A thermal physiological comparison between two Explosives Ordnance Disposal (EOD) suits during work related activities in moderate and hot conditions.

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INTRODUCTION

The work of an explosives ordnance disposal operative is varied and includes long duration searching activity and shorter duration operations in close proximity to identified explosive threats. Therefore the specification of personal protective equipment (PPE) worn for these activities will vary, with one important trade-off being that between the level of ballistic protection and mass of the equipment. From a human factors perspective it is important to consider the impact of the PPE worn and the prevailing environmental conditions on the operative's capacity to safely perform job specific tasks. Hence information on how different PPE impacts on thermal strain, which is associated with decrements in performance (Taylor and Orlansky, 1993), when conducting defined activities within a range of environmental conditions is likely to be of benefit when planning missions. Thus the aim of this study was to describe the thermal physiological response to activities representative of EOD operations in 20°C and 40°C in the Ergotec 3010 (≈18 kg) EOD suit compared to the Ergotec 4010 (≈37 kg) EOD suit.

METHODS

Four non heat acclimated males (age 23±2 yrs; body mass 80.3±7.0 kg; stature 175.8±6.5 cm) participated in this investigation that was approved by Coventry University Ethics committee. Four trials, two when wearing an ≈18 kg EOD suit (Ergotec 3010, NP Aerospace, UK) and two when wearing an ≈37 kg EOD suit (Ergotec 4010, NP Aerospace, UK) were conducted by each participant. The two suit types were each worn in 20°C and 40°C on separate occasions at least one week apart. Suit type and temperature were applied according to a randomised cross-over design. A standard pair of cotton trousers and t-shirt was worn beneath the suit on each occasion. The suit's integral fan system was engaged throughout each trial. The dual fan system of the Ergotec 4010 delivered ≈200 $L \cdot min^{-1}$ of ambient air to the wearers back and 100 $L \cdot min^{-1}$ to the head area whereas the single fan of the Ergotec 3010 delivered ≈200 $L \cdot min^{-1}$ of ambient air to the wearers back.

A modified activity sequence composed of 4 × 16 min 30 sec cycles, representative of EOD operations was conducted (Thake and Price, 2007) within a 3 m × 5 m enclosed area. In brief each cycle consisted of 3 min treadmill walking (4 $km \cdot hr^{-1}$); 2 min manual activity (moving

1.25 kg weights between two shelves 27 cm and 64 cm above the floor whilst kneeling); 2 min crawling and searching activity (forward and back along a 2.40 m ladder with 11 equally spaced rungs interspersed with 'searching' by moving the head twice left and right at each end of the ladder); 3 min unloaded arm ergometry (60 rev·min^{-1}); 5 min seated rest. Each physical activity was separated by a 30 sec transfer period. Work rate (manual activity and crawling and searching activity) was controlled by asking participants to move on the beat of a metronome (30 beat·min^{-1}; Seiko DM-20, Japan).

Heart rate (HR; Polar Vantage, Finland), rectal temperature (T_c) and mean skin temperature (T_{sk}; Ramanathan, 1964; Grant Instruments, Cambridge, UK) were monitored continuously and recorded in the last 30 sec of each component of the activity cycle. Sweat rate was estimated from pre to post trial changes in nude body mass on each visit. Heat storage (HS) was calculated according to Havenith *et al*., (1995). Rating of perceived exertion (RPE; 6-20 scale) and thermal sensation (TS) and thermal comfort (TC; 9 point 0-8 scales) were sought during the final 30 sec of arm ergometry. A physiological strain index (PhSI) was calculated from normalised increases in HR and T_c and a perceptual based strain index (PeSI) was calculated from normalised increases in RPE and TS, both of which are described on a 0 (no strain) to 10 very high strain) scale (Tikuisis *et al.*, 2002).

Data were analysed using a general linear model analysis of variance (ANOVA) that incorporated main effects for condition, time and condition × acclimation interaction. Tukey post hoc tests were used to investigate significant ($P \leq 0.05$) main effects.

RESULTS

All four participants completed the 66 min activity sequence whilst wearing the Ergotec 3010 and Ergotec 4010 EOD suits in both 20°C and 40°C trials. Ambient temperature was maintained at 20±1°C and 40±1 °C throughout; relative humidity (RH) was constant throughout the 20°C trials (50±1%) whereas RH increased from 24±2% to 38±2% within each 40°C trial.

Thermal strain, as indicated by T_c, T_{sk}, HS and PhSI, experienced by participants was determined by both suit type and ambient temperature and was highest at 40°C compared to 20°C and greatest in the heavier Ergotec 4010 suit compared to the lighter Ergotec 3010 suit at each temperature (Table 1). With reference to Figure 1 T_{sk} was higher in 40°C compared to 20°C ($P<0.001$) and did not vary between EOD suits. T_c did not increase until the third activity cycle in the 40°C trials and was higher in the Ergotec 4010 suit compared to the Ergotec 3010 suit ($P<0.001$). The onset of rise in T_c in 40°C trials at 33 min was coincident with the decline in the rate of increase in T_{sk} (33 min). T_c was also higher whilst wearing the Ergotec 4010 in the 20°C trials ($P<0.001$) although T_c only climbed ≈0.2°C over the entire protocol. A transient ≈0.1°C reduction in T_c in the third activity cycle of the Ergotec 3010 trial also contributed to this difference. In the last activity cycle the thermal gradient (T_c-T_{sk}) was ≈1.5°C for both suits in 20°C and was smaller at ≈0.6°C for both suits in 40°C. As expected HS increased with duration in all trials and was highest in the Ergotec 4010 at 40°C ($P<0.001$). HR increased with duration in all trials and followed the same pattern as T_c and HS (40°C >20°C and Ergotec 4010> Ergotec 3010) with difference between conditions becoming more evident after 33 min. PhSI increased with temperature (40°C >20°C; $P<0.001$) and suit mass (Ergotec 4010 > Ergotec 3010; $P<0.001$). PeSI was greater than PhSI in all trials. Although PhSI was slightly higher in the

Ergotec 3010 40°C trial compared to the Ergotec 4010 20°C trial ($P<0.001$) the corresponding PeSI values were similar (NS; Table 1). Sweat loss was higher at 40°C (0.80±0.15 L) compared to 20°C (0.53±0.25 L; $P<0.001$) and did not vary with suit type.

Table 1: Physiological and perceptual variables (±SD) whilst wearing the Erogotec 3010 and

	20°C		40°C	
Variable	3010	4010	3010	4010
Rectal Temp (°C)$^{\#,\dagger}$	37.50±0.22	37.76±0.29	38.12±0.14	38.30±0.14
Mean Skin Temp (°C)$^{\#,\dagger}$	36.01±0.58	36.27±0.68	37.88±0.22	37.67±0.28
Heat Storage (J·g^{-1})$^{\#,\dagger,\Phi}$	2.63±0.29	3.17±0.47	4.67±0.13	5.30±0.29
HR (bt·min^{-1})$^{\#,\dagger}$	111±14	133±23	159±9	170±12
PhSI$^{\#,\dagger,\Phi}$	1.6±0.5	3.0±1.2	4.6±0.4	5.6±0.5
RPE Overall$^{\#,\dagger}$	10±1	14±1.5	14±1.5	17±2
Thermal Sensation$^{\#,\dagger}$	5.3±0.5	5.8±0.5	6.8±0.5	7.0±0
Thermal Comfort$^{\#,\dagger}$	5.0±0.8	5.5±0.6	6.8±0.5	7.0±0
PeSI$^{\#,\dagger}$	5.3±0.4	6.9±0.7	6.8±1.2	8.9±0.8

Ergotec 4010 EOD suits during arm ergometry in the final activity cycle at 20°C and 40°C.
$^{\#}$ main effect for condition; †main effect for cycle; $^{\Phi}$interaction condition × cycle ($P\leq0.001$).

CONCLUSIONS

The additional mass of the Ergotec 4010 EOD suit compared to that of the Ergotec 3010 (Δ19kg) resulted in greater thermal physiological stress when conducting EOD related activities in both 20°C and 40°C. In 20°C heat balance, as indicated by no additional increased in heat storage, appeared to be achieved within the last activity cycle when wearing both suits. Although both PhSI and PeSI were higher in the heavier Ergotec 4010, predominantly due to greater HR and RPE respectively, the dual fan system provided adequate cooling to maintain a thermal state comparable to that in the lighter Ergotec 3010 fitted with one fan. Likewise at 40°C the higher PhSI and PeSI when wearing the Ergotec 4010 suit were also predominantly due to HR and RPE respectively. It is likely that the elevated HR when wearing the Ergotec 4010 compared to the Ergotec 3010 reflects a higher skin blood flow (Moran *et al*., 1998) that facilitated a greater rate of heat transfer. However at 40°C HS continued to rise in both suits indicating a situation of uncompensable heat stress (UHS; Cheung *et al*., 2000), albeit at a faster rate in the heavier Ergotec 4010 suit. Although metabolic heat production would have been higher in the heavier suit sweat loss was no greater than that when wearing the lighter Ergotec 3010 suit. Since both suits were donned in a fixed time period at 20°C prior to entering the experimental area it is likely that engaging the fan systems in the 40°C trials resulted in a more rapid initial rise in T_{sk} than would have otherwise occurred. The four participants reported both TS and TC to be ‘very hot’ and ‘uncomfortably hot’ respectively (corresponding verbal anchors from the 9 point scales), during the last activity cycle in 40°C. However T_c only reached 38.30±0.14 °C when wearing the Ergotec 4010 suit at this temperature. Such a disparity, namely the inability to achieve a higher T_c alongside a relatively high HR (170±12 bt·min^{-1}) during physical activity could be indicative of low fitness levels in these participants (Selkirk and McLellan, 2001).

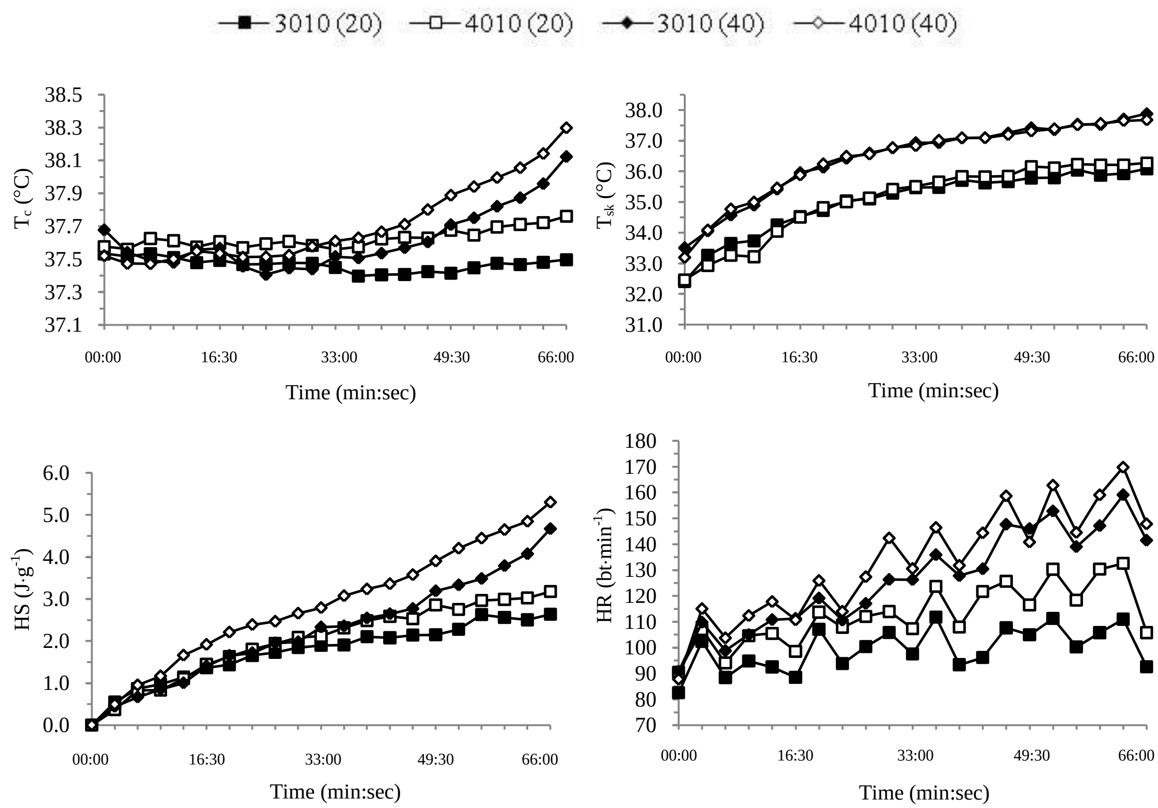

Figure 1: Core temperature (T_c), mean skin temperature (T_{sk}), heat storage (HS) and heart rate (HR) responses to activity when wearing the Ergotec 3010 and Ergotec 4010 EOD suits in 20°C and 40°C. Error bars are omitted for clarity. Refer to table 1 and text for significant differences.

From a practical perspective it is noted that T_c does not begin to rise above resting values for at least 33 min regardless of the suit worn or the ambient temperature applied in this study. In hot environments when EOD activity, particularly in the heavier Ergotec 4010 suit, is likely to last longer than one hour it is apparent that additional cooling strategies to reduce the rate of heat storage and onset of UHS should be considered. To help inform planning for EOD operations it is advised that the thermal physiological responses of EOD suit wearers should be evaluated over the range of ambient conditions in which operations may take place.

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