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Effects of heat acclimatisation on work tolerance and thermoregulation in trained tropical natives

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ABSTRACT

This study aimed to investigate the effects of heat acclimatisation on thermoregulatory responses and work tolerance in trained individuals residing in the tropics. Eighteen male trained soldiers, who are native to a warm and humid climate, performed a total of four heat stress tests donning the Skeletal Battle Order (SBO, 20.5 kg) and Full Battle Order (FBO, 24.7 kg) before (PRE) and after (POST) a 10-day heat acclimatisation programme. The trials were conducted in an environmental chamber (dry bulb temperature: 32 °C, relative humidity: 70%, solar radiation: 400 W/m^2). Excluding the data sets of which participants fully completed the heat stress tests (210 min) before and after heat acclimatisation, work tolerance was improved from 173 ± 30 to 201 ± 18 min (~21%, $p<0.05$, $n=9$) following heat acclimatisation. Following heat acclimatisation, chest skin temperature during exercise was lowered in SBO (PRE=36.7 ± 0.3 vs. POST=36.5 ± 0.3 °C, $p<0.01$) and FBO (PRE=36.8 ± 0.4 vs. POST=36.6 ± 0.3 °C, $p<0.01$). Ratings of perceived exertion were decreased with SBO and FBO (PRE=11 ± 2; POST=10 ± 2; $p<0.05$) after heat acclimatisation. Heat acclimatisation had no effects on baseline body core temperature, heart rate and sweat rate across trials ($p>0.05$). A heat acclimatisation programme improves work tolerance with minimal effects on thermoregulation in trained tropical natives.

1. Introduction

Heat acclimatisation or acclimation mitigates heat strain and improves work output during physical activity in a warm climate. Acclimatisation involves natural exposure to a warm environment, whereas acclimation involves artificial exposure in a controlled environmental chamber. Both result in similar physiological adaptations if all factors are identical in both environments (Armstrong and Maresh, 1991).

Living and working in hot, humid tropics and in hot, dry heat confers some degree of acclimatisation, but the physiological adjustments are likely to be inferior to the degree of adaptation in those subjected to a systematic acclimatisation procedure (Wyndham et al., 1964; Avellini et al., 1980; Buono et al., 1998). The classic description of the heat-acclimatised individual includes lowered rectal temperatures, heart rates, and perceived exertion, and an earlier onset of sweating response during exercise in the heat (Wyndham et al., 1968; Nadel et al., 1974; Roberts et al., 1977; Shapiro et al., 1981). These adaptations reduce physiological strain, improve the individual's ability to exercise in a warm environment and reduce the incidence of heat illness (Armstrong and Maresh, 1991; Wenger, 2002). However, there are limited data on heat acclimatisation or acclimation in tropical natives (Magalhães et al., 2010) and the classical model describing adaptations to consecutive days of heat exposure is based primarily on temperate climate inhabitants.

Natives who work in the tropics may have attained some degree of heat acclimatisation (Wenger, 2002). Lim et al. (1997) investigated the physiological responses of military recruits in the tropics to a heat stress test, over a 16-week basic military training programme. Based on their results, the authors concluded that long-term passive heat exposure was effective at inducing thermoregulatory adaptations. The number of incomplete heat stress tests due to poor work tolerance decreased from 43% at baseline to 14% at the sixteenth week. While these results provide an insight to the degree of heat acclimatisation possible in tropical natives, the 16-week basic military training programme was not a structured heat acclimatisation programme. We are unaware of any study that has investigated the adaptation profiles of trained tropical natives, following systematic heat acclimatisation. Classic physiological adaptations that are stimulated by heat acclimatisation/acclimation, such as expansion of plasma volume and stroke volume, decrease

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in heart rate, increase in sweat rate etc., can also be induced via training. By studying a trained cohort, we can confidently attribute the resultant outcomes to the prescribed heat acclimatisation programme. This information is important for recommending appropriate heat acclimatisation guidelines to tropical native athletes and military personnel undergoing physical training and competition/operation in a warm and humid environment.

Military uniform and equipment are necessary components for the survivability and success of troops, but induce additional stress to the soldier working in warm climates. During physical tasks, protective clothing causes a downward shift in the temperature at which heat strain occurs (Brennan, 2006), resulting in an increased body core temperature, heart rate and sweat rate (Gonzalez, 1988; Havenith, 1999; Lehmacher et al., 2007). The investigation of soldiers carrying standard infantry load will complement previous heat acclimation studies of soldiers in standard combat clothing and clothing protecting against nuclear, biological and chemical agents (Yarger et al., 1969; Aoyagi et al., 1994).

The objective of this study was to evaluate the efficacy of a 10-day heat acclimatisation programme in trained native soldiers (9 months of full-time military training) working with typical military load in warm and humid conditions. It was hypothesised that the heat acclimatisation programme would enhance thermoregulatory and cardiovascular adjustments, thereby improving the soldiers' work tolerance in warm and humid conditions.

2. Material and methods

2.1. Study population

Eighteen male conscript soldiers (mean ± SD (range); age = 20 ± 2 (18–24 y), body mass = 63.4 ± 6.6 (52.0–76.7 kg), stature = 1.71 ± 0.06 (1.61–1.81 m), body mass index = 21.7 ± 2.2 (18.1–25.3 kg/m^2), body surface area = 1.74 ± 0.11 (1.57–1.97 m^2)), from the Singapore Armed Forces (SAF) provided both verbal and written consent to participate in this study. The study was approved by the Institutional Review Board. The participants were all natives of Singapore, which is located near the equator (latitude 1° 14′N, longitude 103° 55′E). The weather in Singapore is generally warm (~24 °C to 32 °C) and humid (~55% to 95%) throughout the year. Prior to recruitment, all participants had completed three months of basic military training, three months of specialists' training and three months of regular infantry training. In addition, each participant underwent a medical screening process and was certified fit to participate in this study.

2.2. Preliminary measurements

Participants were requested to avoid strenuous physical activity and to refrain from ingesting alcohol for 24 h before each laboratory trial. Commencement time for trials was standardised for each participant to control for circadian variations in core temperature (Reilly and Brooks, 1986). Each participant arrived at the testing laboratory 3 h before the start of exercise, and consumed biscuits (Hup Seng Wholemeal Crackers, 25 g, 3 pieces/packet; 0–2 packets), white bread (1–5 slices) and chocolate malt drink (Nestlé Milo; 0–2 cups) *ad libitum*. The amount ingested was recorded on the first visit and was repeated for subsequent trials. Each participant ingested 500 ml of water 90 min prior to the start of exercise. These procedures attempted to ensure that participants were euhydrated and euglycemic at the onset of exercise. Pre-trial control and physiological measurements were only performed during laboratory trials, and not during the 10 days of heat acclimatisation.

2.3. Experimental design

Participants donned a standard infantry Skeletal Battle Order (SBO) and Full Battle Order (FBO) in separate trials. They participated in a total of four laboratory trials before (PRE) and after (POST) heat acclimatisation. The trials were therefore as follows: SBO-PRE, FBO-PRE, SBO-POST and FBO-POST. The SBO weighed 20.5 kg and consisted of a camouflage uniform with underwear, combat boots with socks, body armour, load bearing vest with standard accessories, Kevlar helmet, and rifle replica. The FBO weighed 24.7 kg, and consisted of the SBO and a backpack filled with additional accessories, configured onto a frame. This backpack with additional accessories accounted for the 4.2 kg difference between SBO and FBO. All backpacks used in the study were packed in the same configuration. Trials were separated by at least 7 days to permit adequate recovery, minimise any training effects and limit the development of heat acclimation (Barnett and Maughan, 1993). The trials were counterbalanced such that, out of the 18 participants, nine participants started with SBO while the remaining nine participants started with FBO, before and after the heat acclimatisation programme.

Gastro-intestinal temperature was used as an index of body core temperature (T_c). Participants ingested a telemetric temperature sensor (VitalSense®, Mini Mitter Company, Inc, USA) between 8 and 10 h before the start of each trial. Upon arrival at the laboratory for each trial, a telemetric check was performed to ensure that the temperature sensor was residing within the participant and was transmitting a signal. A urine sample was collected from the participant. Urine osmolality was determined by freezing point depression (Osmomat 030-D, Gonotec, Germany). Stature was obtained to the nearest 0.5 cm using a stadiometer (only on the first visit; Seca, Germany) and nude body mass was measured to the nearest 0.001 kg with an electronic precision balance scale (Mettler Toledo (Albstadt) GmbH, Germany). Any urine produced after nude body mass measurement was quantified for its volume. Body mass index was calculated as (body mass in kg)/(height in m)^2 and body surface area estimated using the equation of Dubois and Dubois (1916) as 0.202 × (body mass in kg)$^{0.425}$ × (height in m)$^{0.725}$. A heart rate (HR) transmitter (Polar Vantage, Polar Electro Oy, Kempele, Finland) was secured on the participant. The ambulatory core temperature data-recording device was placed in a sealable waterproof bag and inserted into a front pouch of the SBO. Skin thermistors (Squirrel, 1000 Series, Grant Instruments, Cambridge, UK) were placed on the right side of the participant's body (chest, upper arm and thigh). Mean weighted skin temperature was computed using: 0.43 × chest temperature + 0.25 × upper arm temperature + 0.32 × thigh temperature (Roberts et al., 1977). Participants entered an environmental chamber (VEKZ10, Vötsch Industrietechnik, Germany) 15 min before the start of marching, to ensure thermal equilibrium with the environment. The dry bulb temperature was set at 32 °C, with relative humidity of 70% and solar radiation of 400 W/m^2.

Each laboratory trial involved a simulated route march comprising three 60-min marches on the treadmill at 4 km/h and 0% gradient, with each exercise bout separated by 15-min seated rest. Body core temperature and chest, upper arm and thigh skin temperatures were obtained every 5 min. Heart rate was monitored by short-range telemetry and recorded every 5 min. Subjective ratings of perceived exertion (RPE; Borg, 1982) and thermal sensation (TS; ASHRAE, 1981) were obtained every 15 min. Participants were offered bottles containing 500 ml of water every 15 min for ad libitum fluid ingestion. The amount of fluids consumed was recorded on each of the SBO-PRE and FBO-PRE trials and was repeated for the SBO-POST and FBO-POST trials. Water temperature was maintained at 37.5–38.0 °C with a heated water bath to minimise the direct influence of water ingestion on the ingestible temperature capsule, in cases where gastro-intestinal transition time might be slow in some individuals. Exercise was prematurely terminated at 39.5 °C T_c (pre-determined ethical threshold), upon request by the participant, or when the researchers observed unusual signs of discomfort. Work tolerance for each load configuration was calculated as: (number of completed trials/number of attempted trials) × 100%.

Upon completion or termination of the simulated route march, participants exited the environmental chamber, removed all instrumentation and provided a complete urine sample. Nude body mass was measured within 10 min following the removal of any unevaporated sweat with a towel. Sweat loss was estimated from the difference in body masses, corrected for fluid intake and urine production, and not corrected for respiratory water loss and metabolic water production: sweat loss=(pre-exercise body mass—post-exercise body mass)+ingested fluid—urine output. Sweat rate was estimated by: sweat loss/exercise time.

2.4. Heat acclimatisation protocol

The 10-day heat acclimatisation programme, executed in two 5-day blocks separated by a weekend, comprised outdoor route marches at 4 km/h in a warm and humid climate (mean dry bulb temperature 29.0 ± 2.5 °C, mean relative humidity 80 ± 13%). Exercise was enforced in two work-rest cycles, with work duration progressively increased from 1 × 30 min and 1 × 45 min to 2 × 60 min. The SBO was donned from Day 1–6 and the FBO from Day 7–10. Distance covered increased progressively from 5 to 8 km. For each day of heat acclimatisation, a rest period of 15-min was given between the work-rest cycles from Day 1–6. From Day 7–10, a rest period of 30-min was given between the work-rest cycles to prevent overreaching. We had previously profiled a similar cohort of soldiers during a standard military route march in our climate (mean dry bulb temperature 28.6 °C, mean relative humidity 84%), consisting of two 60-min exercise sets separated by a 15-min rest interval (unpublished results). In that study, mean T_c was elevated by ~1 °C at 35 min of the second 60-min exercise set and rose further by ~0.3 °C at the end of exercise. These data suggest that the heat acclimatisation programme imposed in our study is sufficient to elevate T_c by 1 °C and maintain the elevation for 30 min. Our heat acclimatisation programme was comparable to the one employed by Magalhães et al. (2010) in a recent study that also studied tropical natives and found to be effective in eliciting classical thermoregulatory responses. The duration, intensity and frequency of the heat acclimatisation sessions used in our study are akin to previous heat acclimatisation/acclimation programmes shown to be effective in eliciting thermoregulatory changes (Wenger, 2002). In addition to the heat acclimatisation programme, the participants continued with non-physically demanding duties (e.g. outdoor lessons) in a tropical climate (24–32 °C dry bulb temperature, 55–95% relative humidity) during the 2-week period. To minimise the decay of adaptations derived following the heat acclimatisation programme, the participants were told to complete a moderate intensity run for 45 min on alternate days during weekdays under the supervision of the unit's commanders until they completed the study.

2.5. Statistical analysis

All statistical computations were performed using the Statistical Package for Social Sciences (SPSS) version 15.0. Data are presented as mean ± standard deviation. The results represent responses of 18 participants, except for end chest skin temperature with FBO, end thigh skin temperature with SBO, end weighted skin temperature and HR responses in 17 participants. One-factor repeated measures analysis of variance (ANOVA) was performed across all four trials to evaluate differences in baseline values. For each load configuration, a paired Student t-test isolated differences in T_c and measured variables at the end of exercise, before and after the heat acclimatisation programme. Two-factor (i.e. trial and time) repeated measures ANOVA was used to evaluate changes in T_c, chest, upper arm, thigh and weighted skin temperatures, and subjective responses over time. Variables were analysed until the time point completed by all participants in each load configuration. With the SBO, variables were analysed up to 105 min and at the end of exercise. With the FBO, variables were analysed up to 120 min and at the end of exercise. A 0.05 level of significance was used for all statistical analyses.

3. Results

3.1. PRE-trial physiological status

There were no statistically significant differences in physiological parameters, namely body mass, urine osmolality, heart rate, and core and skin temperatures, measured prior to all laboratory trials (Table 1). Similar hydration status before each trial was indicated by consistency of body mass and urine osmolality. Participants were considered euhydrated (≤900 mosmol/kg) prior to each trial, as demonstrated by pre-exercise urine osmolality (Shirreffs and Maughan, 1998). A subset analysis of 12 participants revealed similar aerobic fitness, as depicted by their 1.5-mile running times, before (603 ± 37 s) and after (627 ± 45 s; $p=0.075$) undergoing the heat acclimatisation programme.

3.2. Work tolerance

Individual work tolerance times for SBO and FBO before and after heat acclimatisation are depicted in Fig. 1. Maximum tolerance time for the laboratory trial was 210 min (three 60-min marches, two 15-min rest intervals). After the heat acclimatisation programme, work tolerance increased from 16 (SBO-PRE=89%) to 17 individuals in the SBO configuration (SBO-POST=94%) and from 13 (FBO-PRE=72%) to 16 individuals in the FBO configuration (FBO-POST=89%). This implies an overall (SBO and FBO) improvement in work tolerance of ~11%. With SBO, two participants did not complete the laboratory trial before heat acclimatisation. Exercise was prematurely

Table 1
Baseline physiological parameters for each of the four experimental trials. Values are in mean ± standard deviation.

Parameters	SBO-PRE	SBO-POST	FBO-PRE	FBO-POST	*P* value
Body mass (kg)	63.6 ± 6.8	63.9 ± 6.8	63.4 ± 6.9	63.7 ± 6.9	0.997
Urine osmolality (mosmol/kg)	403 ± 260	341 ± 233	376 ± 260	524 ± 331	0.216
Core temperature (°C)	37.2 ± 0.3	37.0 ± 0.3	37.1 ± 0.4	37.0 ± 0.3	0.319
Chest skin temperature (°C)	34.7 ± 0.8	34.5 ± 0.7	34.7 ± 0.8	34.5 ± 0.8	0.786
Upper arm skin temperature (°C)	33.8 ± 0.6	33.6 ± 0.7	33.5 ± 0.8	33.4 ± 0.7	0.350
Thigh skin temperature (°C)	33.6 ± 1.0	33.7 ± 0.4	33.9 ± 0.7	33.6 ± 0.6	0.680
Weighted skin temperature (°C)	34.1 ± 0.7	34.0 ± 0.5	34.1 ± 0.7	33.9 ± 0.5	0.740
Heart rate (beats/min)	77 ± 14	80 ± 14	77 ± 19	79 ± 15	0.960

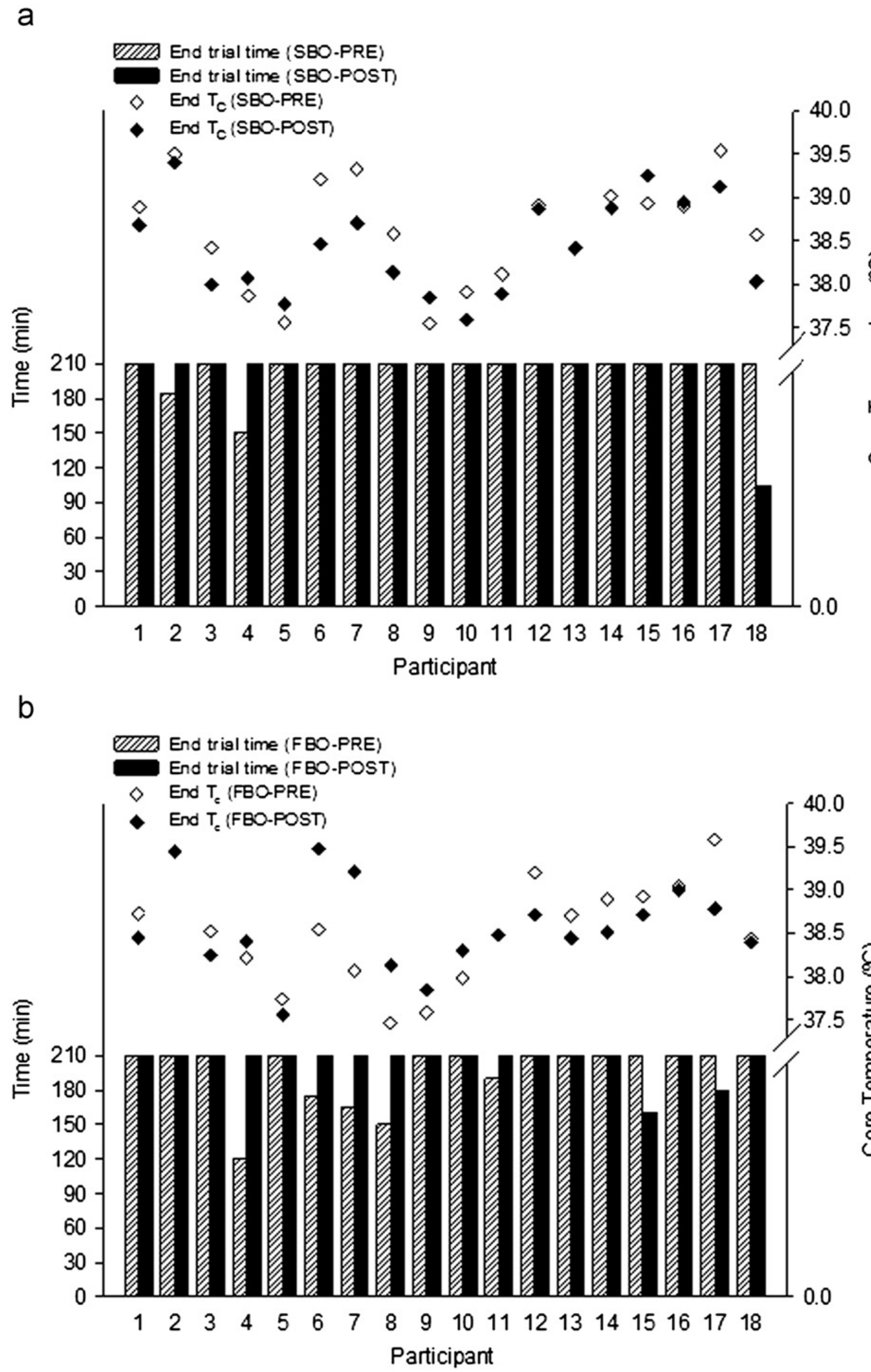

Fig. 1. Individual work tolerance times and end core temperature responses during the laboratory trials ($n=18$) with (a) SBO and (b) FBO before and after heat acclimatisation.

terminated at 185 min for subject 2 and 150 min for subject 4. After heat acclimatisation, one participant did not complete the laboratory trial with SBO. Exercise was prematurely terminated at 105 min for subject 18. It is noteworthy that the termination of trial for subject 18 was due to his sudden complaint of breathing difficulty. With FBO, five participants did not complete the laboratory trial before heat acclimatisation. Exercise was prematurely terminated at 120 min for subject 4, 175 min for subject 6, 165 min for subject 7, 150 min for subject 8 and 190 min for subject 11. After heat acclimatisation, two participants did not complete the laboratory trial with FBO. Exercise was prematurely terminated at 160 min for subject 15 and 180 min for subject 17. A more detailed analysis excluding participants who fully completed both the heat stress tests (and subject 18 who was stopped from continuing due to sudden complaints of breathing difficulty) revealed an improvement in work capacity from 173 ± 30 min to 201 ± 18 min ($\sim$21%; $p<0.05$; $n=9$) before and after heat acclimatisation, respectively.

3.3. *Gastro-intestinal temperature (T_c)*

Resting T_c was similar across trials before and after heat acclimatisation (Table 1). After heat acclimatisation, T_c was lowered from 5 to 15 min with SBO ($p<0.05$) but was similar with FBO (5 min: $p>0.05$; Fig. 2). Mean T_c was similar with SBO (PRE$=38.0 \pm 0.3$; POST$=37.9 \pm 0.3$ °C; $p=0.162$) and FBO (PRE$=38.1 \pm 0.5$; POST$=38.1 \pm 0.4$ °C; $p=0.354$). End T_c was lowered with SBO

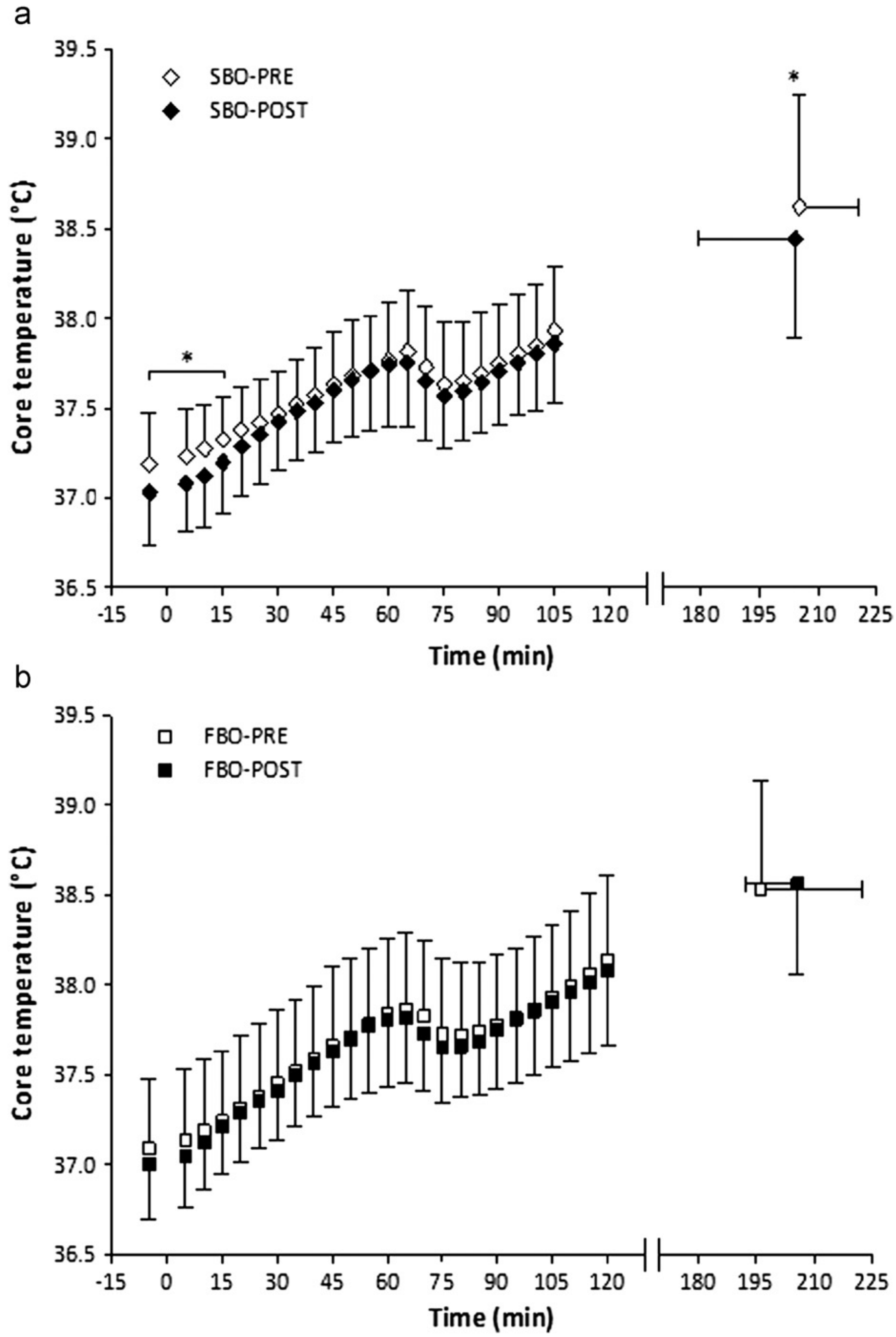

Fig. 2. Core temperature responses during the laboratory trials ($n=18$). Mean values are shown for (a) SBO and (b) FBO. Positive vertical standard deviation is displayed for responses before heat acclimatisation and negative vertical standard deviation after heat acclimatisation. *Significantly different, $p<0.05$.

(PRE $=38.6\pm0.6$; POST $=38.4\pm0.6$ °C; $p=0.032$; Fig. 1a) but was similar with FBO (PRE $=38.5\pm0.6$; POST $=38.6\pm0.5$ °C; $p=0.796$; Fig. 1b).

3.4. Skin temperature

Baseline resting chest, upper arm, thigh and weighted skin temperatures were similar across trials (Table 1). After heat acclimatisation, chest temperature was lowered during exercise with both load configurations. Mean upper arm, thigh and weighted skin temperatures remained similar with both load configurations after heat acclimatisation (Table 2). End chest, upper arm, thigh and weighted skin temperatures were similar with both load configurations after heat acclimatisation.

3.5. Heart rate (HR)

Resting HR was similar across trials (Table 1). After heat acclimatisation, mean HR was similar with SBO (PRE $=115\pm18$; POST $=114\pm16$ beats/min; $p=0.443$) and FBO (PRE $=120\pm16$; POST $=120\pm16$ beats/min; $p=0.698$; Fig. 3).

3.6. Sweat rate

After heat acclimatisation, sweat rate was similar with SBO (SBO-PRE $=0.6\pm0.1$, SBO-POST $=0.6\pm0.2$ l/h; $p=0.905$) and FBO (FBO-PRE $=0.6\pm0.2$, FBO-POST $=0.6\pm0.2$ l/h; $p=0.536$).

Table 2
Mean skin temperature during and at the end of exercise. Values are in mean ± standard deviation.

Skin temperature	SBO			FBO		
	PRE (°C)	POST (°C)	*P* value	PRE (°C)	POST (°C)	*P* value
Chest						
Mean during exercise	36.7 ± 0.3	36.5 ± 0.3*	0.002	36.8 ± 0.4	36.6 ± 0.3*	0.005
End	37.6 ± 0.6	37.2 ± 1.1	0.217	37.5 ± 0.7	37.5 ± 0.6	0.942
Upper arm						
Mean during exercise	34.9 ± 0.6	35.0 ± 0.7	0.634	35.1 ± 0.8	35.0 ± 0.7	0.718
End	35.9 ± 1.4	36.3 ± 0.7	0.172	36.0 ± 1.2	35.9 ± 1.2	0.863
Thigh						
Mean during exercise	35.4 ± 0.4	35.3 ± 0.4	0.152	35.4 ± 0.7	35.3 ± 0.6	0.319
End	36.6 ± 0.6	36.5 ± 0.7	0.424	36.3 ± 1.3	36.4 ± 0.4	0.609
Weighted						
Mean during exercise	35.8 ± 0.4	35.7 ± 0.4	0.261	35.9 ± 0.5	35.8 ± 0.4	0.090
End	36.8 ± 0.6	36.7 ± 0.6	0.706	36.7 ± 0.9	36.7 ± 0.8	0.916

* Significantly different from PRE values, $p < 0.05$.

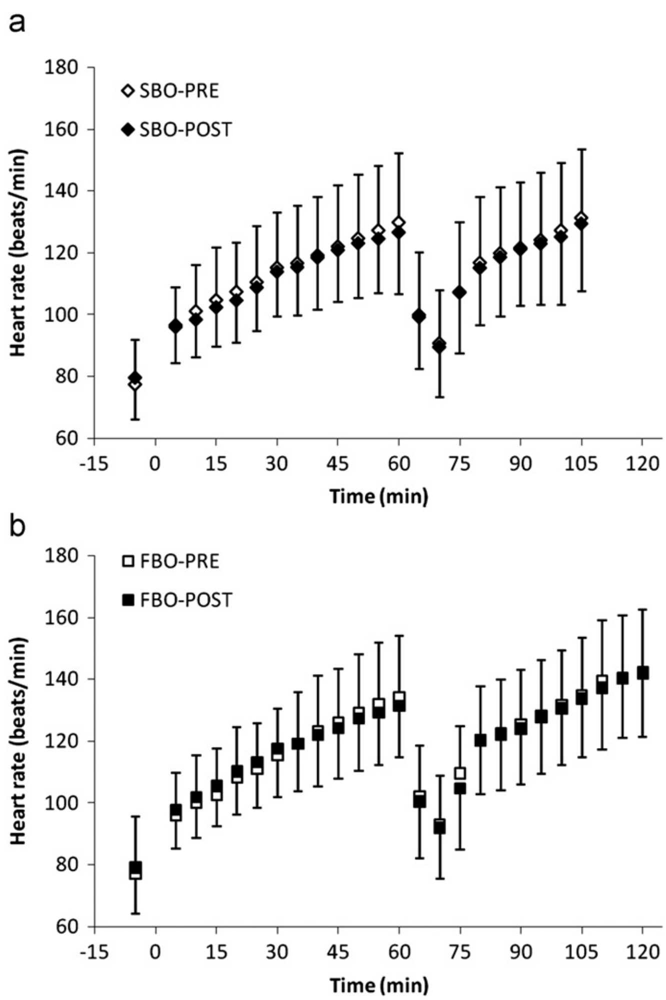

Fig. 3. Heart rate responses during the laboratory trials ($n=17$). Mean values are shown for (a) SBO and (b) FBO. Positive vertical standard deviation is displayed for responses before heat acclimatisation and negative vertical standard deviation after heat acclimatisation.

3.7. Subjective ratings

After heat acclimatisation, RPE was decreased with SBO (PRE$=11\pm2$; POST$=10\pm2$; $p=0.020$) and FBO (PRE$=11\pm2$; POST$=10\pm2$; $p=0.045$; Fig. 4a). Thermal sensation was decreased after heat acclimatisation with SBO (PRE$=1.2\pm0.7$; POST$=0.9\pm0.7$; $p=0.011$), and was similar with FBO (PRE$=1.2\pm0.6$; POST$=1.0\pm0.5$; $p=0.060$; Fig. 4b).

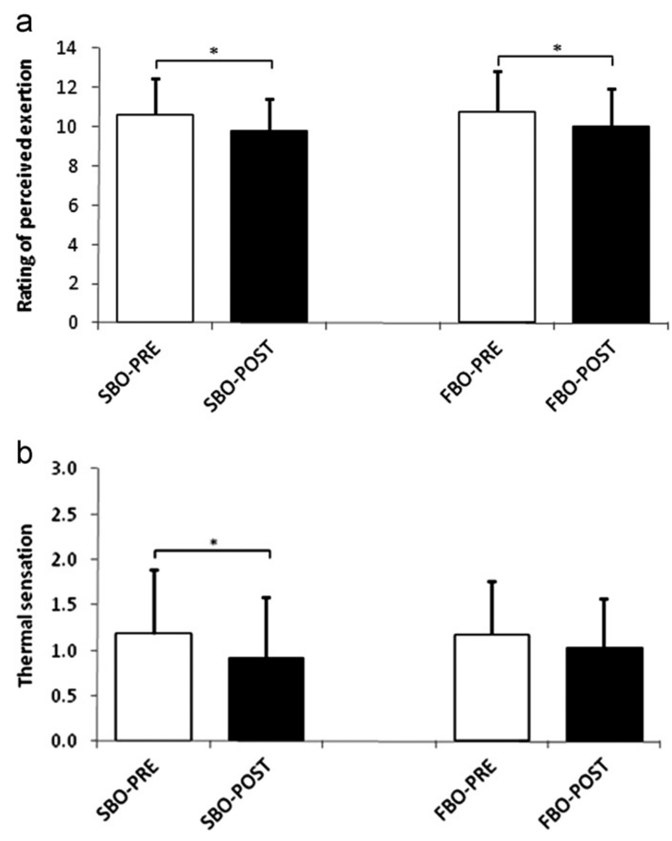

Fig. 4. Mean subjective ratings during the laboratory trials ($n=18$). Mean values+standard deviation are shown for (a) RPE and (b) TS. *Significantly different, $p < 0.05$.

4. Discussion

This study adds to the limited data in the literature on the effects of heat acclimatisation on individuals native to tropical climates. In contrast to our hypothesis, while heat acclimatisation improved work tolerance, minimum thermoregulatory effects were observed, with only a decrease in mean chest skin temperature during exercise with both load configurations. Nevertheless, pertinent to military application, an improvement in work tolerance accentuates the importance of a structured heat acclimatisation programme in soldier training to aid successful completion of military tasks. Our findings are also important to tropical residents who may consider a structured heat acclimatisation programme to augment endurance performance in the heat.

Our results support the findings of Wyndham et al. (1964), who compared highly heat-acclimatised Caucasian males, unacclimatised Caucasian males and Australian males living and working in a hot and humid climate. In that study (Wyndham et al., 1964), ten of the twenty (50%) unacclimatised subjects were unable to complete a 4-h exposure to a warm and humid climate (dry bulb temperature 33.9 °C, wet bulb temperature 32.2 °C), whereas all ten highly acclimatised subjects (100%) completed the exposure in ''high spirits and with no signs of strain''. In addition, all seven Australian males (100%) living and working in a hot and humid climate completed the exposure. As the 'highly heat-acclimatised' and 'living and working in a hot and humid climate' groups were made up of different individuals, our results supplement those of Wyndham et al. (1964) with the comparison of the same 18 tropical male natives before and after a heat acclimatisation programme.

In addition, our results add to an earlier report of untrained Singaporean native soldiers, investigated during a 16-week basic military training programme in a warm and humid environment. In those recruits, the number of incomplete 1-h heat stress trials due to work intolerance decreased threefold from 43% at baseline to 14% after 16 weeks, with no changes in temperature responses (Lim et al., 1997). Similarly, we did not observe any differences in temperature responses. Our study participants were physically active soldiers native to a warm and humid climate, and the lack of classical heat adaptations may be attributed to an existing high degree of heat acclimatisation. Nevertheless, the successive completion of 10 route marches in the heat over two weeks could have induced a learned response, lowering their efforts to complete the heat stress tests following heat acclimatisation. This notion is supported by the lower ratings of perceived exertion reported by the participants after heat acclimatisation. Taken together, these results suggest that heat acclimatisation may still augment work tolerance with minimal effects on thermoregulation in trained tropical natives.

In the classical heat acclimatisation model, acclimatised individuals display 0.4–0.7 °C decreases in T_c responses during heat stress tests compared to unacclimatised individuals (Wyndham et al., 1964; Wyndham et al., 1968; Nadel et al., 1974; Mitchell et al., 1976). In our study, T_c decreased significantly by 0.1–0.2 °C from 5 to 15 min and at the end of exercise with SBO. No differences in T_c were observed at all other time points. We suggest that the transient lowered T_c responses observed in the SBO trial is casual and does not indicate any meaningful enhanced thermoregulation in our study participants after heat acclimatisation. After heat acclimatisation, resting T_c was similar (from ~37.0 to 37.1 °C) in both the SBO and FBO trials. Comparing our baseline values with those of Wyndham et al. (1964), where highly heat-acclimatised South African Caucasian males displayed a 0.7 °C lower resting T_c (36.9 °C) than the less acclimatised Australian Caucasian males living and working in a hot and humid climate (T_c 37.6 °C), our Asian male soldiers may have possessed a greater degree of heat acclimatisation than the Australian males in that study. However, it is necessary to note that the representation of different groups of individuals in the highly heat-acclimatised and less acclimatised cohorts in the study by Wyndham et al. (1964) may have influenced the magnitude of T_c decrease observed.

Reduced local skin temperature may indicate increased local sweat evaporation after heat acclimatisation (Mitchell et al., 1976; Magalhães et al., 2010). In the classical heat acclimatisation model, acclimatised individuals display lowered weighted skin temperature responses compared to unacclimatised individuals (Mitchell et al., 1976; Shapiro et al., 1981). We did not observe any differences in the weighted skin temperature responses before and after heat acclimatisation. However, chest temperature was slightly lower during exercise with both load configurations after heat acclimatisation. Magalhães et al. (2010) also observed a reduced chest skin temperature in tropical natives after heat acclimation, without an increase in local chest sweat rate. The authors attributed the lowered chest skin temperature to an increased chest sweating efficiency. The layers of military uniform and body armour donned by our subjects, however, prevent us from postulating a similar increased chest sweating efficiency.

Adaptation to heat elicits a reduced T_c threshold for sweating onset (Nadel et al., 1974; Roberts et al., 1977), increased sweat rates (Wyndham et al., 1964; Patterson et al., 2004) and an apparent redistribution of sweating toward the limbs (Hofler, 1968; Magalhães et al., 2010). Similar sweat rates and T_c responses, before and after heat acclimatisation in our study, suggest that sweating did not begin at a lower T_c in the participants after heat acclimatisation. Patterson et al. (2004) have shown that reduced sweat thresholds are primarily related to a lower resting mean body temperature, and are dependent on absolute change, rather than the attainment of a specific temperature. Our results are in line with their findings, as similar core temperature responses did not elicit higher sweat rates after heat acclimatisation. Similar upper arm and thigh skin temperatures observed in our study may imply similar limb sweat rates after heat acclimatisation.

With heat acclimatisation, plasma volume and stroke volume increase, enabling the maintenance of cardiac output at lower heart rates. In contrast to reports of decreased heart rates following heat acclimatisation (Wyndham et al., 1964, 1976; Shapiro et al., 1981), similar heart rate responses were observed before and after heat acclimatisation in our study participants. This suggests that our study sample had already attained the cardiovascular advantage of heat acclimatisation from living and training in a warm and humid climate.

Although there were no significant thermoregulatory and cardiovascular changes following heat acclimatisation, it is crucial to appreciate the accompanying enhanced work tolerance. Most of the subjects completed the 3 h of simulated route march in the laboratory even before the heat acclimatisation programme, especially for the SBO trials—16 out of 18 subjects. We therefore suggest that the intensity and duration of the work-rest cycles prescribed in this study may have been too conservative in illustrating the true magnitude of heat acclimatisation in improving work tolerance in the heat. It can be speculated that the effects of heat acclimatisation would have prolonged the work tolerance of our participants if a longer duration and/or increase in exercise intensity had been adopted, i.e. more failures in completing the heat stress test might have been expected prior to the heat acclimatisation programme if the exercise demands were higher. Military training deviates from athletic pursuit in that it requires the team to complete its mission together in a safe manner. Taking our laboratory 210-min exercise trial as a typical military task, heat acclimatisation enhanced completion by one individual (5%) with SBO, and three individuals (17%) with FBO. It is noteworthy that the termination of trial by the researcher for subject 18 after heat acclimatisation was due to a sudden complaint of breathing difficulty. His core temperature at that point was 38.1 °C, implying that thermal strain was not the cause for trial termination. Since this subject did not exhibit unusual signs or symptoms prior to the trial and therefore fulfilled the criteria to perform the trial, we choose to include his data for analysis. Excluding participants who fully completed both the heat stress tests, and subject 18 (who was stopped from continuing), work capacity was improved by 28 min (~21%) after heat acclimatisation. The improved work tolerance observed in our study of trained tropical natives emphasises the importance of a structured heat acclimatisation programme in soldier training to aid successful completion of military tasks.

To our knowledge, there are no performance data on the effects of heat acclimation/acclimatisation on trained tropical natives. The existing evidence on the efficacy of heat acclimation/acclimatisation is mainly derived from Caucasians living in temperate climatic conditions. Comparing the physiological data (core temperature, mean skin temperature, heart rate, sweat rate etc.) before and after the 10-day heat acclimatisation, we attribute the lack of cardiovascular and thermoregulatory improvements in our soldiers to their at least partially acquired heat acclimatisation status from living and training in a warm and humid climate. We speculate that the consecutive exposures (2×5 day) to heat stress while donning load configurations, similar to conditions of the laboratory trials, may have psychologically enhanced participants' confidence in completing the heat stress tests after heat acclimatisation. In addition, there could be other biomarkers, such as cytokines (TNF-α, IL-6, and IL-10) and heat shock proteins, which may be more sensitive for minute physiological adaptations following heat acclimatisation not measured in this study. While the lack of heat acclimatisation in sedentary individuals during summer could be due to frequent air-conditioning use and an avoidance of outdoor activity during the hottest times of day (Bain and Jay, 2011), the natural heat acclimatisation status obtained in physically active soldiers native to the tropics might have already conferred a high degree of tolerance to the heat than that acquired through an acute heat acclimatisation programme (Wenger, 1988).

5. Conclusions

In conclusion, our results suggest that a typical 10-day heat acclimatisation programme can enhance work tolerance with the 20.5 kg and 24.7 kg standard military load configurations in trained soldiers native to a warm and humid climate. However, there were negligible thermoregulatory adaptations and no cardiovascular adjustments were observed. Whether harsher environmental conditions, increased exposure times and/or higher exercise intensities may induce physiological adaptations and further improve work tolerance in our study population needs to be further investigated.

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