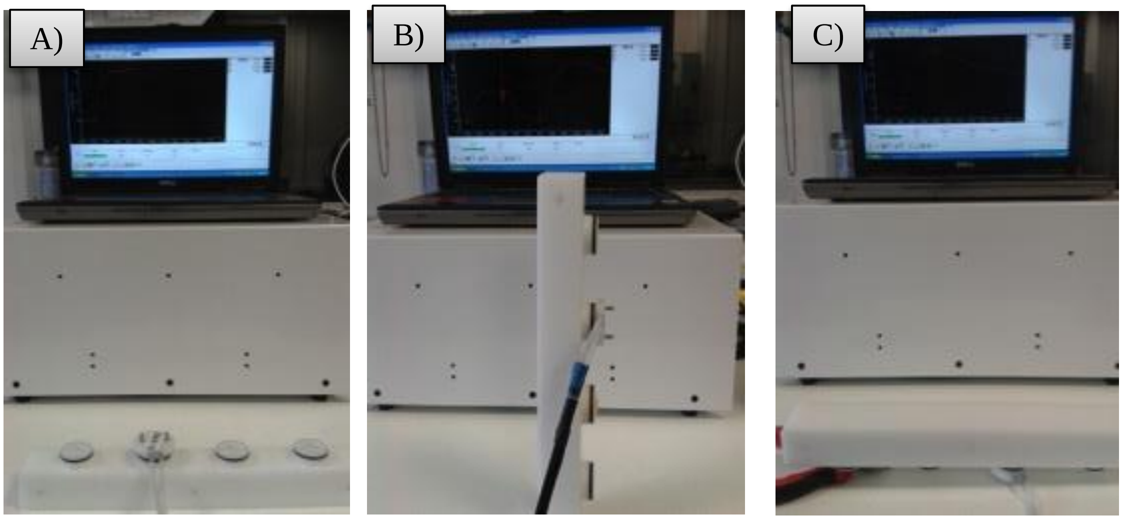

Figure 126: The orientation of the sweat capsule when docked in a wet chamber: A) horizontal orientation (0°) B) vertical orientation (90°) C) rotated by 180°.

Results: The rate of water vapour clearance and response time of the Q-Sweat^{TM} is illustrated in Figure 127.

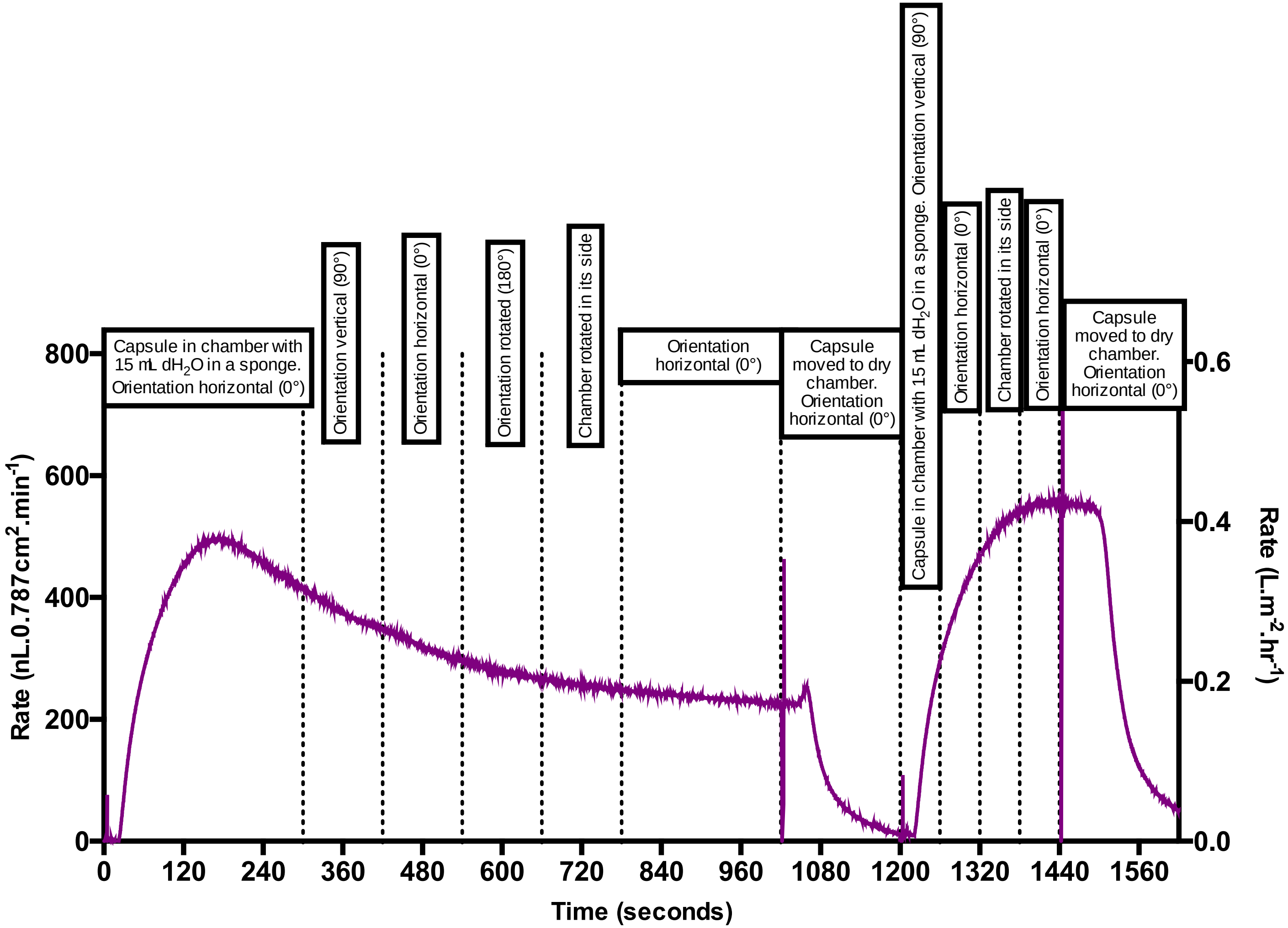

Figure 127: Water vapour clearance measured of a single sweat capsule placed over docking chambers set to varying levels of humidity and orientation.

Conclusion: The results indicated that changing the orientation of the sweat capsule did not affect either the rate of water vapour clearance (from 0 to 1020 seconds) or the rate of water vapour detection (from 1200 to 1440 seconds). Therefore it was concluded that the mechanical orientation of the sweat capsule did not affect the accurate measurement of water vapour present in the system and thus the results of the human studies were validated as a true physiological response.

Appendix 17: Study 4 – Pilot Studies Investigating the Effects of Clothing on Measurement of Sweat Rate

Pilot 1

Background: Wearing CBRN clothing could introduce a non-thermal influence on LSR by touching the skin or possibly placing pressure on the skin at certain postures. As skin pressure could modulate sweating (Kawase, 1952; Inukai *et al*., 2005) an investigation was necessary to determine whether clothing was confounding the sudomotor results from the third study (Chapter 6) and the pilot studies (Appendix 14) conducted thus far, particularly when regional variations in LSR were identified.

The Q-Sweat™ was used to measure sweat rate at the four sites (as in our previous experiments) and works through combining the partial water vapour pressure detected by sensors, with the Ideal Gas Law (taking into account the pressure, volume, amount, temperature and ideal gas constant) to estimate the quantity of evaporated water[9]. The Q-Sweat™ is designed for clinical estimations of the severity of autonomic disorders that modify the normal sudomotor response and as such is calibrated up to 1000 $nL.cm^{-2}.min^{-1}$ (0.76 $L.m^{-2}.hr^{-1}$) with a 5 % accuracy and reproducibility[9]. Recordings can be obtained past 1000 $nL.cm^{-2}.min^{-1}$ and values up to 1300 $nL.cm^{-2}.min^{-1}$ have been obtained in our laboratory however there is no indication of any calibration to this level or linearity of the response above 1000 $nL.cm^{-2}.min^{-1}$. When wearing CBRN clothing in the third study, the maximal average LSR at the chest during exercise reached approximately 0.65 $L.m^{-2}.hr^{-1}$, which was 85 % of the maximum range that the system is calibrated to. Therefore, although the system specifications suggest that the recordings were within the calibrated range of functioning, it was fundamental to rule out the possibility of a plateau in LSR due to inaccurate estimations or slow clearance of sweat from the Q-Sweat™ tubes. Furthermore, it was possible that due to the position of certain postures the CBRN clothing might have been applying extra pressure onto the skin or surface of the sweat capsule which could have affected accurate sampling of sweat rate *e.g.* LSR at the back when sitting leaning forward with forearms on the knees (pulling the clothing close against the back but with no contact of the clothing with the chest) *vs*. sitting upright (clothing exerting possibly zero forces on the chest and back).

Aim: The aim of the first pilot study was to determine whether the LSR patterns observed in the third study (Chapter 6) and pilot experiments (Appendix 14) that indicated regional variations in the sudomotor response were due to the non-thermal confounding effects of the CBRN clothing such as touching the skin or placing pressure on the skin during certain postures.

Method: The Pinsent environmental chamber conditions were set to 40.5 °C and 20 % rh air. The volunteer participant (female, 27 years, 172 cm, 59.53 kg) was dressed in shorts, t-shirt and trainers and was instrumented with a heart rate monitor, a rectal thermistor and four skin surface thermistors to estimate $\overline{T}_{sk}$ (Ramanathan, 1964). Sweat capsules were attached to the chest and back while a further two sweat capsules were clamped to a bench to read baseline measures in the environmental chamber (Figure 128). The participant entered into the chamber and was passively heated while seated for 30 minutes to ensure all clothes were heat soaked and the sweating response was initiated. The participant then stepped continuously to a height of 22.5 cm at a rate of 18 steps.min^{-1} for 30 minutes followed by a further 30 minutes of stepping at a faster rate of 20 steps.min^{-1}. The chamber's ambient temperature was then increased to a target of 50 °C to increase the thermal load placed on the participant while the participant continued to step at a rate of 20 steps.min^{-1} for a final 30 minutes. This protocol was an attempt to induce maximal sweating so that if sweat was building up in the Q-Sweat™ system due to a high LSR and saturating the capsules or tubes, then when the capsules that were on the participant were replaced with the clamped capsules, the true sweat rate would be identified. After the exercise bout, the participant then recovered seated for 40 minutes in the chamber. After 10 minutes into the post-exercise recovery period, the sweat capsules attached to the chest and back were removed and replaced with the clamped capsules. After 20 minutes, the original sweat capsules were repositioned back onto the chest and back for a final 10 minutes.

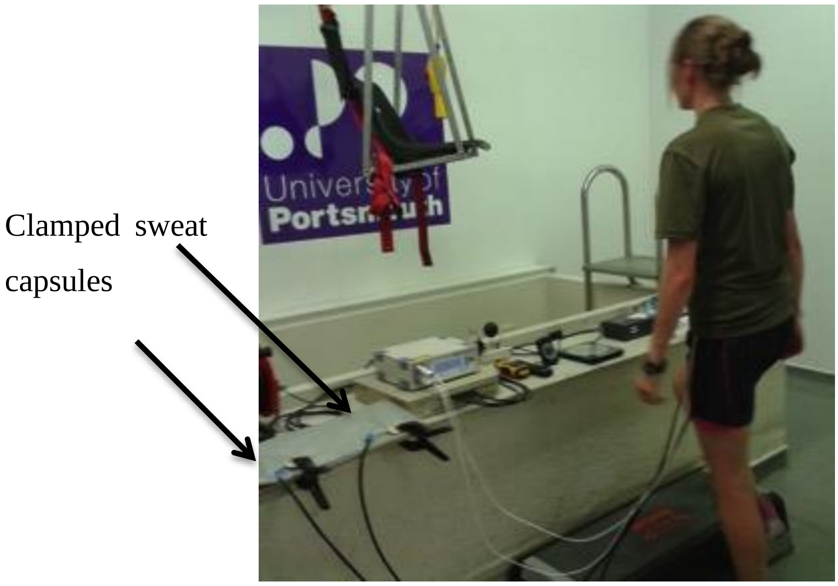

Figure 128: Participant stepping in 40.5 °C and 20 % rh air instrumented with sweat capsules at the chest and back while two sweat capsules (bottom left of the picture) remained clamped at baseline measuring environmental humidity that equated to a rate of 0.07 $L.m^{-2}.hr^{-1}$.

Results: $\overline{T}_b$, environmental chamber conditions and sweat data are illustrated in the figures below.

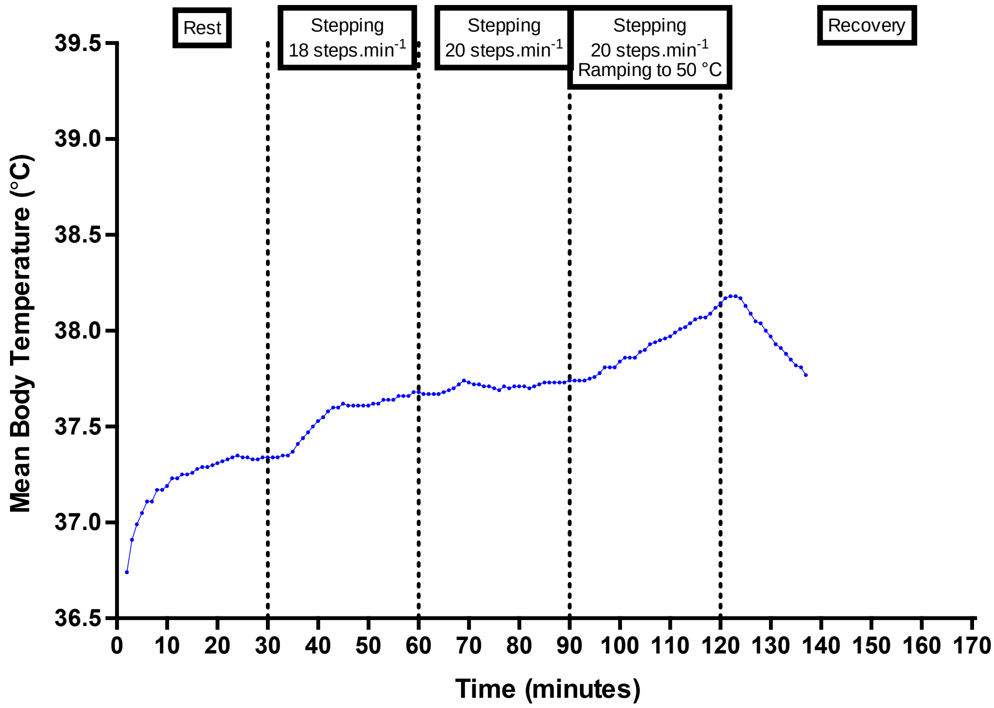

Figure 129: Mean body temperature during rest, exercise and recovery in 40.5 °C and 20 % rh air whilst wearing shorts, T-shirt and trainers (n = 1).

Note that data is missing from 136 minutes due to a software crash.

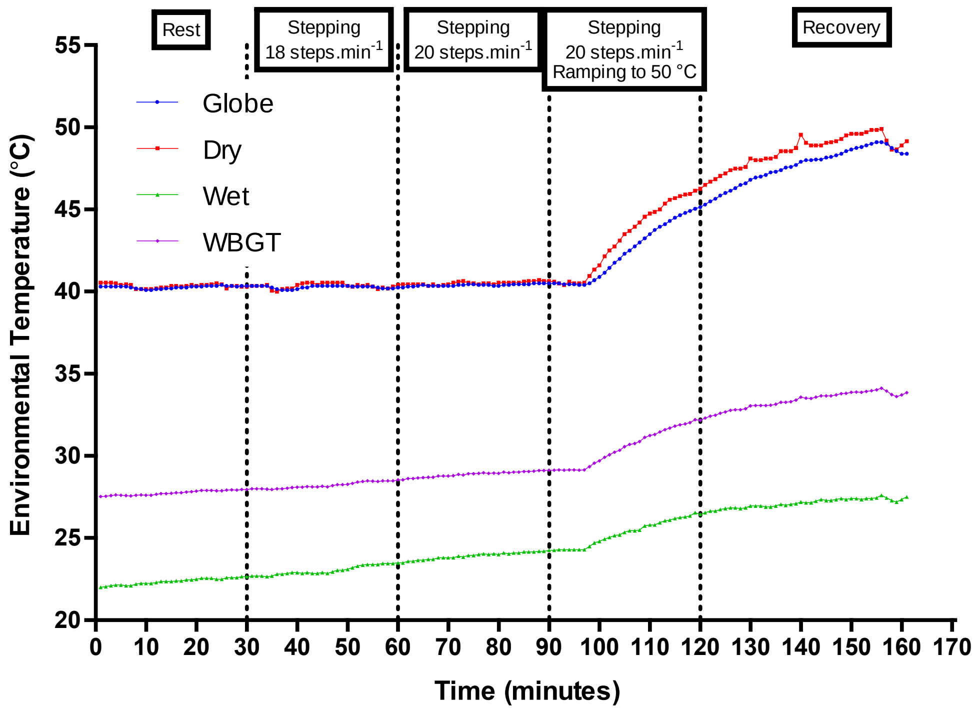

Figure 130: Wet-bulb globe temperature of Pinsent environmental chamber during rest, exercise and recovery.

Figures 131 and 132 illustrate LSR at the chest and back throughout the test and during the recovery period only.

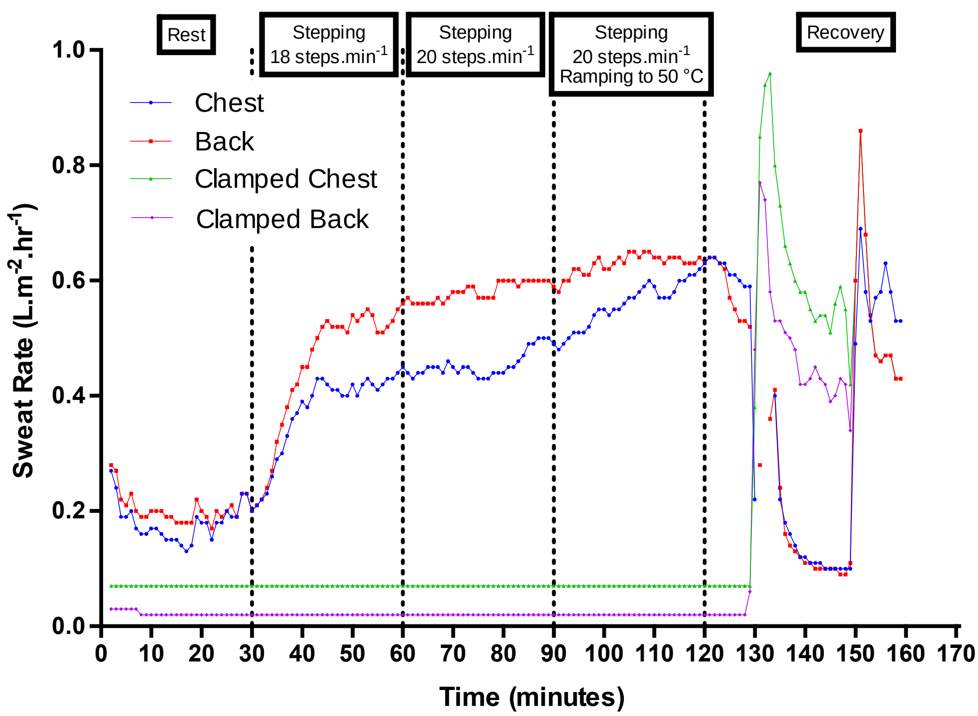

Figure 131: Sweat rate at the chest and back during rest, exercise and recovery in a 40.5 °C and 20 % rh air whilst wearing shorts, T-shirt and trainers (n = 1).

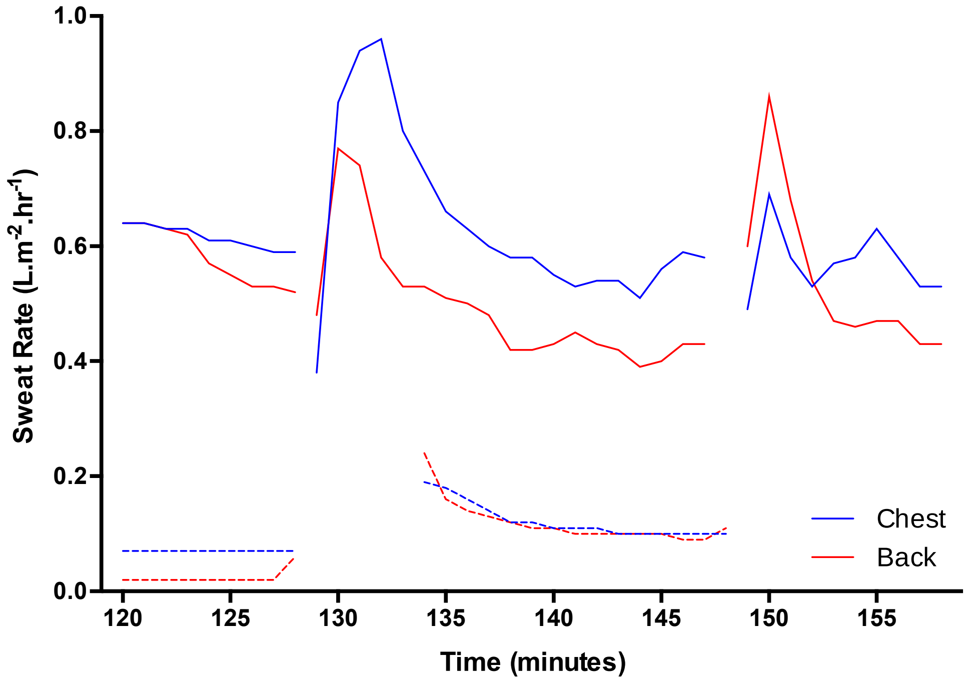

Figure 132: Sweat rate at the chest and back during seated recovery only (final 40 minutes) in 40.5 °C and 20 % rh air whilst wearing shorts, T-shirt and trainers (n = 1).

Note that when the capsule was placed on the body the line is solid and when the capsule was clamped the line is dashed.

Discussion: The sweat responses at the chest and back followed a similar pattern in that at both sites LSR decreased on sitting. This was unlike the response obtained during the third study and pilot studies when CBRN clothing was worn, whereby LSR at the chest remained elevated on sitting yet decreased at the back. Indeed $\overline{T}_b$ did fall upon the cessation of exercise in this experiment unlike the third study when $\overline{T}_b$ remained elevated however what was most interesting was that the chest and back responded uniformly when CBRN clothing was not worn (current experiment). Therefore it was thought that the CBRN clothing was exerting some influence on LSR. Additionally, when the original chest sweat capsule (blue line) was replaced with the clamped chest sweat capsule (dashed blue line) LSR at the chest followed on the similar trend. Moreover when the original chest sweat capsule (blue line) was removed and clamped, the trace decreased rapidly to baseline thereby indicating the absence of a build-up of sweat in the sweat capsule. The same trend was noticed when the original back sweat capsule (red line) was replaced with the clamped back sweat capsule (red dashed line). Repositioning of the original sweat capsules at the chest (blue) and back (red) during the final ten minutes showed the LSR returned to reading similar values to the previously clamped capsules.

Conclusions: As both LSR at the chest and back displayed homogenous sweat responses when sitting post-exercise when no CBRN clothing was worn (current experiment) compared to heterogeneous responses when CBRN clothing was worn during post-exercise sitting (previous pilot experiments and the third study), it was possible that the CBRN clothing could have been exerting some influence on LSR in the previous experiments and the third study. Also, when the clamped capsules were positioned on the chest and back post-exercise, the response trace followed on from the original sweat capsule's response suggesting the original capsules were measuring a true real-time sweat response post-exercise. In addition, when the original capsules were removed from the participant, there was an immediate and rapid decline in the measured sweat rate again representing the absence of a sweat build-up.

In the current study, maximal sweat production was over 0.61 $L.m^{-2}.hr^{-1}$, which was similar to the average response seen in the third study (0.65 $L.m^{-2}.hr^{-1}$) and falls within the Q-Sweat's^{TM} calibrated range (up to 0.76 $L.m^{-2}.hr^{-1}$). In retrospect, it might have been advantageous to elicit a higher LSR by changing the mode of activity to cycling where there is a higher workload compared to stepping or increasing environmental humidity to increase the thermal load on the participant and attenuate the rate of cooling post-exercise thereby maintaining a large driver for continued sweat production post-exercise in the absence of wearing CB clothing.

Pilot 2

Aim: The aim of the second pilot study was to again to try and indicate whether the regional variations in the sweating response observed in the third study and pilot experiments were due to pressure applied directly to the sweat capsule (Part A) or the confounding effects of CBRN clothing (Part B) when a variety of posture manipulations were undertaken.

Method Part A: The Pinsent environmental chamber conditions were set to 40.5 °C and 40 % rh air. The participant was dressed in a CBRN protective suit with butyl gloves and four sweat capsules were attached to the chest, back, forearm and thigh. The participant entered into the chamber and stepped to a height of 22.5 cm at a rate of 14 $steps.min^{-1}$ for 25 minutes to elevate $\overline{T}_b$ and stimulate the sweating response. The participant then adopted a series of postures interspersed with stepping periods to elevate LSR. Toward the end of the protocol the participant lay down supine and pressure was applied to the thigh capsule. The participant then lay down prone and pressure was applied to the back capsule.

Method Part B: The Pinsent environmental chamber conditions were set to 40.5 °C and 40 % rh air. The participant was dressed in shorts and trainers only and four sweat capsules were attached to the chest, back, forearm and thigh. The participant entered into the chamber and cycled at 60 W for 30 minutes to elevate $\overline{T}_b$ and stimulate the sweating response. The participant then sat for 5 minutes and lay down supine for 7 minutes before cycling again to elevate the sweat rate, after which the participant sat for a final 13 minutes.

Results: LSR rate at all four sites are presented in the figures below for each study.

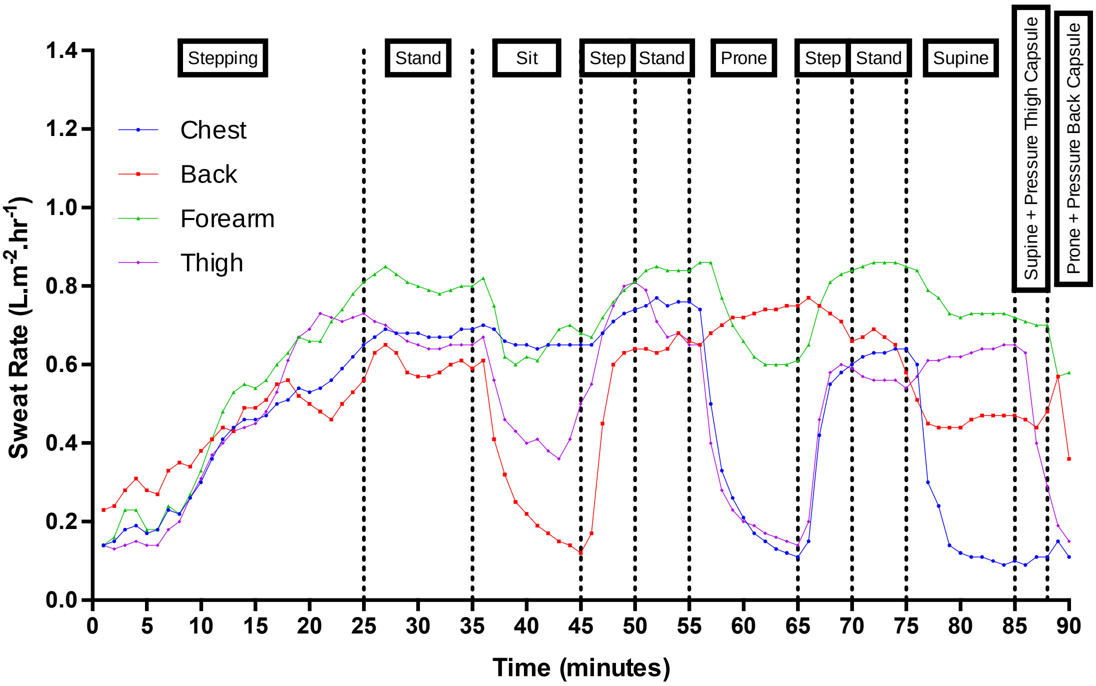

Figure 133: Sweat rate at the chest, back, forearm and thigh during exercise and posture manipulations in 40.5 °C and 40 % rh air whilst wearing a chemical protective suit and butyl gloves (n = 1).

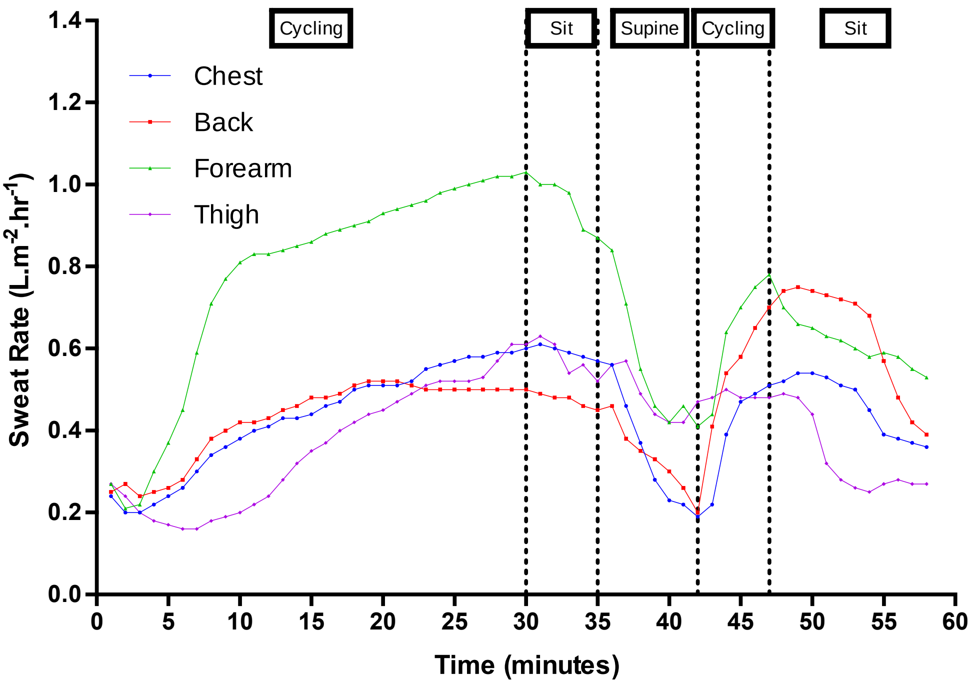

Figure 134: Sweat rate at the chest, back, forearm and thigh during exercise and posture manipulations during recovery in 40.5 °C and 40 % rh air whilst wearing shorts and trainers (n = 1).

Discussion: When wearing a CBRN suit and butyl gloves, regional variations in LSR in response to postural shifts were identified (Figure 133). Additionally, when external pressure was applied to the thigh capsule in a supine posture, LSR at the thigh decreased. When external pressure was applied to the back capsule when lying prone, LSR at the back decreased. Therefore it appeared that direct pressure on the sweat capsule might be responsible for regional variations in LSR during postural manipulations depending on if the posture adopted exerted pressure on the capsule. However, as LSR at the chest also decreased during a supine posture when no pressure, except possibly slight pressure from the CBRN suit, was exerted on the capsule; capsule pressure does not exclusively explain the LSR responses obtained. When CBRN clothing was not worn (Figure 134), LSR at all sites appeared to follow a similar pattern when posture was manipulated. For example, when lying supine, LSR at all sites decreased. Previously, when CBRN clothing was worn it was shown that when lying supine LSR decreased at the chest and back and then either remained unchanged, increased or decreased at the forearm and thigh (Appendix 14). Likewise, when sitting LSR at the chest was unchanged but decreased at the back, forearm and thigh post-exercise when wearing CBRN clothing (Chapter 6) whilst all sites responded similarly during this experiment when sitting (Figure 134). Therefore it was possible that when the LSR response varied regionally during the previous studies, that the CBRN clothing might have been exerting some influence on LSR.

Appendix 18: Pilot Study Comparing Rectal and Aural Temperature

Aim: The aim of this pilot study was to determine the extent of error of a potential lag in T_{re} compared to T_{au}.

Background: The first three studies and most of the pilot studies thus far used T_{re} as the primary measure of T_c. This was mainly due to equipment availability, the robustness of the technique and practical reasons such as wearing a respirator not comfortably allowing for measurement of T_{au} or T_{oe}. However it was important to acknowledge that there might have been a lag in the T_{re} measurement as is often reported (Ash *et al*., 1992; Greenes & Fleisher, 2004). Therefore it was possible that during periods of recovery when no exercise was present, T_c responses as measured by T_{re} might have appeared to be continually heating after the cessation of exercise but in fact could have been cooling (first and second studies). In addition, sudomotor responses as measured during the third study and pilot studies might have appeared to precede changes in T_{re}, when it is possible that the rectal probe had just not yet detected the change in T_c due to the potential lag in the T_{re} measurement. During each study an attempt to minimize the potential error associated with the lag in T_{re} was undertaken. For example, in the first three studies recovery periods were never shorter than 20 minutes. During the pilot studies however, postures were changed after 5-minute periods and therefore it could not be confirmed that the potential lag in T_{re} did not impact on the results. As T_{au} has been deemed more indicative of T_c compared to T_{re} (Cotter *et al*., 1995a; Taylor *et al*., 2014b; Todd *et al*., 2014), this pilot study was conducted which aimed at comparing the thermal profile of three participants as measured by T_{re} compared to T_{au}.

Methods: The pilot study was performed in conjunction with previous pilot experiments detailed in Appendix 14 (fourth experiment) with P3, P4 and P5 who, in addition to self-inserting a rectal thermistor, were also instrumented with an aural thermistor as shown in Figure 135. After the participant was instrumented with the aural thermistor, all other instrumentation and donning of equipment then took place as the fourth experiment detailed in Appendix 14. The aural thermistor was inserted first in an attempt to ensure the thermistor reached equilibrium in the auditory canal before starting the experiment. The participants were then instructed to complete the experimental protocol and procedures as outlined in the fourth experiment of Appendix 14.

Figure 135: Measuring core temperature using an aural thermistor. A) A participant instrumented with an aural thermistor, B) a participant stepping, C) a participant lying down supine.

Results: The T_c results are illustrated in the figures below for each of the three participants.

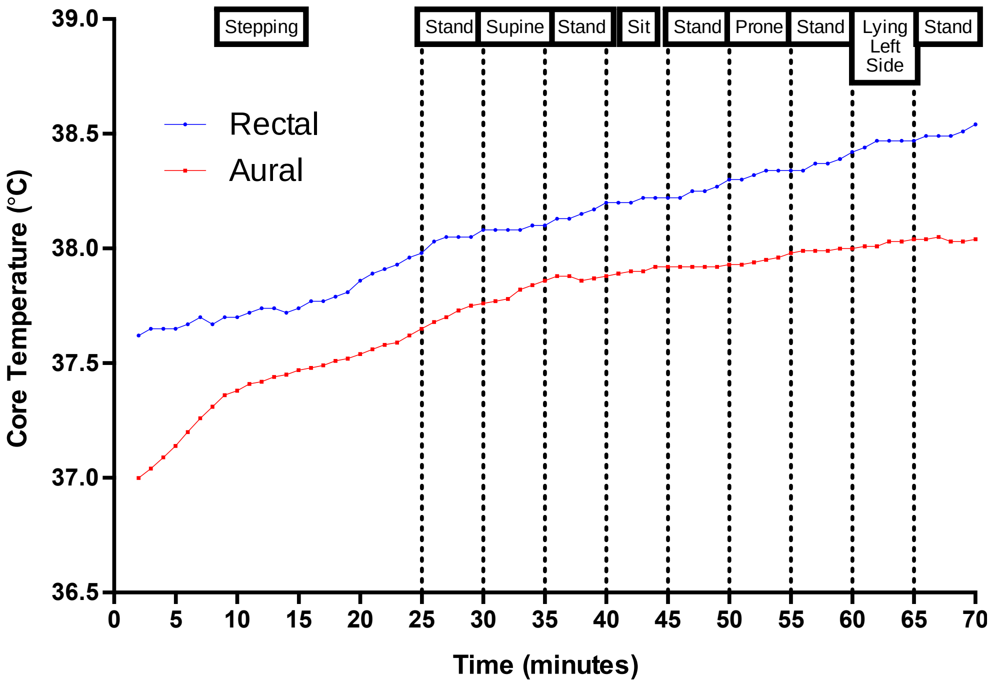

Figure 136: Individual rectal and aural temperature profiles during exercise and recovery whilst posture was manipulated when wearing chemical protective equipment without the respirator and hood 40.0 °C and 40 % rh air (n = 1, P5).

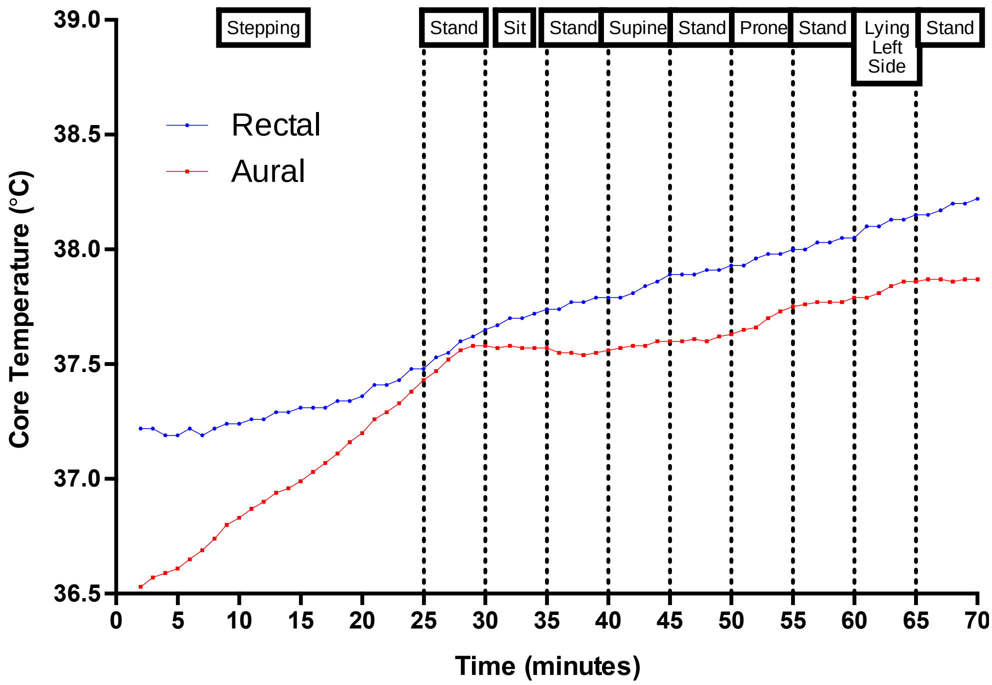

Figure 137: Individual rectal and aural temperature profiles during exercise and recovery whilst posture was manipulated when wearing chemical protective equipment without the respirator and hood 40.0 °C and 40 % rh air (n = 1, P3).

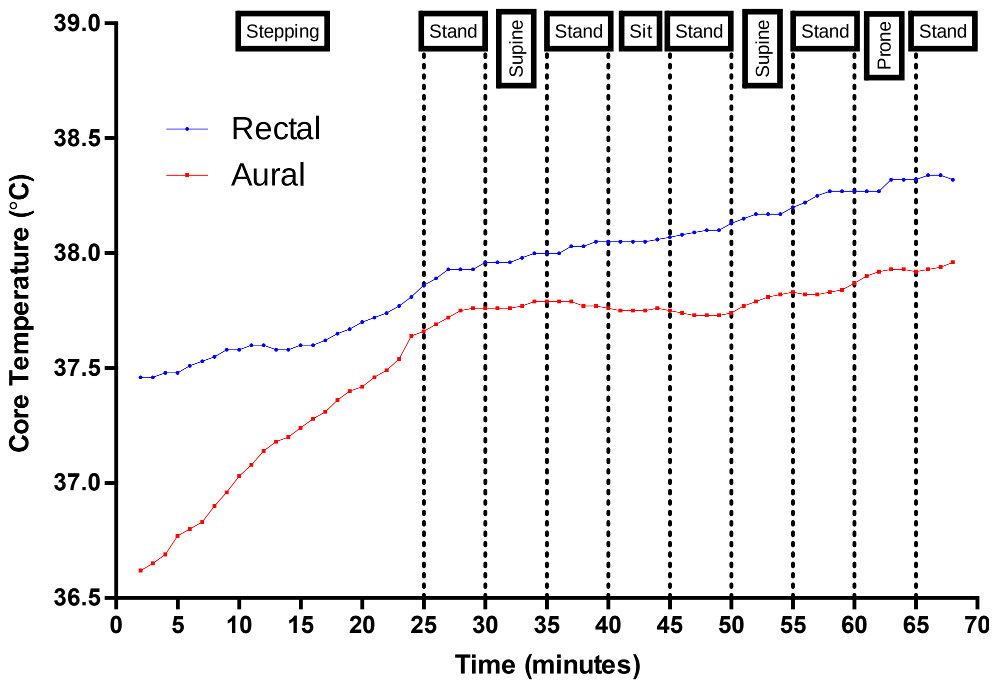

Figure 138: Individual rectal and aural temperature profiles during exercise and recovery whilst posture was manipulated when wearing chemical protective equipment without the respirator and hood 40.0 °C and 40 % rh air (n = 1, P4).

Conclusions: Whilst the T_{re} profile was always elevated compared to the T_{au} profile, the pattern of response appeared similar between the two measures. Whenever T_{re} increased so too did T_{au} except from 27 minutes to 38 minutes for P3 (Figure 137) and from 38 minutes to 49 minutes for participant P4 (Figure 138). Reasons for the opposite rates of change between T_{re} and T_{au} for P3 and P4 within those time frames were not entirely clear and it was possible that as T_{au} was falling, the time period might have been too short to be reflected in the T_{re} measurement. Speculation could be made that due to both the discrepancies occurring during the same postural change (changing from a standing position to a sitting position), that perhaps the perturbation to posture was also influencing the measure. However, as this was not apparent for participant P5 (35 minutes to 45 minutes, Figure 136) this assumption could not be confirmed. Nonetheless, the aim of this pilot study was to determine the extent of error that a potential lag in T_{re} had on estimating T_c, and as in most postures, T_{re} and T_{au} followed a similar pattern of response, the lag in T_{re} compared to T_{au} was minimal. This was most likely due to the methodological use of CBRN clothing in maintaining and elevating T_{sk} through its insulative and vapour restrictive properties. It was recommended however that in the fourth study, T_{oe} be used as a measured of T_c as no CBRN clothing was worn and therefore using an oesophageal probe would not pose a practical problem.

Appendix 19: Rating of Perceived Exertion Scale

THE RATING OF PERCIEVED EXERTION	
6	14
7 VERY VERY LIGHT	15 HEAVY
8	16
9VERY LIGHT	17 VERY HEAVY
10	18
11 LIGHT	19 VERY VERY HEAVY
12	20
13 SOMEWHAT HEAVY	

Appendix 20: Visual Analogue Scales

Thermal Sensation

0

Very Cold | Cold | Cool | Slightly Cool | Neutral | Slightly Warm | Warm | Hot | Very Hot

Thermal Comfort

0

Very Uncomfortable | Uncomfortable | Just Uncomfortable | Just Comfortable | Comfortable | Very Comfortable

Skin Wettedness

0

Very Dry | Dry | Just Damp | Damp | Very Damp | Wet | Very Wet

Ministry of Defence
Research Ethics Committee

From the Chairman
Professor Allister Vale
National Poisons Information Service (Birmingham Unit),
City Hospital, Birmingham B18 7QH

Telephone: 0121 507 4123
e-mail:allistervale@npis.org

Dr James House
Department of Sport and Exercise Science
University of Portsmouth
Spinnaker Building
Cambridge Road
Portsmouth
Hampshire PO1 2ER

Our Reference:
470/MODREC13

Date: 2 January 2014

Dear Dr House,

Thank you for submitting your revised Protocol 470 with tracked changes, and with a covering letter with responses to my own letter. The revised protocol has been approved by the Officers of MODREC ex-Committee, with a number of minor further changes shown in red. If you agree with these further minor changes please send the protocol without tracked/marked changes to the Secretariat, copied to me.

I wish you and your colleagues a successful study and we look forward to receiving in due course a brief summary of the results so that these can be filed in accordance with the arrangements under which MODREC operates.

Yours sincerely

Allister Vale

Allister Vale MD FRCP FRCPE FRCPG FFOM FAACT FBTS FBPhamacolS Hon FRCPSG

cc Dr John Scadding, Professor David Jones, Dr Paul Rice OBE, Marie Jones

Faculty of Science
University of Portsmouth

Christie Garson
Department of Sport and Exercise Science
University of Portsmouth
Portsmouth
PO1 2ER

Faculty of Science
University of Portsmouth
St Michael's Building
White Swan Road
PORTSMOUTH
PO1 2DT

15th October 2013

FAVOURABLE OPINION WITH MINOR AMENDMENTS/CONDITIONS

Protocol Title: Reducing thermoregulatory strain, whilst wearing fully encapsulating chemical protective clothing, through partitioned removal of moisture vapour impermeable (MVIP) materials when exercising in desert conditions
Date Reviewed: 1st – 15th October 2013

Dear Christie,

Thank you for submitting your protocol for ethical review. The proposal was reviewed by the Science Faculty Ethics Committee between 1st to 15th October 2013.

Your responses have been reviewed and I am pleased to inform you that your application has been given a favourable opinion subject to minor clarifications (listed below) by the Science Faculty Ethics Committee:

- Is the payment made for turning up or completing the exercise?
- If someone withdraws/is withdrawn from an exercise are they able to retry the same exercise and/or participate in subsequent exercises. If they do not complete all phases are partial results kept or dropped.

Please resubmit your revised proposal and notify us in the future of any substantial amendments that may be required. On completion of the study please send the SFEC a final study report.

Good luck with the study.

CMEglin

Clare Eglin
DSES, Science Faculty Ethics Committee

CC -
Dr Chris Markham – Chair of SFEC
Dr Jim House – Vice Chair of SFEC
Holly Shawyer – Faculty Administrator

Faculty of Science

University of Portsmouth

University of Portsmouth
St Michael's Building
White Swan Road
PORTSMOUTH
PO1 2DT

Christie.Garson@port.ac.uk/Jim.House@port.ac.uk
12/01/15

Science Faculty Ethics Committee

Protocol Title: SFEC 2014-100, An investigation as to whether regional differences in thermosensitivity affects the whole body thermoregulatory response during manipulation of local heat loss in individuals exercising in a hot environment.

Date application received: 15/12/15
Date Reviewed: 19/01/15

FAVOURABLE OPINION WITH MINOR CONDITIONS, SFEC 2014-100

Dear Ms Garson,

Thank you for your submission for ethical review. Having completed their review, members of the Science Faculty Ethics Committee have reached a Favourable opinion, with minor conditions, of your proposed research. Please note that you are *not* required to resubmit your documents confirming that these conditions have been actioned.

Participant Information Sheet

1. It is not clear from the documentation where in the experiment a participant may have an opportunity to void urine (if needed to do so). The opportunity to void and the method of collection of urine should also be made clear.
2. In the following section: "We are seeking male volunteers aged between 18 and 39 years who are fit, currently active and free from injury", you should define fit and currently active e.g. you may wish to be specific and define 'active' using frequency, intensity, time, and type of exercise parameters.

Ethical Review Application Form

1. As urine samples may be processed, section XXi should be marked 'Yes' (but qualified as 'on request of the participant')

Poster

1. On the poster we suggest that you qualify that 'Participants will receive up to a maximum of £70 on completion of the experiments'.

Protocol

1. The Risk assessments in the Protocol document although comprehensive should be transposed to the UoP Health and Safety risk assessment template (completed and signed off, before any testing is undertaken). Please include urine collection, weighing and disposal. As urine is relevant material according to the HT Act it should be disposed of in accordance with HT guidance.

Please notify the committee of any substantial amendments to the proposed procedures, send an annual report to the committee regarding study progress and a final study report once the study has concluded. Please send these to sci.fac@port.ac.uk.

Thank you for your submission and the Committee wishes you well with your study.

Dr Chris Markham – Chair of SFEC

CC -
Holly Shawyer – Faculty Administrator

If you would like to offer any feedback on the Science Faculty Ethics Committee process please email sci.fac@port.ac.uk, to be forwarded to the Chair

Faculty of Science
University of Portsmouth
St Michael's Building
White Swan Road
PORTSMOUTH
PO1 2DT

Christie.garson@port.ac.uk
06/03/2015

Science Faculty Ethics Committee

Protocol Title: SFEC 2014 – 100 B 'An investigation as to whether regional differences in thermosensitivity affects the whole body thermoregulatory response during manipulation of local heat loss in individuals exercising in a hot environment'
Date received: 02/03/2015
Date Reviewed: 06/03/2015

FAVOURABLE OPINION – SFEC 2014-100 B

Dear Ms Garson,

Thank you for your submission for ethical review. Having completed their review, members of the Science Faculty Ethics Committee have reached a Favourable opinion of your proposed research.

Please notify the committee of any substantial amendments to the proposed procedures, send an annual report to the committee regarding study progress and a final study report once the study has concluded. Please send these to ethics-sci@port.ac.uk.

Thank you for your submission and the Committee wishes you well with your study.

Dr Chris Markham – Chair of SFEC
CC -
Holly Shawyer – Faculty Administrator

If you would like to offer any feedback on the Science Faculty Ethics Committee process please email ethics-sci@port.ac.uk, to be forwarded to the Chair

Ministry of Defence
Research Ethics Committee

From the Chairman
Professor Allister Vale
National Poisons Information Service (Birmingham Unit),
City Hospital, Birmingham B18 7QH

Telephone: 0121 507 4123
e-mail:allistervale@npis.org

Dr Jim House
Department of Sport and Exercise Science
University of Portsmouth
Spinnaker Building
Cambridge Road
Portsmouth
PO1 2ER

Our Reference:
515/MODREC/14

Date: 1 June 2014

Dear Dr House

Thank you for submitting your revised Protocol 515 with tracked changes, and with a covering letter with responses to my own letter. The revised protocol has been approved by the Officers of MODREC ex-Committee.

I wish you and your colleagues a successful study. In due course please send the Secretariat a final report containing a summary of the results so that these can be filed in accordance with the arrangements under which MODREC operates. Please would you also send a brief interim report in one year's time if the study is still ongoing.

This approval is conditional upon adherence to the protocol – please let me know if any amendment becomes necessary.

Yours sincerely

Allister Vale MD FRCP FRCPE FRCPG FFOM FAACT FBTS FBPhamacolS FEAPCCT Hon FRCPSG

cc Professor David Jones, Professor David Baldwin, Dr Paul Rice OBE, Marie Jones

FORM UPR16

Research Ethics Review Checklist

University of Portsmouth

Please include this completed form as an appendix to your thesis (see the Postgraduate Research Student Handbook for more information

Postgraduate Research Student (PGRS) Information		**Student ID:**	709632
PGRS Name:	CHRISTIE NICOLE GARSON		
Department:	SPORT AND EXERCISE SCIENCE	**First Supervisor:**	JAMES R. HOUSE
Start Date: (or progression date for Prof Doc students)		**4 JUNE 2013**	

Study Mode and Route:						
	Part-time	☐	MPhil	☐	MD	☐
	Full-time	☒	PhD	☒	Professional Doctorate	☐

Title of Thesis:	THERMOREGULATION IN THE ENCAPSULATED ENVIRONMENT
Thesis Word Count: (excluding ancillary data)	61 805

If you are unsure about any of the following, please contact the local representative on your Faculty Ethics Committee for advice. Please note that it is your responsibility to follow the University's Ethics Policy and any relevant University, academic or professional guidelines in the conduct of your study

Although the Ethics Committee may have given your study a favourable opinion, the final responsibility for the ethical conduct of this work lies with the researcher(s).

UKRIO Finished Research Checklist:
(If you would like to know more about the checklist, please see your Faculty or Departmental Ethics Committee rep or see the online version of the full checklist at: http://www.ukrio.org/what-we-do/code-of-practice-for-research/)

a) Have all of your research and findings been reported accurately, honestly and within a reasonable time frame?	YES ☒ NO ☐
b) Have all contributions to knowledge been acknowledged?	YES ☒ NO ☐
c) Have you complied with all agreements relating to intellectual property, publication and authorship?	YES ☒ NO ☐
d) Has your research data been retained in a secure and accessible form and will it remain so for the required duration?	YES ☒ NO ☐
e) Does your research comply with all legal, ethical, and contractual requirements?	YES ☒ NO ☐

Candidate Statement:

I have considered the ethical dimensions of the above named research project, and have successfully obtained the necessary ethical approval(s)

Ethical review number(s) from Faculty Ethics Committee (or from NRES/SCREC):	470/MODREC/13 SFEC 2013-044 SFEC 2014-100 SFEC 2014-100B 515/MODREC/14

If you have *not* submitted your work for ethical review, and/or you have answered 'No' to one or more of

questions a) to e), please explain below why this is so:		
Please note that this is a Ministry of Defence part-funded PhD thesis and is subject to the terms of an embargo. Please contact academic registry before depositing in the University of Portsmouth library.		
Signed *(PGRS)*:	CHRISTIE NICOLE GARSON	**Date:** 23 MAY 2016