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Title Page

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Heat Strain Evaluation of Overt and Covert Body Armour in a hot and humid environment

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Title:

Heat Strain Evaluation of Overt and Covert Body Armour in a hot and humid environment

Abstract

The aim of this study was to elucidate the thermophysiological effects of wearing lightweight non-military overt and covert personal body armour (PBA) in a hot and humid environment. Eight healthy males walked on a treadmill for 120 minutes at 22% of their heart rate reserve in a climate chamber simulating 31°C (60%RH) wearing either no armour (control), overt or covert PBA in addition to a security guard uniform, in a randomised controlled crossover design. No significant difference between conditions at the end of each trial was observed in core temperature, heart rate or skin temperature (P>0.05). Covert PBA produced a significantly greater amount of body mass change (-1.81±0.44%) compared to control (-1.07±0.38%, P=0.009) and overt conditions (-1.27±0.44%, P=0.025). Although a greater change in body mass was observed after the covert PBA trial; based on the physiological outcome measures recorded, the heat strain encountered while wearing lightweight, non-military overt or covert PBA was negligible compared to no PBA.

Practitioner Summary. The wearing of bullet proof vests or body armour is a requirement of personnel engaged in a wide range of occupations including police, security, customs and even journalists in theatres of war. This randomised controlled crossover study is the first to examine the thermophysiological effects of wearing lightweight non military overt and covert personal body armour (PBA) in a hot and humid environment. We conclude that the heat strain encountered while wearing both overt and covert lightweight, non-military PBA was negligible compared to no PBA.

Key terms heat stress, hydration, personal protective equipment.

1. Introduction

The wearing of bullet proof vests or body armour is a requirement of personnel engaged in a wide range of occupations including military, police, security, customs and even journalists in theatres of war. The primary purpose of the body armour is to protect the wearer from ballistic trauma; however an unintended consequence of wearing body armour in hot and humid environments is an increased risk of heat strain (Caldwell et al., 2011; Cheung et al., 2000; Havenith et al., 1999; Sawka et al., 2011; Taylor et al., 2008). Depending on its thickness and fit, PBA can form a barrier between the wearer's skin and the environment, impairing the amount of sweat that can be evaporated due to the impermeable nature of the material (relative to normal or work clothing) (Craig and Moffitt, 1974; Havenith, 1999). Sweat can also become trapped or absorbed into the clothing layer, further impairing and decreasing the amount of heat transfer (Craig and Moffitt, 1974). PBA can also inhibit sweat loss by establishing a microclimate that sweat has to travel across and subsequently inhibits the evaporative capacity of the human body to transfer heat to the environment (Candas and Hoeft, 1995; Nunneley, 1989; Nunneley et al., 1978).

The combination of these factors may cause an imbalance between heat production and heat dissipation (Holmér, 1995) eventually leading to increased heart rate and core temperature and consequently an increase in heat strain and perceived exertion. Increasing levels of heat stress is associated with dehydration, heat cramps, heat exhaustion, heat stroke and ultimately death if left untreated (Armstrong, 2007; Taylor et al., 2008). Prolonged heat stress coupled with exercise, even if at low intensity, can pose a challenge to the regulation of temperature and oxygen delivery to the working muscles, brain and heart (Gonzalez-Alonso, 2012) and ultimately reduce human performance. Changes in physiologic function have been reported in a military setting (Cheuvront et al., 2008; Majumdar et al., 1997) but inconsistencies exist as to whether lightweight non-military body armour can be detrimental to performance (Caldwell et al., 2011; Caldwell et al., 2012).

Cash in transit security guards, otherwise known as armoured vehicle officers (AVOs), are one such example of personnel required to wear lightweight PBA in hot-humid environments (Stewart and Hunt, 2011). AVOs wear PBA in operational activities which can be conducted in hot conditions depending on their geographical location. Although the armour is effective in reducing the risk of mortality its influence on thermal balance needs to be considered. To date, there is a paucity of research examining the thermophysiological effects of wearing this type of non-military lightweight PBA. To our knowledge only two studies (Lehmacher et al., 2007; Stewart and Hunt, 2011) have examined the effects of wearing lightweight body armour on security guards in the field, and a controlled, laboratory based study is warranted. Therefore the current study sought to elucidate the thermophysiological effects of wearing lightweight non military overt and covert personal body armour (PBA) in a hot and humid environment.

2. Methods

2.1 Participants

A convenience sample of eight, healthy, physically active males was recruited to participate in the experiment. Demographic data is displayed in table 1. The study was approved by Human Research Ethics Committee of the Queensland University of Technology and participants were informed of the requirements of the study prior to signing a consent form.

2.2 Protocol and study design

The participants attended the laboratory on four separate occasions. The first session involved the collection of anthropometric data and a maximal incremental treadmill test to determine maximal aerobic capacity ($\dot{V}O_{2max}$) and heart rate (HR_{max}). The remaining three sessions involved the participants completing 120 minutes of treadmill walking that differed only in the PBA that was worn by the participants:

(1) Control: tactical utility pants (Frontline, Australia), short sleeve shirt with collar (Under Armour, Curtis Bay, MD, USA) and utility belt. Participants wore underwear and shoes of their own choice.

(2) Overt: as per control conditions plus the addition of overt PBA (worn over the top of the shirt) weighing 2.977 kg (Craig International Ballistics, South Port, QLD, Australia).

(3) Covert: as per control condition plus the addition of an under armour t-shirt (Under Armour, Curtis Bay, MD, USA) and covert PBA (worn beneath the shirt) weighing 2.571 kg (Point Blank Body Armour, Pompino Beach, FL, USA).

Maximal aerobic capacity was determined from an incremental exercise test, as previously described (Stewart et al, 2014). Maximal and resting heart rates (Polar Team[2], Kempele, Finland) were also recorded during this session and utilised in the determination of the trial workloads. During the remaining three trials participants walked on a treadmill (Stairmaster Club track 2100-LC, Nautilus, Louisville, USA) at a workload that elicited a heart rate, within the first five minutes of the 120 minute trial, of 22% heart rate reserve. This workload averaged 4.5 (range 4 – 5) $km \cdot h^{-1}$ and 1.6 (range 1 – 2) % grade and was selected because the previous field study conducted on armoured vehicle officers found 22% of HRR was the average work intensity from a standard 8 hour shift (Stewart and Hunt, 2011). The order of testing (overt, covert, control) was randomised using a random number generator in a controlled crossover design. In addition, all trials were performed at the same time of the day and separated by a minimum of seven days. Participants were requested to abstain from alcohol, tobacco, caffeine and strenuous exercise, and consume an additional 15 ml of water per kg of body mass in the 24 hours preceding each trial.

Upon arrival, for the three PBA trials, participants were asked to collect a mid-stream urine sample that was assessed for specific gravity (USG) (PAL 10s, ATAGO, Tokyo, Japan). Participants' with a USG value less than 1.020 were classified as euhydrated (Armstrong, 2005; Hunt et al., 2012) and those with higher values were provided with an additional 500 ml of water to consumed prior to the commencement of walking. Nude body mass was measured, to the nearest 50gm (Tanita BWB-600, Wedderburn, Australia) and corrected for fluid consumption, both pre and post-trials to determine sweat losses.

During the 120 minutes of walking, intestinal core temperature (CorTemp, HQ inc, Palmetto FL, USA) (Byrne and Lim, 2007; Hunt and Stewart, 2008), heart rate (Polar Team[2], Kempele, Finland) and mean skin temperature (eTemperature, OnSolution, Baulkham Hills, Australia), calculated from the neck, scapula, hand and shin (ISO 9866, 2004; Smith et al., 2010), were monitored continuously and recorded at 15 minute intervals. Additionally, subjects were asked every fifteen minutes to rate their perceived exertion (Borg, 1962), thermal comfort (Gagge et al., 1969) and thermal sensation (Gagge et al., 1969). At the 30, 60, and 90 minute periods the subjects were given 500ml of water to drink for a total fluid consumption of 1.5L (Caldwell et al., 2011). The drinking water was provided at the same temperature as the climate chamber (31°C) to minimise any cooling effect of the consumption.

2.2.1 Experimental Conditions

All subjects completed the three PBA trials in a climate chamber (4x3x2.5 m; length, width, height) at an ambient temperature of 31°C, 60% relative humidity, 4.7 km/h simulated wind speed and with a radiant heat load (two radiant heaters positioned 0.8 m-1.8 m from the participant), that produced an average wet bulb globe temperature of 29±1.3°C. The climatic conditions represented the upper limit for acclimatized individuals undertaking continuous activity at a low metabolic rate in an occupational setting (ISO7933, 2004). Subjects were assumed to be acclimatized given the sub-tropical location within Australia that they resided and that data collection occurred during the summer months. The average temperatures of the geographical location during the testing period were approximately 28.3°C and 69% relative humidity (Meteorology, 2013).

2.3 Statistical Analysis

The experiment was based on a repeated measures experimental design with subjects acting as their own controls, participating in all trials and wearing each of the PBA ensembles. Between-trial differences were measured using two-way [ensemble (control, overt, covert) x time (0, 15, 30, 45, 60, 75, 90, 105 and 120 minutes)] repeated measures analyses of variance.

The effect of ensemble, time and ensemble by time interactions were all tested in the analysis. When significant main effects were found ($P < 0.05$), paired sample t-tests using a Bonferroni correction was used to investigate within-group differences. All variables were tested for normality via a Shapiro-Wilks test, where sphericity was violated; the Greenhouse-Geisser correction was used. All statistical analyses were done via the Statistical Package for the Social Sciences (SPSS version 19.0, Chicago, IL). Alpha was set at 0.05 for all statistical comparisons.

3. Results

All subjects completed all three trials. T_c was similar at the start of each trial (control 37.2±0.1, overt 37.2±0.2, covert 37.2±0.3; P=0.892) and significantly increased after the onset of exercise in all ensembles (P<0.01) (Fig. 1). Post-hoc analysis revealed that T_c from 15-120 minutes was greater than T_c at the start of the trial (P<0.05). However, at no point was there any difference between ensembles (P=0.58) nor was there any significant interaction between ensembles and time observed (P=0.381).

HR was similar at the start of each trial (control 78±12 bpm, overt 84±20 bpm, covert 84±11 bpm; P=0.399) (Fig. 2). HR significantly increased after the onset of exercise (P<0.01). Post-Hoc analysis revealed that heart rate from 15-120 minutes was greater than heart rate at the start (P<0.05). However, at no point was there any significant difference between ensembles (P=0.07) nor was there any significant interaction between ensembles and time (P=0.29).

No significant difference was observed between ensembles for mean T_{sk} (control 34.7±0.2, overt 34.8±0.2, covert 35.0±0.1˚C; P=0.46). A significant main effect for time was observed (P<0.01), with post-hoc analysis revealing that mean T_{sk} was greater from the 15 minute time point on compared with baseline (Fig. 3). A time by ensemble interaction was also observed (P<0.01). Secondary analysis of all individual skin temperature sites (neck, right scapula, left hand and right shin) revealed that only the right scapula skin temperature had a significant ensemble main effect (P=0.04). Pair wise comparisons indicated that the right scapula skin temperature in the covert condition (35.8±0.3˚C) approached statistical significance against the control condition (34.8±0.2˚C, P=0.09) but not against the overt condition (35.3±0.4˚C, P=0.57).

A significant difference in percent body mass change was observed between ensembles (control -1.07±0.38, overt -1.27±0.44, covert -1.81±0.44˚C, P<0.01) (Fig. 4). Post hoc analysis showed that participants wearing covert body armour had a higher percentage body mass loss compared to the control (P=0.009) and the overt body armour trials (P=0.025). No differences were observed when control was compared to overt (P=0.422).

Subjective measures of exertion, thermal comfort and sensation showed no significant difference between ensembles or interaction (P>0.05).

4. Discussion

This study sought to evaluate the thermophysiological effects of wearing two different ensembles of lightweight PBA (overt and covert). Although the adverse thermal effects of protective clothing in military settings have been well documented there is a scarcity of research that solely focuses on light weight, non-military body armour (Larsen et al., 2011; Larsen et al., 2012; Stewart and Hunt, 2011; Stewart et al., 2013). To our knowledge this was the first study that examined these ensembles in a controlled laboratory setting.

The Australian Institute of Occupational Hygienists (DiCorleto et al., 2003) and the International Standards Organisation (ISO 9866, 2004) recommend that core body temperature should not increase past 38.5°C for medically selected and/or acclimatized personnel. None of the participants in this study recorded a T_c of this magnitude (highest single core temperature of any participant was 38.2°C) nor do the results suggest that either body armour ensemble (control, overt or covert) in 30ºC WBGT for 120 minutes of low intensity exercise places the wearer at an increased risk of exceeding this value (Fig 1.). These findings were consistent with the previous field studies conducted on security guards (Lehmacher et al., 2007; Stewart and Hunt, 2011).

Heart rate at a workplace should not get within 20 beats of an individual's maximum heart rate (ISO 9866, 2004). Using this value and the participant's maximum heart rate from their $\dot{V}O_{2max}$ test, no subject in the current study exceeded this limit (Fig 2). Indeed, on average participant's heart rate was 56±7 bpm below their maximum heart rate. In an earlier field study (Stewart and Hunt, 2011) on armoured vehicle officers, the average heart rate across the entire work shift was found to be 22% of their HRR and the gait speed in the current investigation was altered to elicit this percentage of heart rate reserve within the first five minutes of the 120 minute trial. Although HRR increased in all trials, as expected with thermally-induced cardiovascular drift (Montain and Coyle, 1992), no differences between ensembles were observed at any time (Fig 2).

Elevated skin temperatures are indicative of an increase in cardiovascular strain (Cheuvront et al., 2010) and are reflective of increased blood flow to the skin for heat removal (Kenefick et al., 2010). Skin temperatures in excess of 35°C are considered outside the thermoneutral zone (Savage and Brengelmann, 1996) and work is recommended to cease before skin temperature at any anatomical site reaches 43°C (ISO 9866, 2004). The highest skin temperature recorded in the current study was 37.3°C. The modest increase of skin temperature compared to international standards confirms that the exercise intensity and the body armour were not sufficient to increase skin temperature to occupationally unsafe levels. This finding is similar to one of the field studies (Lehmacher et al., 2007) that reported a significant increase in mean skin temperature of 2°C in a vested condition regardless of external environmental conditions.

Interestingly, a significant change in percent body mass was observed between ensembles (Fig. 4). Our results indicate the covert body armour condition produced a higher sweat loss relative to the other conditions. The average loss in body mass with the covert ensemble (1.81±0.44%) was however below the 2-3% body mass loss typically considered as a dehydrated state (Armstrong et al., 2007; Casa et al., 2000; Cheuvront et al., 2007; Montain, 2008). The significantly different amount of body mass change observed in the covert body armour ensemble relative to the other trials was most likely a result of the bio-physical properties and the constricting nature of the covert armour forming a microenvironment close to the skin. A microenvironment can influence the cooling capacity of the skin by increasing vapour resistance, thereby reducing conductive heat loss and forming a layer of ‘still air’ close to the skin, reducing convective heat loss (Havenith et al., 1999). It is likely that this microenvironment would have resulted in significantly higher skin temperatures in that area and this is supported by the observation of a higher scapular skin temperature in the covert ensemble.

Of the 24 individual trials conducted across three ensembles only 4 resulted in a body mass change exceeding 2% with the highest being 2.3% in the covert ensemble trial. These findings may have implications for hydration strategies as 2% decrements in body mass have previously been associated with physical and cognitive performance (Armstrong, 2007; Casa et al., 2000); however, no significant differences were observed between ensembles in subjective ratings of exertion, thermal sensation and discomfort. It is worth noting that the current study permitted participants to consume 500ml of water every 30 minutes. This protocol mimicked a previous laboratory based study that examined military PBA for the same duration of time (Caldwell et al., 2011) and also was designed to replace an expected 1 L/hr sweat loss commonly associated with mild to moderate levels of activity in the heat (Sawka and Noakes, 2007).

Subjective ratings of perceived exertion, thermal sensation and comfort all increased within trials yet no differences were observed between the ensembles. Increases in perceived exertion and thermal comfort and sensation are most likely a result of increased skin temperatures and cardiovascular strain (Gagge et al., 1969).

The findings of the present study are limited to young, healthy males. Future studies should utilise security guards from within the industry for greater generalizability of findings. Although the exercise intensity and environmental conditions were controlled, the protocol employed in the current study did not mimic the intermittent activity undertaken by security guards detailed in previous field studies (Lehmacher et al., 2007; Stewart and Hunt, 2011). However, the continuous exercise intensity and high WBGT is in line with the upper limits of international testing standards (ISO 9866, 2004) for determining physiological strain of individuals wearing personal protective equipment and would have on average produced a more challenging combination of environment and workload than experienced by security guards in the field.

In conclusion, the heat strain encountered in a hot and humid environment while wearing both overt and covert lightweight, non-military PBA was negligible compared to no PBA.

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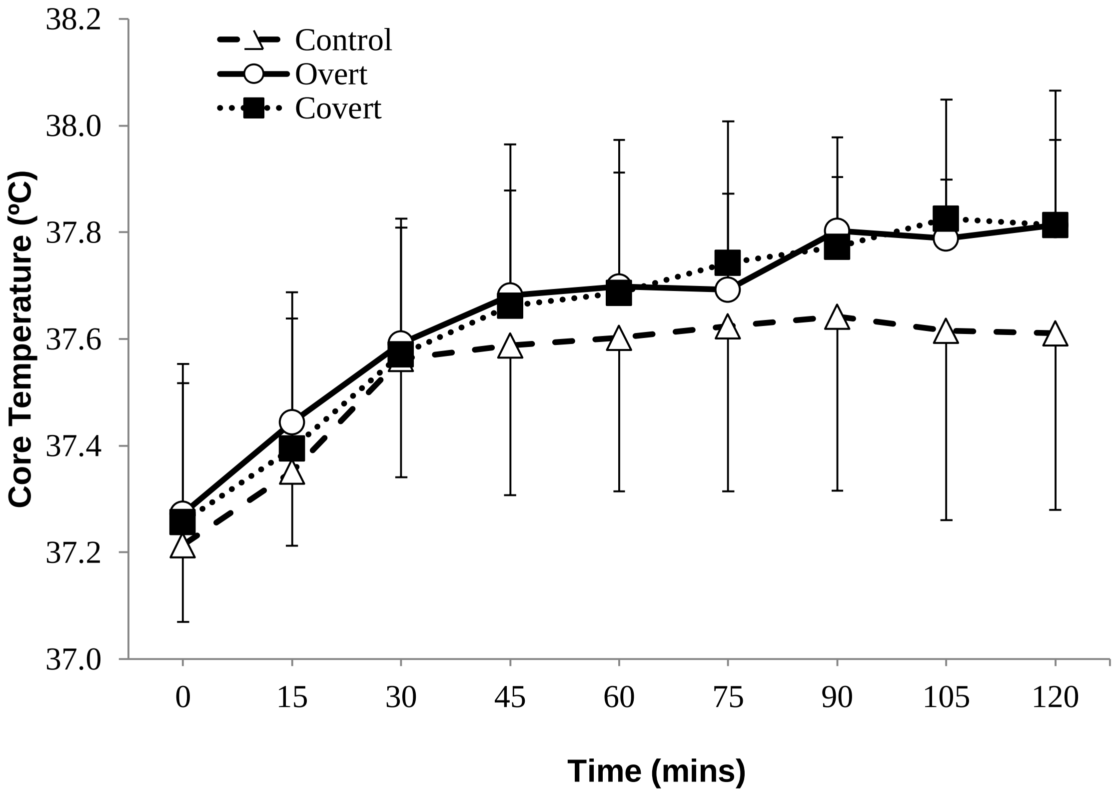
Figure 1 Core Temperature response during 120 minutes of low intensity exercise (22% HRR in 30°C WBGT) whilst wearing either no (control), overt or covert armour. Data are means and standard deviation.

Figure 2 Heart rate response during 120 minutes of low intensity exercise (22% HRR in 30°C WBGT) whilst wearing either no (control), overt or covert armour. Data are means and standard deviations.

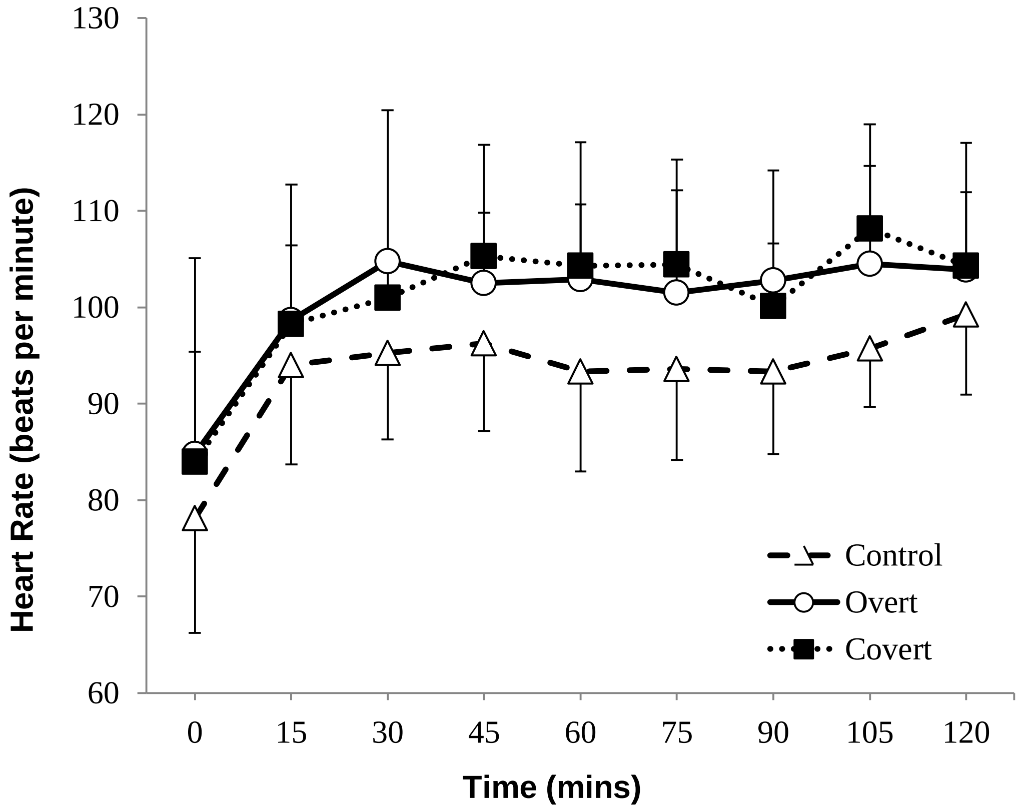
Figure 3 Mean skin temperature response during 120 minutes of low intensity exercise (22% HRR in 30°C WBGT) whilst wearing either no (control), overt or covert armour. Data are means and standard deviations. * Indicates a significant difference between control and covert. # indicates a significant difference between overt and covert.

Figure 4 Body mass change following 120 minutes of low intensity exercise (22% HRR in 30°C WBGT) whilst wearing either no, overt or covert armour. Individual data represented by closed circles and mean data by cross. * Indicates a significant difference between covert and the other conditions.

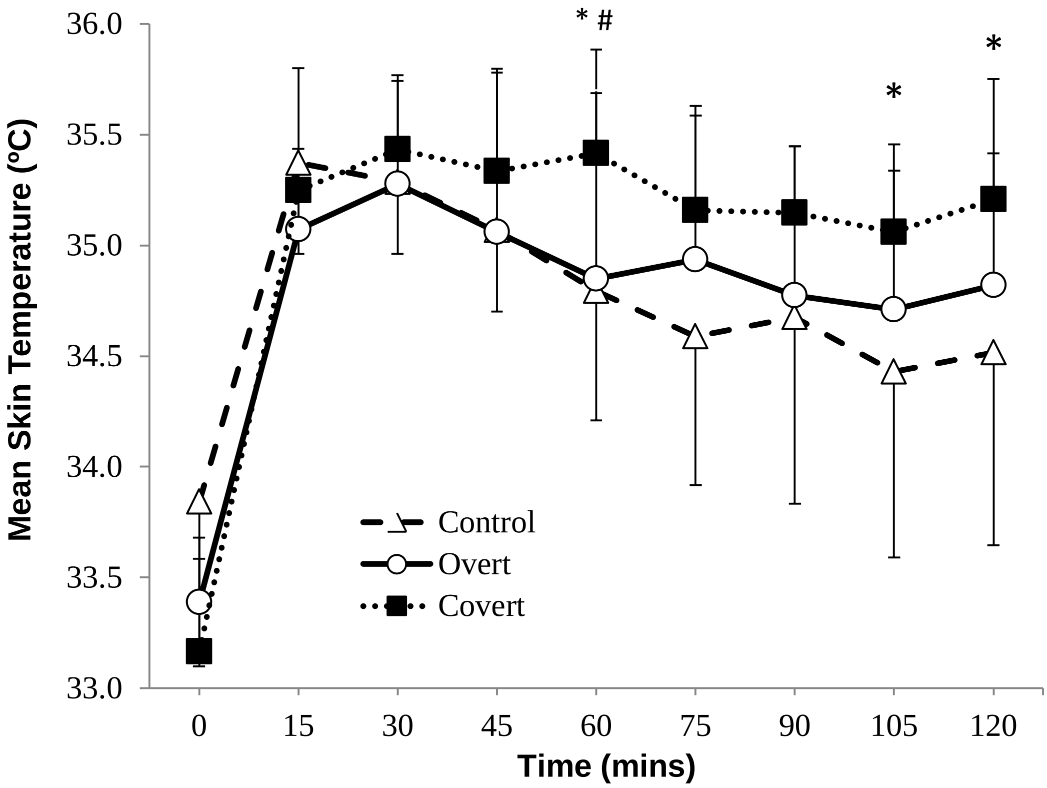
Table 1. Subjects' anthropometric and physiological characteristics. Values are mean ± SD and range.



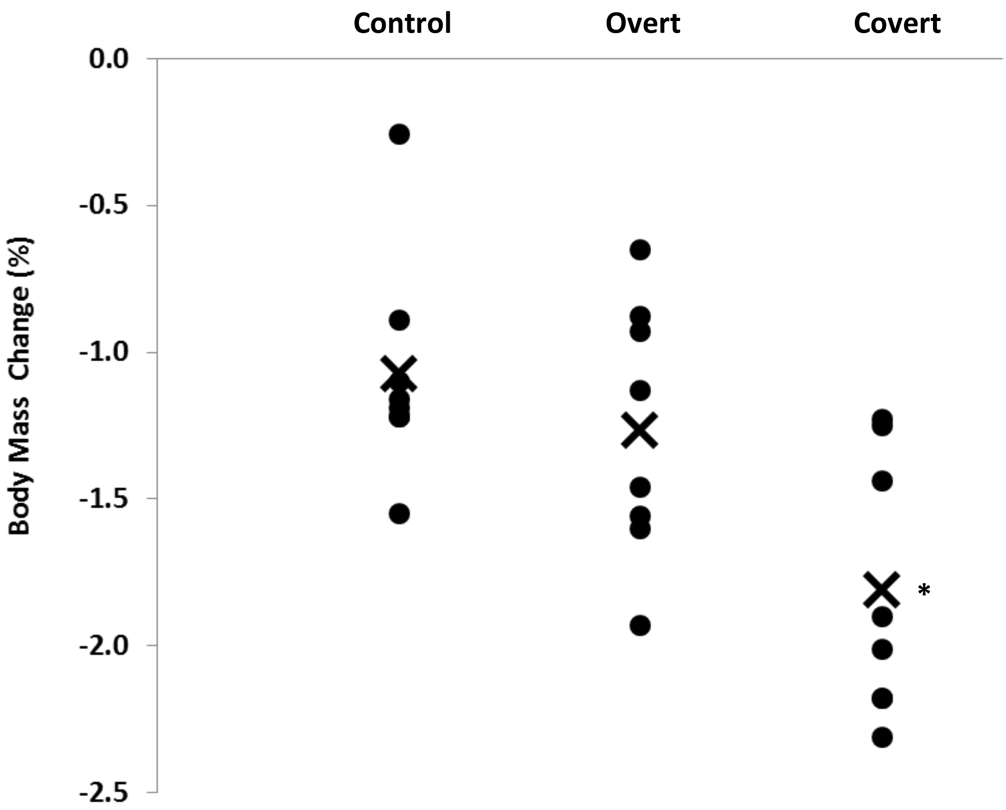
Control
Overt
Covert
38.2
38.0
37.8
37.6
37.4
37.2
37.0
Core Temperature (ºC)
0
15
30
45
60
75
90
105
120
Time (mins)



Heart Rate (beats per minute)
130
120
110
100
90
80
70
60
0
15
30
45
60
75
90
105
120
Time (mins)
Control
Overt
Covert



Mean Skin Temperature (ºC)
36.0
35.5
35.0
34.5
34.0
33.5
33.0
* #
*
*
Control
Overt
Covert
0
15
30
45
60
75
90
105
120
Time (mins)


Control
Overt
Covert
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Body Mass Change (%)
*

Age (yrs)	Mass (kg)	Height (m)	$V0_{2max}$ (ml.kg^{-1}.min^{-1})	Heart Rate Max (bpm)	Σ 6 Skin folds (mm)
26±5.9 (20-39)	76±6.3 (71-87)	1.7±0.6 (1.7-1.9)	55.5±7.9 (42-66)	191±7.4 (185-201)	59.9±21.8 (38.5-104.6)