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Moisture vapour permeable gloves extend thermal endurance and safe work time more than other similarly permeable chemical-biological ancillary protective items.

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Moisture vapour permeable gloves extend thermal endurance and safe work time more than other similarly permeable chemical-biological ancillary protective items.

Working in chemical biological (CB) protective equipment causes thermoregulatory strain by restricting evaporative cooling. We quantified which impermeable ancillary items [gloves(G), body armour liner(BAL), respirator(R), overboots(OB)] imposed the greatest and least thermoregulatory strain through restricting evaporative cooling. The study was a five-condition repeated-measures design with male volunteers (n=13) who stepped intermittently with recovery periods in a desert-like environment (40.5 °C, 20% rh). Conditions varied in the ensemble worn, with a matched weight secured to the area when an item was not worn: CON(CB suit plus all items), N_R(no R), N_{BAL}(no BAL [170g liner]), N_G(no G), N_{OB}(no OB). The greatest reduction in thermoregulatory strain compared to CON occurred in N_G when the rise of rectal temperature was attenuated by 0.37 °C.hr⁻¹ (p<0.001), extending tolerance time by 21.3% (p<0.05) and improving perceived thermal comfort. The least improvement occurred for N_{OB}. It is recommended that the G permeability be examined further.

Keywords: thermoregulation; permeability; gloves; CBRN; heat strain

Practitioner Summary: Thermoregulatory strain was quantified when wearing impermeable protective equipment. The thermal burden of intermittent exercise in desert-like environments was best alleviated by removing gloves compared to removing a respirator, overboots or body armour liner. Reducing the evaporative resistance of materials used for such kit, particularly gloves, should be investigated.

Introduction

Many occupations, both civilian and military, require personnel to wear protective clothing. On some occasions such as in Fire and Rescue Services, Chemical and Energy Industries and the military this protective clothing, whilst alleviating one form of risk, can introduce another in the form of heat illness due to the impairment in thermoregulatory capacity imposed by the protective clothing. The warfighter working

whilst wearing chemical and biological (CB) personal protective equipment (PPE) is at risk of developing heat illness due to the moisture-vapour restrictive and insulative properties of the clothing and equipment. The typical ensemble comprises of a hooded jacket and trouser made from air permeable materials, thus allowing some moisture vapour (evaporated sweat) to pass through the clothing to the environment thereby gradually contributing to evaporative cooling. Additionally, various ancillary CB moisture-vapour impermeable (MVIP) items are worn. These MVIP ancillary items: a respirator (R), gloves (G) and overboots (OB) block the transfer of moisture vapour to the environment and thus prevent evaporative cooling once the underlying microclimate becomes saturated. Body armour (BA) is also worn in most military operations and is usually made from materials that are either primarily, or partly, MVIP. If metabolic heat production and any environmental heat gain exceeds thermophysiological heat loss mechanisms, for example when exercising in PPE, uncompensable heat strain can develop (Lind 1963; Montain et al. 1994). This results in a continued rise of body temperature, which if unchecked by a reduction in metabolic heat production or the implementation of cooling strategies, will culminate in heat illness that can be fatal. Improving the moisture vapour permeability (MVP) of ancillary CB items and BA, particularly in a hot, dry desert environment that fosters a favourable vapour pressure gradient with saturated skin, would allow for a greater transfer of moisture vapour through the PPE. This would enhance evaporative cooling, reducing whole body thermoregulatory strain and extend endurance time. The aim of this study was to quantify the thermoregulatory impact of each ancillary item to determine the potential advantage of making future items from MVP materials.

The ancillary items: R, G and OB cover the face, hands and combat boots respectively with BA covering the suit over the torso. Therefore, when investigating

which of these items impose the greatest or the least thermoregulatory strain on the wearer, regional characteristics favouring heat loss such as surface area available for moisture vapour exchange, sweat rate and cutaneous blood flow will determine the degree of reduction to whole body thermoregulatory strain. The approximate percentage of total body surface area of each region is 2.7 % for the face (manikin Newton, Thermetrics, US), 4.6 % for both hands (Yu, Hsu, and Chen 2008), 8.1 % for both feet (Yu and Tu 2009), whilst bearing in mind that the feet are enclosed in largely MVIP combat boots, and 39.5 % for the torso (Weiner 1945), again noting that the CB suit covers majority of the body including the entire torso area. The rate of sweat production for minimally clothed males undertaking moderate exercise (treadmill running at 55 % of $\dot{V}O_{2max}$) in warm conditions is greatest at the back (approximately $771 \text{ g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) and forehead (approximately $697 \text{ g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) with lower rates found at the dorsal hand (approximately $126 \text{ g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) and foot (approximately $202 \text{ g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$), and the cheek displaying the lowest rate overall (approximately $85 \text{ g}\cdot\text{m}^{-2}\cdot\text{hr}^{-1}$) (Smith and Havenith 2011). Regional variations in cutaneous blood flow have not been extensively cited in the literature for all the areas of interest in this study however, the hands and feet in particular support a large blood flow made possible by the high densities of capillaries (Grant and Bland 1931) and cutaneous arteriovenous anastomoses (Hales 1985).

Regional thermoreception might also affect whole body thermoregulatory strain, particularly as thermal comfort is known to drive thermoregulatory behaviour (Weiss and Laties 1961; Frank et al. 1999). The density and sensitivity of thermoreceptors are not homogenously distributed throughout the skin (Nadel, Mitchell, and Stolwijk 1973; Cotter et al. 1996; Cotter and Taylor 2005) and many cooling strategies for heat stressed individuals target the highly sensitive face (Mündel et al. 2006). Penfield and Boldrey (1937) when developing the somatosensory homunculus which, although not exclusive

to temperature sensation alone, highlighted that, along with the face, the hands provide large sensory feedback to the brain in comparison to the trunk for example. Fukazawa and Havenith (2009) found that the periphery (arms and thighs) also possesses a higher sensitivity of thermal discomfort to skin wettedness compared to the torso. The current study is concerned with regional thermal perturbations on the whole body response and Zhang (2003) found that in a warm environment, overall thermal comfort tends to follow the local thermal comfort of the head and face.

The general aim of this study was to independently quantify the reduction to thermoregulatory strain (physiological and perceptual) when each MVIP ancillary item (R, G, OB and BAL) was not worn during exercise and recovery in a desert-like environment. To eliminate the influence of removing varying weights between conditions on metabolic heat production, when an item was not worn a weight matching the mass of the item was secured to the area from where the item had been removed as a surrogate for making the item completely MVP. We hypothesized that the largest reduction to thermoregulatory strain would be evident when G were not worn, with the OB the least; while the largest reduction to perceived thermoregulatory strain being evident when the R was not worn.

Methods

Experimental Design

The study protocol was given a favourable opinion by the University of Portsmouth Scientific Faculty Ethics Committee, alongside approval from The Ministry of Defence Research Ethics Committee for the use of equipment. All procedures are compliant with the Declaration of Helsinki. Thirteen volunteer male participants (mean [SD] age: 21.5 [2.4] years, height: 178.3 [5.0] cm, weight: 75.7 [9.7] kg, body fat: 14.4 [4.1] %) were

recruited from the University of Portsmouth student cohort and gave informed consent. The study was a counter-balanced five-condition repeated measures design in which each participant undertook intermittent work-recovery periods in an environmental chamber for up to 170 minutes (Figure 1).

Figure 1. The work and recovery experimental design to allow for calculations of rates of heating and cooling as well as to optimize the detection of differences between conditions. Note that grey shaded areas represent exercise.

The study conditions were varied by the combinations of ancillary items that were worn. In the control (CON) condition all items were worn (CB suit + R + BAL + G + OB). Subsequent conditions involved the removal of one item whilst all other items were worn (N_R: No R thereby exposing the face; N_{BAL}: No BAL thereby uncovering the torso section of the suit; N_G: No G thereby exposing the hands; N_{OB}: No OB thereby exposing the combat boots). To quantify the thermal burden imposed by each item independently of the mass, when an item was not worn for a condition a weight equivalent to the mass of the item was attached to the body site from where the item had been removed. For example, when G were not worn, weights with an equivalent mass (120 g, Table I) were attached to each wrist. Thus, any reductions to whole body thermoregulatory strain could be attributed to the improved MVP at the area of interest rather than a reduced overall metabolic heat production. Furthermore, when quantifying the thermal burden of BA, a weight of 180 g that represented the mass of the impermeable liner reflecting the impermeability and shape of BA was secured to the torso rather than attempting to secure 15 kg (approximate weight of actual BA) to the torso.

The characteristics of the PPE worn during the experiment are shown in Table I, and give, for the particular size shown, a total mass of PPE worn + participants own

underwear and socks. The mass of each item varied with size, so the information below relate to the sizes reported below.

Table I. Clothing and personal protective equipment characteristics.

Experimental Protocol

Environmental Chamber Preparation

Environmental conditions were controlled at 40.5 °C air temperature and 20 % rh in an environmental chamber. These values represent the mean conditions between 08:00 and 21:00 for countries in a hot and dry category of the UK Ministry of Defence Standard produced by the Meteorological Office (2000). The environmental conditions were constantly recorded using a wet-bulb globe thermometer (Edale Instruments Ltd, UK) and electronically logged every minute (Squirrel 1000, Grant Instruments [UK] Ltd, UK).

Participant Preparation and Instrumentation

All experiments took place in the morning, between 08:00 and 13:00 to eliminate any influence of the circadian rhythm on thermoregulation (Kräuchi and Wirz-Justice 1994). On each test day, participants were instructed to eat a light breakfast and arrive at the laboratory in a euhydrated state. Participants were asked to refrain from alcohol the day prior to testing, and caffeine for two hours prior to testing. Participants were weighed naked (Model I10, Ohaus Corporation, US) and then self-inserted a rectal thermistor (Edale Instruments Ltd, UK) to 15 cm beyond the anal sphincter to measure rectal temperature (T_{re}) from which the rate of change of T_{re} was calculated when the data were linear. That being from the final 10 minutes in each period, except during Work

period 3 when data were obtained from 10 minutes into the work period onwards. As a conservative safety limit, participants ceased exercising when $T_{re} > 39.0$ °C but it is of interest to predict the time for T_{re} to reach 40 °C. Therefore, assuming that thermal balance would not be achieved and the measured rate of increase of T_{re} was linear, predicted TT to a T_{re} of 40 °C (from 37.5 °C) was calculated. This provides a clear, albeit partly extrapolated, calculation for the end user as to predicted TT that could theoretically be achieved whilst working at a constant intensity with no recovery periods.

Participants were instrumented with skin thermistors (Grant Instruments [UK] Ltd, UK) at four sites: calf, thigh, chest and upper arm, to estimate mean skin temperature (\bar{T}_{sk}) and mean body temperature (\bar{T}_b) in conjunction with T_{re} .

$$\bar{T}_{sk} = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf}) \text{ [}^\circ\text{C]} \quad (\text{Ramanathan 1964})$$

$$\bar{T}_b = 0.79(T_{re}) + 0.21(\bar{T}_{sk}) \text{ [}^\circ\text{C]} \quad (\text{Colin et al. 1971})$$

Additional skin thermistors were also placed on the cheek and the right finger pad to monitor cheek temperature (T_{cheek}) and finger temperature (T_{finger}). Heart rate (HR) was monitored by a three-lead electrocardiogram (ECG) attached to the chest with gel electrodes (Blue Sensor SP, Ambu, DK) and a conservative safety limit was $HR > 10 \text{ beats} \cdot \text{min}^{-1}$ below age predicted maximum. The ECG and human temperature data were continuously transmitted wirelessly to a data acquisition system (Sharktooth System, MIE Medical Research Ltd, UK). Post-instrumentation, participants donned CB equipment relevant to their condition. A dressed weight was taken.

Test Procedure

After instrumentation and donning of equipment, participants were escorted into the

environmental chamber and undertook ten minutes of seated rest before the commencement of light to moderate exercise of stepping to a height of 22.5 cm at a rate of 12 steps.min⁻¹ (Figure 1). To avoid dehydration, participants were provided with 250 mL of moderately chilled water (approximately 15 °C) every 20 minutes. To determine whether metabolic heat production was equal between conditions due to the matched weight, work rate $\dot{V}O_2$ (STPD), was determined from expired air collected in Douglas bags in the last minute or 2 minutes of each work and recovery period. Subjective measures were taken every 20 minutes, and initially at baseline, using the Borg scale (1976) to represent a rating of perceived exertion (RPE) and visual analogue scales to quantify perceived whole body thermal comfort, thermal sensation and skin wettedness. On completion of each experiment clothed and nude masses were measured. The rate of whole body sweat evaporation and production (L.hr⁻¹) were calculated from the difference in clothed and nude mass accounting for fluid intake as well as individual TT. The sweat evaporation / production ratio (SwE/P), which provides an indication of the efficiency of sweating, was calculated as a ratio of absolute sweat evaporation to absolute sweat production.

Statistical Analysis and Data Handling

All statistical analyses were conducted using Prism 6 (GraphPad, US) or SPSS (Version 22, IBM SPSS Statistics, US). Column statistics were conducted to check for normal distribution with the D'Agostino and Pearson normality test. One-way or two-way repeated measures ANOVA were conducted 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. 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]). Data were statistically compared at 10-minute intervals to the time point at which the first participant ceased stepping (110 minutes) for all conditions. Recovery 3 data were analysed separately. For measures when Recovery 3 data were linear, such as T_{re} , the hourly rate of change was calculated based upon the rate of rise or fall from 10 minutes into Recovery 3 onwards to ensure linearity. For measures when data were not linear during Recovery 3, such as HR, the change in recovery ($r\Delta$) data were calculated for the final 10 minutes of Recovery 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 (Work 3) before reaching Recovery 3.

Results

Oxygen Uptake

N_G resulted in a marginally ($0.84 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) greater mean $\dot{V}O_2$ during Work 2 compared to CON ($p < 0.01$). The mean $\dot{V}O_2$ during Work 1 for N_{OB} was again marginally ($0.81 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) greater compared to CON ($p < 0.05$).

Tolerance Time

Table II. Participant completion data with actual and predicted mean (SEM) tolerance times whilst stepping and recovering in an environmental chamber controlled at 40.5°C and 20 % rh ($n = 13$). * $p < 0.05$, *** $p < 0.001$ vs. CON; # $p < 0.05$, ## $p < 0.01$ vs. N_G .

N_G resulted in the greatest number of participants completing the full 60 minutes of

stepping during Work 3 (7 participants), with N_{OB} the least (2 participants) after CON (1 participant) (Table II). N_G was the only condition that resulted in an extended TT during Work 3 of 9.2 minutes (21.3 %) compared to CON ($p < 0.05$). Compared to CON, all conditions except N_{OB}, resulted in an extended predicted TT from a T_{re} of 37.5 °C to a T_{re} of 39.5 °C and 40.0 °C ($p < 0.05$). As TT provides an indication of the overall level of strain, an additional comparison was calculated for this variable which highlighted that predicted TT to a T_{re} of 39.5 °C and 40.0 °C was also extended during N_G compared to all conditions ($p < 0.05$). Furthermore, the T_{re} if the full 60 minutes of Work 3 were completed was predicted for each condition and the results indicated that the final predicted T_{re} of all conditions except N_{OB} were reduced compared to CON (39.44 [0.11] °C). Additionally, N_R (39.17 [0.08] °C, $p < 0.001$), N_{BAL} (39.22 [0.09] °C, $p < 0.05$) and N_G (39.02 [0.07] °C, $p < 0.001$) all displayed a significantly reduced predicted T_{re} compared to N_{OB} (39.34 [0.10] °C).

In the cases of non-completion of the 60-minute 3rd work period, the prime reason for stopping was reaching the T_{re} stopping limit of 39.0 °C which occurred in 10 of the 13 participants in CON, $n = 5$ for N_R, $n = 8$ for N_{BAL}, $n = 3$ for N_G, and $n = 8$ for N_{OB}. The other withdrawals were either for reaching the HR limit ($n = 1$ for N_R, $n = 1$ for N_G, $n = 2$ for N_{OB}) or wishing to stop due to fatigue ($n = 2$ for CON, $n = 2$ for N_R, $n = 2$ for N_G, $n = 1$ for N_{OB}).

Whole Body Sudomotor Response

Figure 2. 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 when wearing varying combinations of protective ancillary items ($n = 13$). * $p < 0.05$, **** $p < 0.0001$ vs. CON.

When adjusted for individual TT the mean rate of sweat evaporation during N_{BAL} 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). Mean SwE/P was also improved by 8.1 % during N_{BAL} compared to CON (55.32 [2.11] % vs. 47.25 [2.68] %, p < 0.0001). N_{OB} resulted in an improved mean whole body SwE/P by 6.7 % compared to CON (53.98 [2.01] % vs. 47.25 [2.68] %, p < 0.05).

Rectal Temperature

Figure 3. Mean (SEM) rate of change of rectal temperature whilst stepping and recovering in 40.5 °C and 20 % rh when wearing varying combinations of protective ancillary items (n = 13). * p < 0.05, ** p < 0.01, *** p < 0.001, **** p < 0.0001 vs. CON.

For N_G the mean rate of change of T_{re} was attenuated by 19.0 % during Work 2 (1.11 [0.08] °C.hr⁻¹ vs. 1.37 [0.09] °C.hr⁻¹, p < 0.05) and by 20.3 % during Work 3 (1.45 [0.05] °C.hr⁻¹ vs. 1.82 [0.06] °C.hr⁻¹, p < 0.001) compared to CON. Cooling was evident during Recovery 3 for N_G compared to CON (-0.25 [0.14] °C.hr⁻¹ vs. 0.03 [0.07] °C.hr⁻¹, p < 0.05). The mean rate of rise of T_{re} was attenuated only during Work 2 for N_R by 29.9 % compared to CON (0.96 [0.06] °C.hr⁻¹ vs. 1.37 [0.09] °C.hr⁻¹, p < 0.0001). Again, it was only during Work 2 that the mean rate of rise of T_{re} was attenuated during N_{BAL} compared to CON by 24.8 % (1.03 [0.10] °C.hr⁻¹ vs. 1.37 [0.09] °C.hr⁻¹, p < 0.01).

Mean Body Temperature

Figure 4. Average change in mean body temperature whilst stepping and recovering in 40.5 °C and 20 % rh when wearing varying combinations of protective ancillary items (n = 13). Data were truncated at the last point where n = 13 for each condition.

During N_G , \bar{T}_b was lowered compared to CON from 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 %). During Recovery 3, the mean $r\Delta\bar{T}_b$ was improved by 0.09 (0.03) °C for N_G compared to CON ($p < 0.05$). N_R lowered \bar{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 %). N_{BAL} lowered \bar{T}_b compared to CON from 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 %). During Recovery 3, the mean $r\Delta\bar{T}_b$ for N_{BAL} was improved by 0.06 (0.02) °C compared to CON ($p < 0.01$).

Local Skin Temperature

Cheek

During the first 30 minutes into the protocol, N_R resulted in a significantly greater mean T_{cheek} compared to CON and all other conditions by a maximum of 1.76 °C (36.54 [0.12] °C vs. CON: 34.78 [0.31] °C, $p < 0.0001$).

Finger

N_G did not significantly affect T_{finger} or $r\Delta T_{finger}$ during Recovery 3 even though a trend was apparent for a lowered T_{finger} during N_G compared to CON later in the protocol ($p = 0.057$). N_{BAL} resulted in a lowered T_{finger} at 10 minutes compared to CON (34.72 [0.89] °C vs. 35.35 [0.73] °C, $p < 0.05$). At 20 minutes into the protocol, T_{finger} was lowered during N_{OB} compared to CON (36.27 [0.64] °C vs. 36.91 [0.15] °C, $p < 0.05$).

Heart Rate

Figure 5. Mean heart rate whilst stepping and recovering in 40.5 °C and 20 % rh when wearing varying combinations of protective ancillary items (n = 13). Data were truncated at the last point where n = 13 for each condition.

N_R resulted in lowered mean HR 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, $p < 0.01$) by a maximum of 8 beats.min⁻¹. Compared to CON, mean HR for N_{BAL} was 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 HR 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. There were no significant differences in heart rate between CON and N_G nor CON and N_{OB} throughout the protocol, although there was a trend for heart rate to be lower during N_G compared to CON at 110 minutes (CON: 150 [4] beats.min⁻¹ vs. N_G : 144 [5] beats.min⁻¹, $p=0.058$).

Perceptual Measures

Significant differences were only located for perceived whole body thermal sensation, thermal comfort and skin wettedness. There were no significant differences for the mean RPE between any conditions.

Thermal Sensation

Significant differences to the mean perceived thermal sensation were only noted for N_{BAL} . Initially at baseline, participants reported feeling less warm during N_{BAL}

compared to CON (11.42 [0.70] vs. 12.80 [0.74], $p < 0.01$). N_{BAL} also 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], $p < 0.01$).

Thermal Comfort

Figure 6. Mean (SEM) perceived thermal comfort whilst stepping and recovering in 40.5 °C and 20 % rh when wearing varying combinations of protective ancillary items (n = 13). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ vs. CON.

Participants reported feeling less thermally uncomfortable during N_G 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], $p < 0.001$) where participants' reported feeling "just uncomfortable" during N_G compared to "uncomfortable" during CON. It was only at the end of Recovery 3 that participants rated N_{BAL} less thermally uncomfortable than CON (-3.31 [1.14] vs. -5.52 [1.17], $p < 0.05$). Again, it was only at the end of Recovery 3 that participants rated N_{OB} less thermally uncomfortable compared to CON (-3.52 [1.50] vs. -5.52 [1.17], $p < 0.05$).

Skin Wettedness

N_{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], $p < 0.01$) whereby participants reported feeling "very damp" (N_{BAL}) compared to "wet" (CON). N_{OB} was reported as feeling less wet compared to CON 20 minutes into Work 3 only (15.00 [0.86] vs. 16.85 [0.88], $p < 0.05$).

Discussion

Ancillary items that are MVIP worn by warfighters to protect against contaminating agents impose a thermal burden, which was lessened to the greatest degree when the gloves were not worn and to the least degree when the overboots were not worn, as hypothesized. Exposing the hands attenuated the rate of rise of T_{re} during the final work period compared to CON, which resulted in the greatest number of participants completing the protocol and extended TT during continuous work. The exact mechanism responsible for the large heat dissipation at the hands was not directly measured in this study. However, we speculate that due to the high density of sweat glands, particularly on the volar surfaces (Taylor and Machado-Moreira 2013), there was a high rate of sweat production with concomitant support for large increases in cutaneous blood flow (Grant and Bland 1931; Hales 1985) distributing the cooled extremity blood back to the core. Although the surface area of the hands is small (approximately 4.6 % of total body surface area [Yu, Hsu, and Chen 2008]), due to the nature of the exercise prescribed (stepping) and the consequent hand swinging motion that accompanies stepping, there was probably a greater degree of forced evaporative cooling from the hands (although not directly measured).

Any substantial quantity of sweat produced or evaporated when the hands were exposed was not expressed in the whole body measure and subsequent studies should measure local sweat rates. Nonetheless, this suggests that the mechanism was not only sudomotor and subsequent studies should examine local cutaneous blood flow to quantify the contribution of the vasomotor component. Furthermore, there was no significant lowering of T_{finger} , that would be indicative of evaporative cooling at the finger, when the gloves were not worn. It is most likely that this measure would have been balanced with heat gain from the warmer environment (40.5 °C) and arterial

blood. Moreover, the finger thermistor was secured to the finger pad using thin waterproof adhesive but porous surgical tape, which may have partly inhibited evaporation of sweat directly from the site of T_{finger} measurement and might have fostered a slight insulative microclimate (Buono and Ulrich 1998). Whilst the rest of the hand was exposed, due to the tape, T_{finger} might not have provided an accurate representation of total hand temperature, but should be similar, and indicate changes similarly.

Exposing the hands extended predicted TT from a hypothetical starting T_{re} of 37.5 °C to a T_{re} of 39.5 °C and 40.0 °C by 17.0 minutes and 21.3 minutes respectively compared to CON and was also significantly extended compared to all other conditions. This would equate to the patrolling individual covering an extra 1.12 km or 1.41 km (if walking at a light intensity at a speed of 1.11 m.s⁻¹ with a hypothetical gradient of 0 % [McLellan, Meunier, and Livingstone 1992]) before there is an increased risk of heat stroke causing serious systemic dysfunction (Knochel and Reed 1994) simply by permitting evaporative cooling from the hands alone. Additionally, the individual would, where possible, stop exercising and recover when the thermoregulatory strain of CB equipment becomes overwhelming. Therefore, the augmented rate of cooling during Recovery 3 (-0.25 °C.hr⁻¹) when the hands were exposed would allow for dynamic and extended operations if recovery periods are feasible, rather than operational TT being limited by, among other factors, metabolic rate and the time taken to reach microclimate saturation.

The physiological improvements to thermoregulatory strain during N_G were also detected perceptually. It is important to note that perceptual improvements were identified during Recovery 3 even though participants had, by that time, spent a longer duration in the heat (an additional 9.2 minutes) during N_G compared to CON. N_G

resulted in participants feeling less thermally uncomfortable compared to CON and whilst the somatosensory homunculus indicates that the hands (and fingers) provide a large amount of sensory feedback to the brain, the homunculus also indicates that the face is equally as sensitive (Penfield and Boldrey 1937), a result that was not identified in the current study when rating perceived thermal comfort. Thus, perhaps when considering thermoreception in isolation to other sensory cues, a different weighting / homunculus would be identified. Body areas possess varying limits of local thermal comfort and as suggested by Fukazawa and Havenith (2009) the periphery (arms and thighs) possess a higher sensitivity of thermal discomfort to skin wettedness compared to the torso. The current study found that thermal comfort was improved compared to CON for N_G during both exercise and recovery but was only improved for N_{BAL} during recovery, although no significant differences were identified between N_G and N_{BAL} . Nonetheless, these results taken together with the sensory cortical homunculus (Penfield and Boldrey 1937) suggest that the extremities such as the hands could potentially possess a higher sensitivity of thermal discomfort than the torso and perhaps even the arms and thighs. These findings also extend the work of Fukazawa and Havenith (2009) to include analysis of regional thermal discomfort during recovery.

N_R and N_{BAL} resulted in equal numbers of participants completing the protocol. Considering that the surface area of the torso is approximately 14 times that of the face (manikin Newton, Thermetrics, US; Weiner 1945), it would appear that exposing the face resulted in thermoregulatory improvements that are greater than expected for its surface area. However, whilst the face was directly exposed to the environment when the respirator was not worn, the torso, when the BAL was not worn, was still covered by the protective suit that possesses a low air permeability. Nonetheless, this result still indicates the practical, end-user benefits of improving the MVP of the respirator or BA.

During the first 30 minutes of the protocol, N_R resulted in a greater T_{cheek} as the exposed facial skin was gaining heat from the warmer ambient environment. For the remainder of the protocol, T_{cheek} was not different whether the respirator was worn or not. Again we acknowledge the limitation associated with the use of tape to attach the cheek thermistor. Additional calculations identified that if all participants had completed the protocol, T_{re} would have been 0.27 °C and 0.42 °C cooler during N_R and N_G respectively compared to CON, with final T_{re} during N_G also being significantly lower compared to N_R . This highlights the reduction in thermoregulatory strain when evaporation from the hands was permitted compared to the face, most likely because the hands are approximately 1.7 times larger than the face (manikin Newton, Thermetrics, US; Yu, Hsu, and Chen 2008). N_R also lowered HR compared to CON which was most likely indicative of the lowered thermoregulatory strain (Figure 4), although HR was not significantly lowered during N_G ($p = 0.058$). Therefore, there was another factor influencing HR other than purely thermoregulatory strain. Early work investigating physiological responses when wearing a respirator found that during two hours of exercise, HR was elevated when a respirator was worn even though core temperature (unspecified) was not significantly different, although \bar{T}_{sk} was elevated (Robinson and Gerking 1945; quoted in Muza, 1986). An elevated HR when wearing a respirator could be associated with anxiety that some individuals might experience during exercise when the face is covered or even hyperventilation that can induce tachycardia (Morgan 1983).

There were no significant improvements to any perceptual measures during N_R compared to CON, which was unexpected as the face is greatly represented on the somatosensory homunculus (Penfield and Boldrey 1937) and more recently, Cotter and Taylor (2005) found that the face displayed a greater sudomotor and alliesthesial thermosensitivity compared to the upper and lower limbs and limb extremities.

Measuring whole body, rather than local perceptual responses might explain this finding. Furthermore, the initial facial heat gain from the warmer environment may have resulted in negative thermal perceptual responses that were not overcome later. Nonetheless, the greatest reduction to perceptual thermoregulatory strain compared to CON was when the gloves or BAL were not worn and therefore we fail to reject our null hypothesis.

The torso does not possess as great a density of sweat glands as the hands and feet (Taylor and Machado-Moreira 2013), but due to its large surface area (approximately 39.5 % of total body surface area [Weiner 1945]), it was expected that N_{BAL} would greatly reduce whole body thermoregulatory strain. Therefore, the improved rate of sweat evaporation by 10 % and the improved SWE/P by 8 % compared to CON were not surprising. However, it was unexpected that there would be no significant impact on the rise or fall of T_{re} during continuous work or recovery as a result of the enhanced rate of sweat evaporation, although N_{BAL} did lower \bar{T}_b compared to CON during Work 3. Using the rate of cooling during Recovery 3 (N_{BAL} : 0.05 [0.17] °C.hr⁻¹, N_G : 0.25 [0.14] °C.hr⁻¹), it can be predicted that for T_{re} to cool by 0.5 °C it would take approximately 2 hours if the gloves were made completely MVP as opposed to 10 hours if the BAL was made completely MVP. N_{BAL} also improved ratings of thermal sensation and skin wettedness. The torso is not often the site targeted for positive thermal alliesthesia, nor is greatly represented on the somatosensory homunculus (Penfield and Boldrey 1937). Although, in cool conditions Nakamura et al. (2008) found that humans would preferentially warm the chest and abdomen as opposed to the face, thus highlighting the sensitivity of the torso to thermal stimuli. In the current study, the detection of these perceptual measures (improved thermal sensation and skin wettedness) might possibly be explained by the large surface area of the torso.

Although N_{OB} improved the whole body SwE/P by 6.7 % compared to CON and resulted in participants feeling less wet and less thermally uncomfortable, there were no reductions to other markers of thermoregulatory strain. Furthermore, additional calculations predicted that if the full 60 minutes of Work 3 were completed, all conditions except CON, would have displayed a significantly reduced T_{re} compared to N_{OB} . Thus, making the overboots completely MVP would result in the least decrease to thermoregulatory strain compared to any other item as hypothesized. The minimal reductions to thermoregulatory strain were most likely because during N_{OB} the feet were not exposed (as the hands or face were during N_G or N_R), but were still covered by the socks and combat boots. It was unexpected that N_{OB} would impact perceptual measures more so than physiological measures. However, it may be that the bulk and design of the overboots, possibly making stepping more cumbersome when worn, might have influenced perceptual responses.

Conclusions

The greatest decrease to thermoregulatory strain and improvement in TT in the heat in individuals wearing CB clothing occurred when the gloves were not worn. The least decrease to thermoregulatory strain occurred when overboots were not worn and not wearing a respirator had less impact on whole body perceptual responses than expected. Thermoregulatory strain when wearing military CB equipment in desert-like environments would decrease to the greatest extent if the gloves and BA were made MVP. We have shown that the user would benefit less if the respirator and overboots were made MVP.

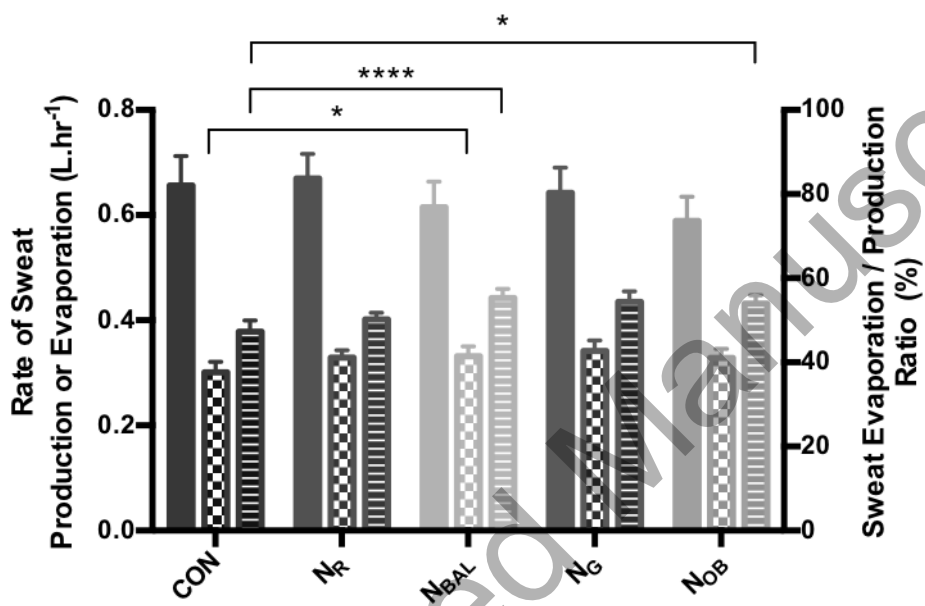
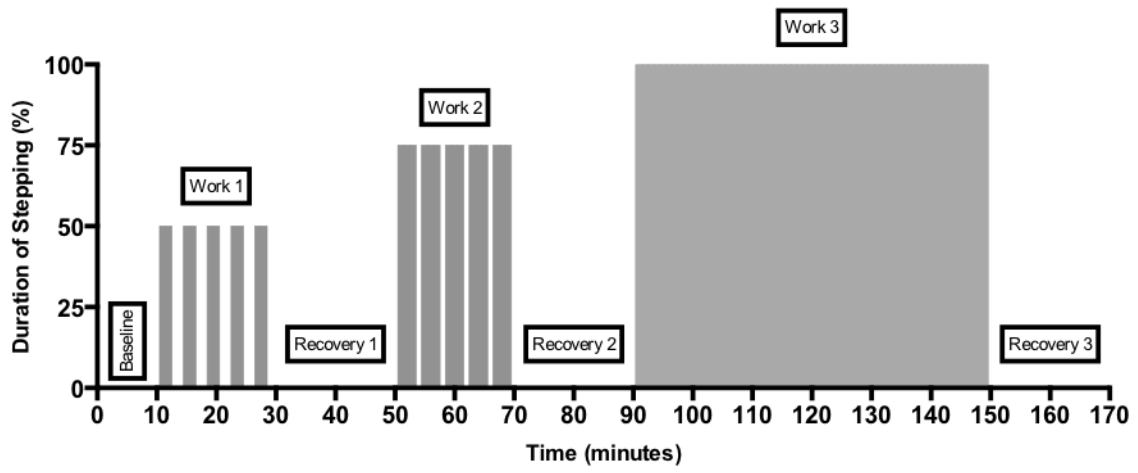
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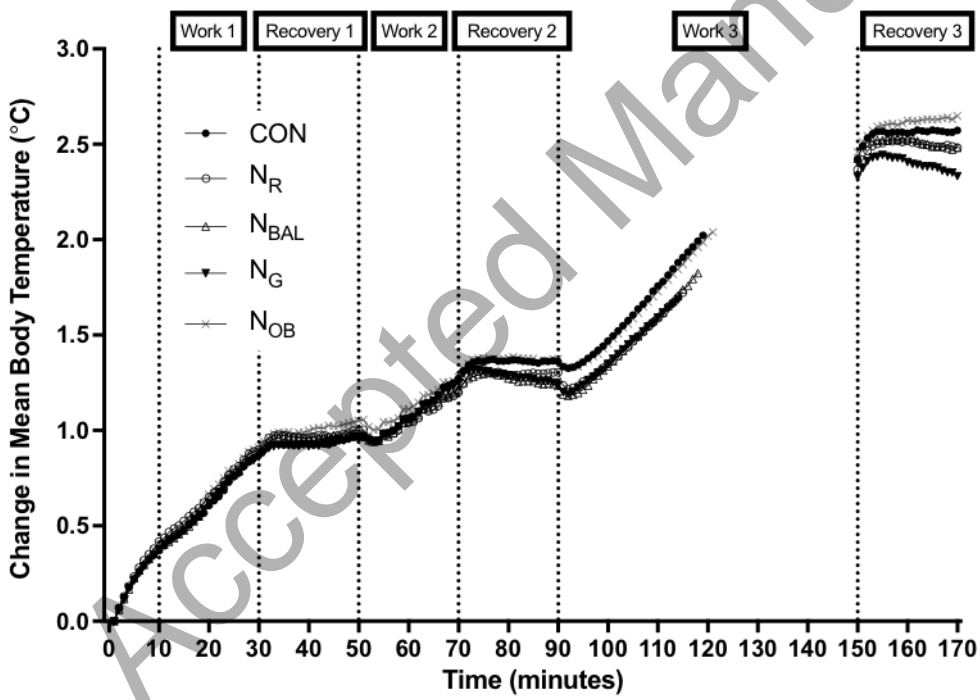
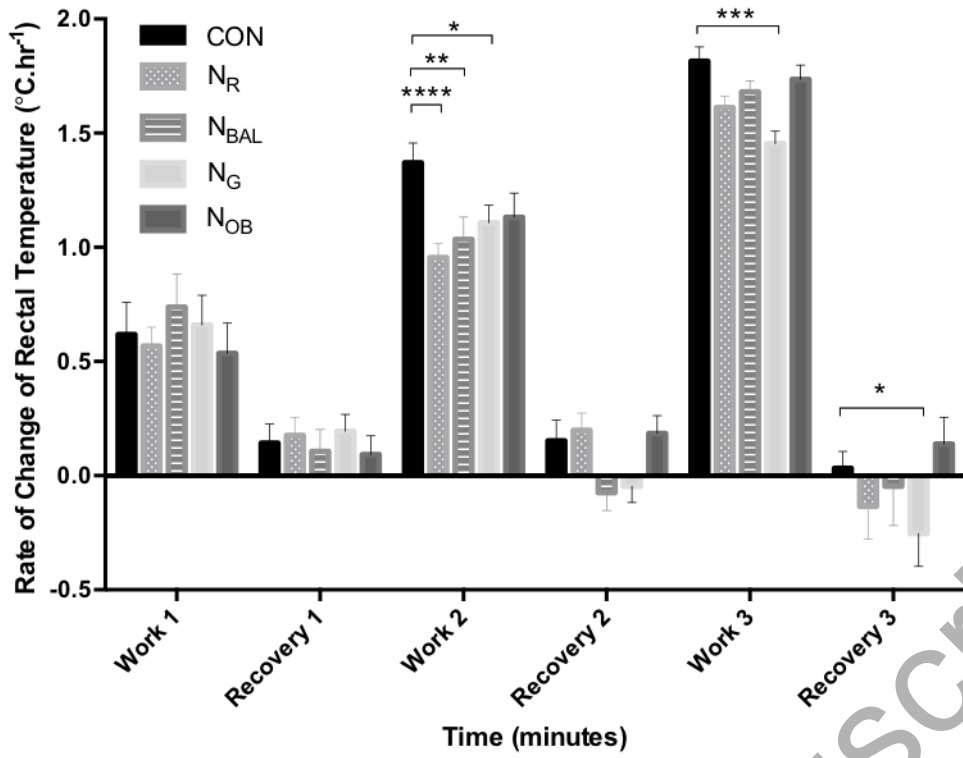
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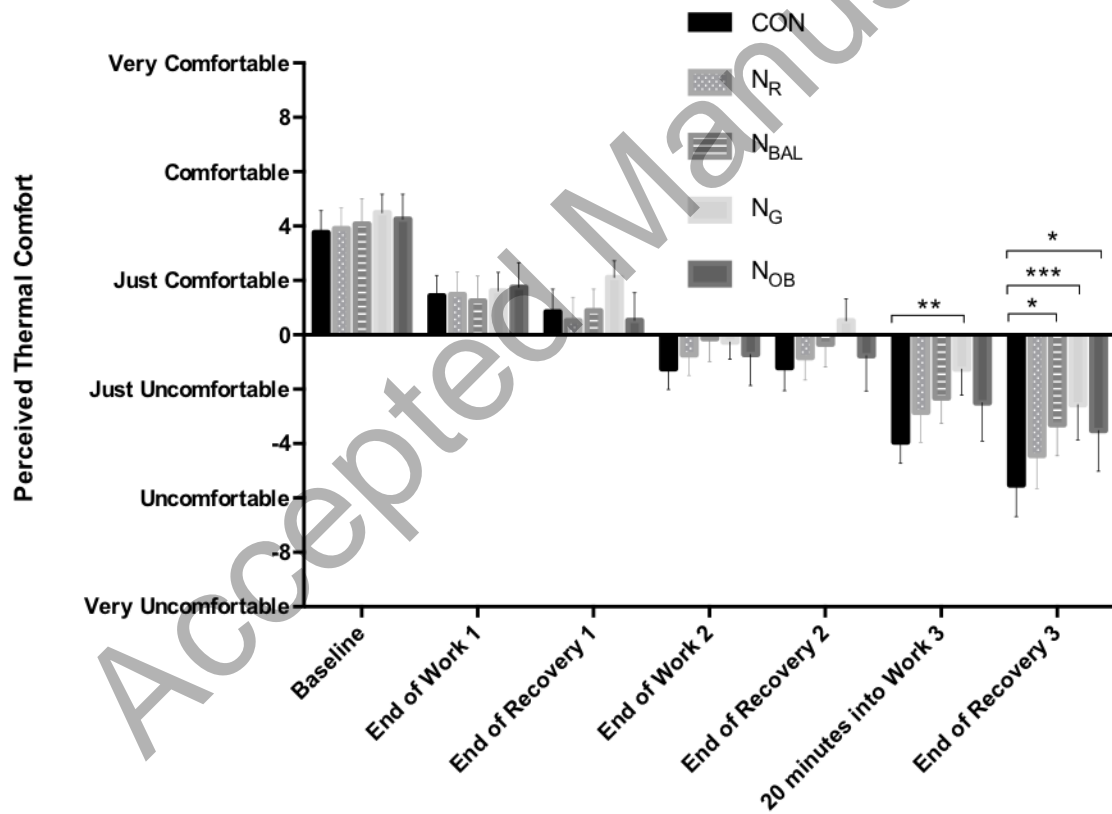
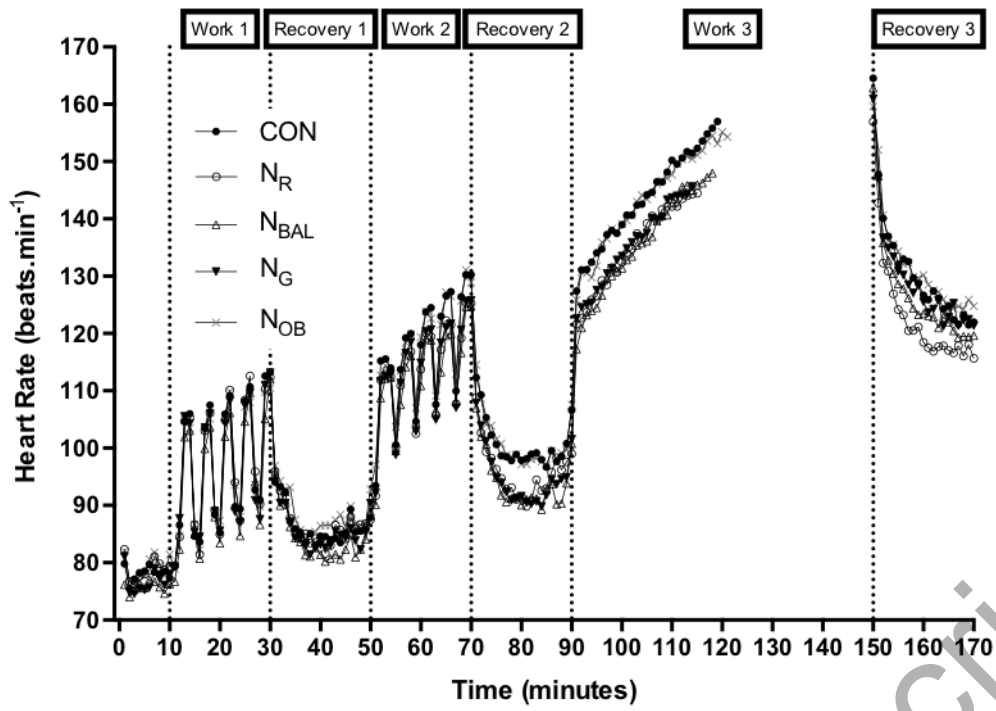
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CBRN PPE Item	Item Characteristics	
	Weight	Material
MiKVa CBRN PPE Suit Size 190/180 cm (height / chest)	Trousers 1.04 kg Jacket 1.36 kg	Trouser and jacket 2-layer suit with integrated hood. Tightly woven cotton ripstop outer with activated carbon loaded woven liner fabric. The lining is stitched to the outer at seams and edges only, so air-gap can be present between layers. Double-layer thickness (1.3 mm)
General Service Respirator (Large)	0.85 kg	Butyl rubber mask and plastic eye visor with butyl rubber straps. Moisture Vapour Impermeable
Body Armour Liner (Medium)	0.18 kg	Impermeable woven nylon (polyurethane blend with a thermoplastic polyurethane coating). Moisture Vapour Impermeable
Gloves (Size 10 – Large)	Inner liner pair: 0.09 kg	Cotton
	Outer glove pair: 0.15 kg	Butyl rubber. Thicker towards fingers (0.9 mm) and thinner to wrist (0.5 mm). Moisture Vapour Impermeable
Overboots (Extra-large)	Pair: 1.31 kg	Butyl rubber. Thickness varies between 1.1 mm to 2.4 mm, with a thicker tread-sole. Moisture Vapour Impermeable.
Combat Boots (Size 7)	1.296 kg (pair)	Leather and 1150 Denier Nylon Upper Quick Drying and Breathable Lining Non-slippery and Oil Resistant Rubber Outsole Composite Toecap

Note: Total clothing mass for CON for the sizes given above is 6.276 kg.

Condition	Number of Participants Completing the Protocol (n / 13)	Mean (SEM) TT during Work 3 (minutes)	Mean (SEM) Predicted TT from a T_{re} of 37.5 °C to 39.5 °C (minutes)	Mean (SEM) Predicted TT from a T_{re} of 37.5 °C to 40.0 °C (minutes)
CON	1	43.2 (2.5)	68.4 (2.4)	85.2 (2.9)
N_R	5	50.5 (3.2)	76.6 (2.4) ^{*#}	95.5 (2.9) ^{*#}
N_{BAL}	5	51.4 (2.9)	73.5 (2.2) ^{*##}	91.7 (2.7) ^{*##}
N_G	7	52.4 (3.0) [*]	85.4 (3.5) ^{***}	106.5 (4.4) ^{***}
N_{OB}	2	45.8 (2.6)	71.8 (2.6) [#]	89.2 (3.2) [#]

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