Characterisation of physiological performance measures in arid and humid military operational environments

Edward T. Ashworth[1] [*], James D. Cotter[2], Andrew E. Kilding[1]

[1] *Sport Performance Research Institute of New Zealand, Auckland University of Technology, New Zealand*
[2] *School of Physical Education, Otago University, New Zealand*

ABSTRACT

Military personnel often deploy into hot environments that impose substantial strain on physical and cognitive performance. Hot environments can present as arid or humid and occur in different terrains, requiring different operational approaches. The aim of this study was to characterise the physiological, cognitive and perceptual strain experienced by military personnel during typical operations in arid and humid environments. Nine pack-fit military personnel participated in two heat-stress tests to exhaustion, one in an arid environment (44°C, 21% humidity) and the other in a humid environment (33°C, 78% humidity). Participants walked at 5 km.h-1 while physiological, cognitive and perceptual measures were recorded. Tests were terminated volitionally, or by excessive core temperature or heart rate. The operational environments induced similar physiological strain, resulting in no difference in time to exhaustion (p = .155). The humid environment saw a greater elevation in core temperature (+0.3°C, p < .001) and heart rate (+5 b.min-1, p < .001). Skin temperature was greater in the arid environment (+0.4, p < .001) as was sweat evaporation (+0.3 L.h1, p = .045). Baseline performance predictors only provided moderate predictions of performance, whereas changes in perceptual measures provided the best performance predictors during the exercise, specifically perceptions relating to thermal sensation (β = -.65 - -.80) and sleepiness (β = -.79 - -.87). No differences in cognitive performance were observed (p > .075). The humid operational environment elicited a greater thermal strain that may threaten safety, and impair performance, to a greater degree than the arid environment. Perceptual measures of thermal sensation and sleepiness were the best predictors of test termination and could likely be used to monitor thermal tolerance in field settings.

1. Introduction

Military personnel deployed abroad are often exposed to different environments from that which they typically live and train in (Parsons et al., 2019). Regions with tropical climates are predisposed to conflict as weather patterns that affect food production can lead to civil unrest, which in extreme cases leads to conflict and international military intervention (Humphreys, 2005; Koubi, 2019). Climate change is already exacerbating resource competition and conflict and will worsen. Therefore, military operations in extreme environments are expected to rise (CNA, 2007; Reuveny, 2007; Smith, 2007; Brzoska & Fröhlich, 2016).

Hot environments pose a unique challenge to military operations as military-specific factors, such as carrying heavy loads and wearing protective gear, increase endogenous heat production and restrict heat loss (Taylor, 2015), thereby impairing work capacity and predisposing military personnel to exertional heat illness (Casa et al., 2012). Exertional heat illness can present as heat syncope, heat exhaustion, and in extreme cases heat stroke, which can cause organ damage, and in some cases death (Carter et al., 2005; Howe & Boden, 2007; Goforth & Kazman, 2015). Therefore, understanding the effects and mitigation of heat stress is important for military performance and safety in such environments.

[*] Corresponding Author: Edward Ashworth, Auckland University of Technology, New Zealand, eashworth@health.ucsd.edu

Hot environments are typically characterised by either very high ambient temperatures and low humidity (i.e., arid), or high ambient temperatures and high humidity. Arid conditions are typical of desert environments and have been encountered recently by numerous international militaries in Afghanistan and the Middle East (Armed Forces Health Surveillance Branch, 2019). Humid environments are often found in jungle environments, and have been encountered in tropical regions of Asia (Forster, 1951; Haisman, 1972). Heat stress differs between these environments, with the high ambient temperature in arid environments causing heat gain via sensible exchanges (Nadel, 1979), while the vapour pressure in humid environments minimises sweat evaporation (Akerman et al., 2016; Gonzalez et al., 1974). Given that evaporative heat loss is the main avenue for heat loss during moderate and heavy physical activity in humans, a greater thermal challenge is likely to occur in humid environments (Maughan et al., 2012; Muhamed et al., 2016).

In military contexts the environmental characteristics and terrain influence the carried loads and protective clothing requirements of each soldier (Eddy et al., 2015; Larsen et al., 2011), which may inadvertently augment the effects of hot environments (Boffey et al., 2019; McLellan, 2001). For example, arid environments consist primarily of open areas where air support is more often available, and soldiers often move alongside vehicles. Consequently, the carried pack is relatively light, but as open conflict is more likely, more body armour is worn, further restricting heat loss from the torso (Johnson et al., 1995). Conversely, a humid jungle environment often requires self-sufficiency, requiring a larger pack. However, as camouflage and stealth play a greater role, less body armour may be worn.

Given the environmental differences in the presentation of heat and the expected mission objectives dictating a unique gear loadout it is likely that the environments place different physiological strain on soldiers. Understanding these differences allows training plans prior to deployment to be tailored for each environment. Additionally, identification of physiological variables that influence or predict subsequent performance in the heat is important to help inform safety outcomes and assist both deployment selection and real-time monitoring of military personnel in the field. Therefore, the aims of the current study were two-fold. Firstly, to determine physiological responses to military activity in arid and humid environments, and secondly, to determine factors that may predict performance both prior to, and during, exercise in arid and humid environments.

2. Methods

2.1. Participants

A randomised cross-over design was used, with 9 participants completing two heat-stress tests (HSTs); one HST in a humid environment (33°C, 75% relative humidity (RH) [27 g.m-3 absolute humidity]) and the other in an arid environment (46°C, 10% RH [7 g.m-3 absolute humidity]). Temperatures were matched on wet-bulb globe temperature (~30°C WBGT). During each HST several physiological, perceptual, and cognitive assessments were conducted (Figure 1). Each HST was conducted at least one week apart. University (AUTEC: 17/420) and New Zealand Defence Force (6755/1) ethical approval was obtained, and informed consent obtained in writing from all participants as per the Declaration of Helsinki. Nine pack-fit military personnel (8 males, 1 female) volunteered to participate in the study (age 32.6 ± 9.4 y, body mass 81.1 ± 10.0 kg, 2.4 km run time 9:40 ± 1:11 min:s, estimated $\dot{V}O_2$ 54.2 ± 6.1 mL.kg^{-1}.min^{-1}).
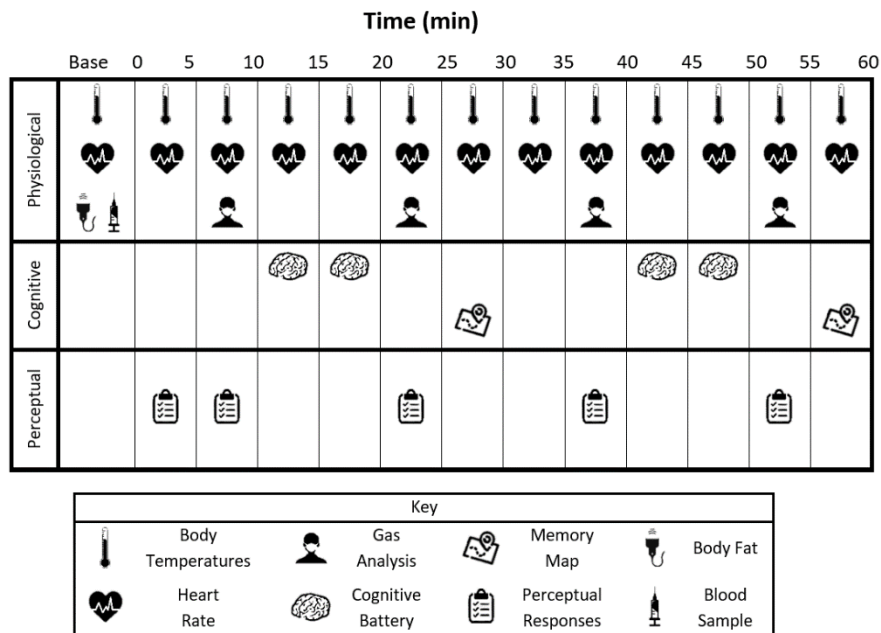

Figure 1: Schematic of tests conducted over the first 60 min in each heat-stress test. From 60 to 120 min measures were taken in the same order.

2.2. Heat-Stress Test

Heat-stress tests were conducted at the same time of the day for each participant. Participants were asked to avoid strenuous activity for the 24 h preceding each HST and were asked to record their food intake so that it could be replicated for the subsequent trial. Each HST was carried out in an environmental chamber (Design Environmental, Simultech Australia, Australia), beginning with 10 min of seated rest, followed by walking on a treadmill (Platinum Club Series, Life Fitness, Illinois, USA) at a fixed speed of 5 km.h^{-1} for 2 h or until termination criteria were met. Termination criteria were voluntary termination or ethical end points being reached for core temperature (> 39.3°C) (Aoyagi et al., 1995) or heart rate (> 95% age-predicted maximum for 1 min) (Tanaka et al., 2001). Time to exhaustion (TTE) was taken as the time at test termination. Participants were dressed according to the environment they would be operating in. For the arid environment participants wore body armour (~10 kg), a small backpack (~15 kg), helmet, and hiking shoes (total ensemble 31.1 ± 2.3 kg) (Figure 2). For the humid environment participants wore load-carrying webbing (~ 8 kg), a large backpack (25 kg), a jungle hat, and jungle boots (total ensemble 36.4 ± 2.1 kg) (Figure 2). In both environments participants also carried a rifle (~3 kg, included in total ensemble weights) and wore military uniform comprised of long-sleeved shirt and trousers. Fluid intake was allowed *ad libitum* up to a maximum of 2 L.h^{-1}, as per military rations, and was recorded.

2.2.1. Baseline Measures

Prior to the start of each trial, a resting urine and a blood sample were obtained from each participant. Urine was used to assess hydration status from urine specific gravity (USG) (Atago, Japan). There was no euhydration requirement to begin each trial. Blood was obtained by venepuncture of an antecubital vein, without stasis, into a 6 mL K$_2$EDTA vacutainer (Becton Dickinson and Co, USA). Vacutainers were then centrifuged (1500g for 15 min at 4°C) and the separated plasma was stored at -80°C until heat-shock protein analysis. Body fat was assessed via ultrasound (12L, Vivid S5, GE Healthcare, Chicago, IL) of the abdomen, 2 cm lateral to the umbilicus (Leahy et al., 2012; Marfell-Jones & Lindsay, 2006), given that subcutaneous adipose tissue thickness at the abdomen has been shown to correlate strongly with body fat measured by DEXA (Leahy et al., 2012; Wagner, 2013). Participants were weighed both semi-nude and fully dressed (i.e. all protective equipment on), pre- and post- HSTs, for calculation of whole-body sweat rate (*(semi-nude weight change + fluid consumption) ÷ walking time*) (Buono et al., 2009). Evaporated sweat rate was calculated by observing the difference between the undressed and dressed weight, thereby accounting for sweat absorbed by the clothing (*[semi-nude weight change – fully dressed weight change] ÷ walking time*) (Amos et al., 2000).

2.2.2. Continuous Measures

Core body temperature was recorded rectally, using a flexible thermistor (Hinco Instruments, Australia) self-inserted ~10 cm beyond the anal sphincter. Skin temperature was measured on the right-hand side of the body at the chest, bicep, thigh, and calf using skin temperature probes. Rectal and skin temperature were logged at 1 Hz (SQ2020, Grant Instruments, Cambridge, UK). In preparation for analysis, rectal and skin temperature readings were filtered due to noise caused by connections with the logger and occasional skin temperature probes losing contact with the skin due to the humid microenvironment. A filter was applied to remove readings that changed by more than 0.1°C.s^{-1}. Then a low-pass Butterworth filter of 0.02 Hz was applied to the data. Missing data were filled with linear interpolation.

Figure 2: Gear loadouts for the humid (left) and arid (right) environments for each heat-stress test.

Mean skin temperature was calculated using the following formula (Ramanathan, 1964):

$$T_{Sk} = 0.3T_{Chest} + 0.3T_{Bicep} + 0.2T_{Thigh} + 0.2T_{Calf}$$

If a thermistor became askew or off the skin, the equation was modified to proportionally compensate the weights of the three remaining sensors to maintain the summation of coefficients to 1.0, as has been done previously (Ashworth et al., 2021).

Cardiac frequency was measured from ventricular depolarisation using a heart rate monitor (Polar RS800CX, Kempele, Finland), with values recorded every 5 min.

The slope of each continuous measure was calculated by the change from walking onset to exercise termination divided by walking time.

2.2.3. Periodic Measures

Several measures were taken periodically throughout each HST. Perceptual measures were taken every 15 min, involving ratings of perceived exertion (RPE) (15-point scale ranging 6-20 arbitrary units (AU)), thermal discomfort (1-10 AU), thermal sensation (1-13 AU), feeling (-5 - +5 AU) and sleepiness (1-9 AU). Respiratory gas analysis was conducted for 4 min every 15 min with participants breathing through a mouthpiece connected to a calibrated, automated system (Trueone 2400, Parvo Medics, Utah, USA). Rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) and the respiratory exchange ratio (RER) were measured to evaluate substrate use during exercise. Carbohydrate oxidation (g.min^{-1}) was calculated from the following equation (Jeukendrup et al., 2005):

$$4.21 \dot{V}CO_2 + 2.962 \dot{V}O_2$$

Change scores for these measures were taken as the difference between the first and last measurement of the variable within each participant within each session. Due to the greater carried load, walking in the humid condition was predicted to incur a 6% higher metabolic rate (and therefore also rate of heat production), based on published calculations (Pandolf et al., 1977).

2.2.4. Cognitive Testing

A series of cognitive assessments were completed during each HST. Each battery lasted ~10 min and commenced at 10, 40, 70 and 100 min, unless test termination occurred prior. Simple reaction time was assessed using an electronic tablet (Nova 2 Lite, Huawei, Shenzhen) application (Reaction Time Tests for Science, Andrew Novak, 2016), which required participants to respond to a red circle appearing on a screen. Discrimination reaction time was assessed in a similar manner, with participants again responding to a red circle, but also avoiding responding to blue and black circles that appeared. A serial arithmetic task was used to assess cognitive throughput (Kase, 2009) to determine information processing speed. This required subtracting either 7 or 9 from a 4-digit number as many times as possible within one minute. A digit span task was used to assess working memory (Hocking et al., 2001). Participants were required to memorise a series of numbers read out to them, and then repeat them back, but

in the reverse order. The test began with 3 digits being read out and increased by 1 digit after correctly recalling numbers twice at a given level, with the test ending once an incorrect sequence was repeated twice at the same level. Due to a lack of familiarisation, the first test for all non-reaction time cognitive tasks was removed from analysis. Following completion of this cognitive testing battery a NASA task-load index (TLX) was given to participants to indicate how they perceived the tasks to be, specifically in relation to mental, temporal and physical demands, as well as performance, effort and frustration (21-point scale).

Furthermore, a declarative memory task was also conducted using a memory map. The task involved memorising a simplified, fictional urban town plan, regarding a predefined route, the roads travelled along, landmarks and directions. The task was presented to participants at 25 and 85 min for 2 min, alongside a list of predetermined questions they would be required to answer. Following removal of the memory map participants were required to retain the information for ~30 min. At 55 and 115 min the predetermined questions were read aloud, and participants answered orally.

2.2.5. Blood Analysis

Thawed plasma samples were analysed for extracellular heat-shock protein 70 (HSP70) using a commercially available HSP70 High Sensitivity Enzyme-Linked Immunosorbent Assay (ELISA) kit (ab133061, Abcam, Cambridge, UK) run according to the manufacturer's instructions. The intra assay coefficient of variation for HSP70 was 4.9%.

2.3. Statistical Approach

Data analysis was conducted in two phases: the first compared the change in physiological variables over time between the two environments, while the second involved a linear regression for each variable and performance in each environment. All analyses were conducted in R version 3.6.1 (R foundation for Statistical Computing, Vienna, Austria).

To compare variables between environments, linear mixed models were fitted for each variable. Environment, time, and order (whether the arid or humid heat-stress test was conducted first) were used as fixed effects, with participant as the random effect. The model-generated estimated means are reported, with either standard deviation or 95% confidence intervals and p-values where appropriate. The alpha level was 0.05. For data with multiple time points, *post hoc* tests, with Bonferroni correction, were conducted using a time by environment interaction.

For regression analyses, predetermined variables of interest were selected and inputted into a linear regression model along with the performance outcome; walking time. Before running regression analysis each variable was checked for normality using a Shapiro-Wilk test, and homoscedasticity by plotting residuals. Data that did not meet normality were either log transformed or reciprocated prior to regression analysis, which overcame issues of non-normality. The lm.beta function, from the QuantPsyc package, was used for analysing each regression. Data are reported as both standardised (β) and unstandardised (B) regression coefficients, with a 95% confidence interval shown. The strengths of the standardised regressions were classified by

the following correlation guidelines: very weak < 0.2, weak 0.2-0.4, moderate 0.4-0.6, strong 0.6-0.8, and very strong 0.8-1.0 (Evans, 1996).

3. Results

3.1. Environmental Differences

The actual temperature and humidity during the humid trials was $33.4 \pm 0.6°C$ and $78 \pm 2\%$ RH (28 g.m^{-3} absolute humidity), while in the arid trials it was $44.3 \pm 0.5°C$ and $21 \pm 2\%$ RH (13 g.m^{-3} absolute humidity), providing WBGTs of $31.1°C$ and $31.5°C$, respectively. Baseline characteristics of body mass, body fat, USG and sleep quality were not different between environments (all $p > .262$).

No differences were observed in TTE between the two environments (Humid: 73.1 ± 12.8 min; Arid: 82.3 ± 22.0 min; $p = .155$) (Figure 3). Of nine HSTs in the humid environment, 5 (56%) were terminated due to rectal temperature rising beyond the ethical threshold limit, one due to heart rate, and the remaining three were voluntarily terminated. In the arid environment HST, 4 (44%) were terminated due to rectal temperature, one due to heart rate, and the remaining four were voluntarily terminated.
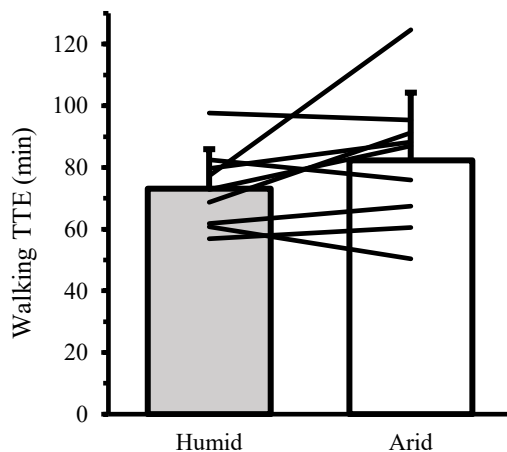

Figure 3: Walking time to exhaustion (TTE) in a simulated pack march in humid and arid environments in full military protective equipment. Individual responses are displayed by individual black lines.

3.1.1. Physiological Differences Between Environmental Conditions

While no significant differences were evident at rest or in the slope of rectal temperature between environments, during exercise rectal temperature was higher in the humid environment ($p < .001$; Table 1, Figure 4). When extrapolated to determine how long it would be before rectal temperature reached $40°C$, exercise in the humid environment was projected to last 95 min, compared to 120 min in the arid environment (Figure 4). Conversely, the arid environment had a ~0.5°C higher skin temperature across the trial, despite no baseline differences, or differences in the rate of rise in skin temperature (Table 1). Heart rate in the humid environment was elevated by a time-averaged ~5 b.min^{-1} in comparison to the arid environment, although other differences in heart rate were minimal (Table 1). Although overall sweat rate was not significantly different between conditions, evaporated sweat rate was ~40% greater in the arid environment (Table 1). No differences were observed in any measure of hydration (Table 1).

The $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$ all increased significantly throughout the trial (all $p < .001$). Between conditions, a 10% greater $\dot{V}O_2$ was present in the humid condition (Humid: 19.8 ± 2.5 mL.kg^{-1}.min^{-1}; Arid: 18.0 ± 2.2 mL.kg^{-1}.min^{-1}; $p < .001$), which was close to the 6% predicted, and was supported higher $\dot{V}_E$ (Humid: 47.0 ± 12.1 L.min^{-1}; Arid: 42.6 ± 9.8 L.min^{-1}; $p < .001$) and $\dot{V}CO_2$ (Humid: 1.40 ± 0.21 L.min^{-1}; Arid: 1.28 ± 0.18 L.min^{-1}; $p < .001$). Estimated substrate partitioning was comparable between conditions, based on respiratory exchange ratio (Humid: 0.88 ± 0.04; Arid: 0.88 ± 0.05; $p = .848$), and showed a trend for faster oxidation of carbohydrate in humid conditions (Humid: 1.2 ± 0.3 g.min^{-1}; Arid: 1.1 ± 0.4 g.min^{-1}; $p = .063$).

3.1.2. Perceptual Differences

All perceptions worsened throughout each condition (all $p < .001$). RPE was slightly but significantly elevated in the humid environment compared to the arid environment (Humid: 12.9 ± 2.6; Arid: 12.4 ± 2.8; $p = .040$). However, there were no differences between environments for thermal discomfort, thermal sensation, sleepiness or feeling state (all $p > .186$).

3.1.3. Cognitive Differences

No differences in cognitive performance existed between environments (all $p > .220$) or over time (all $p > .075$). Similarly, cognitive perception was not different between the environments in the task-load index (all $p > .075$), although increases in mental, physical, and temporal demand, as well as effort and frustration all occurred over time in both environments (all $p < .011$) (Figure 5).

3.2. Regression

Both standardised and unstandardised regression coefficients between individual measures and walking TTE are presented in Table 2. Baseline measures were generally poor/weak predictors of TTE. During exercise the change in physiological values produced moderate to strong relationships, although the variability was pronounced. Perceptual changes were the strongest indicators in both conditions.

Table 1: Physiological and perceptual responses during a simulated pack march in full military protective in humid (33°C, 78% RH) and arid (44°C, 21% RH) environmental conditions.

Variable	Humid	Arid	*p*-value
Rectal Temperature (°C)			
Average	38.1 ± 0.8	37.8 ± 0.7	**< .001**
Resting	36.9 ± 0.8	36.9 ± 0.7	.967
Slope (°C.h^{-1})	1.7 ± 0.3	1.6 ± 0.3	.462
Skin Temperature (°C)			
Average	36.2 ± 0.7	36.6 ± 0.8	**< .001**
Resting	34.1 ± 0.7	34.2 ± 0.8	.423
Slope (°C.h^{-1})	1.9 ± 0.7	2.0 ± 0.7	.642
Heart Rate (b.min^{-1})			
Average	146 ± 21	141 ± 23	**< .001**
Resting	76 ± 14	76 ± 13	.880
Slope (b.min^{-1}.h^{-1})	39 ± 13	40 ± 14	.893
Sweat Rate (L.h^{-1})	1.2 ± 0.1	1.3 ± 0.1	.187
Evaporated Sweat Rate (L.h^{-1})	0.6 ± 0.6	0.9 ± 0.4	**.045**
Rate of Fluid Consumption (L.h^{-1})	0.6 ± 0.3	0.7 ± 0.5	.577
USG Pre	1.011 ± 0.006	1.016 ± 0.007	.069
USG Post	1.017 ± 0.009	1.017 ± 0.010	.827

Note: slopes are calculated from exercise onset, and not resting values.

4. Discussion

The first aim of this study was to compare the physiology of each environment. Results showed the humid environment to be marginally more stressful, with higher core temperature, higher heart rate and a greater oxygen requirement. The understanding of these differences allows for specific preparation ahead of deployment, including heat acclimation, equipment design and mission planning. The second aim was to assess the strength of physiological variables at predicting performance in hot environments. To this end several factors were found in each environment that predicted performance, including factors unique to each environment.

4.1. Performance

Despite differences in environmental conditions, gear loadouts and physiological responses, there was no difference seen in performance between arid and humid environments (Figure 3), with minimal differences in the reasons for test termination. Together these similarities indicate the overall thermal strain in both environments was similar, likely due to the comparable WBGT, originally developed to quantify heat stress (Yaglou & Minard, 1957). However, the WBGT does not account for the difference in clothing and protective equipment worn by soldiers. It was expected that the larger and heavier pack carried in the

humid environment would exacerbate endogenous heat production while also impairing evaporative heat loss and thereby cause earlier test termination (Dorman & Havenith, 2009). However, it is possible that the combination of body armour and backpack in the arid environment may have comparatively restricted heat loss from the chest (Johnson et al., 1995), helping to nullify the effects of a heavier pack in the humid condition.

4.2. Body Temperatures

Higher rectal temperatures were observed in the humid environment than the arid environment (Table 1, Figure 4). While this is likely partially accounted for by the additional metabolic heat production caused by the heavier carried load (Dorman & Havenith, 2009), there was also a reduced evaporated sweat rate, with the same absolute sweat rate, suggesting reduced evaporative heat loss. Despite no statistical difference in the rate of rise in rectal temperature, extrapolation of the data revealed that rectal temperature would reach 40°C 25 min faster in the humid environment (Figure 4). While military personal can likely still perform beyond this threshold safely (Ely et al., 2009; Lee et al., 2010; Veltmeijer et al., 2015), it represents a limit at which heat stroke is known to occur, and therefore safety guidelines suggest that exercise should be
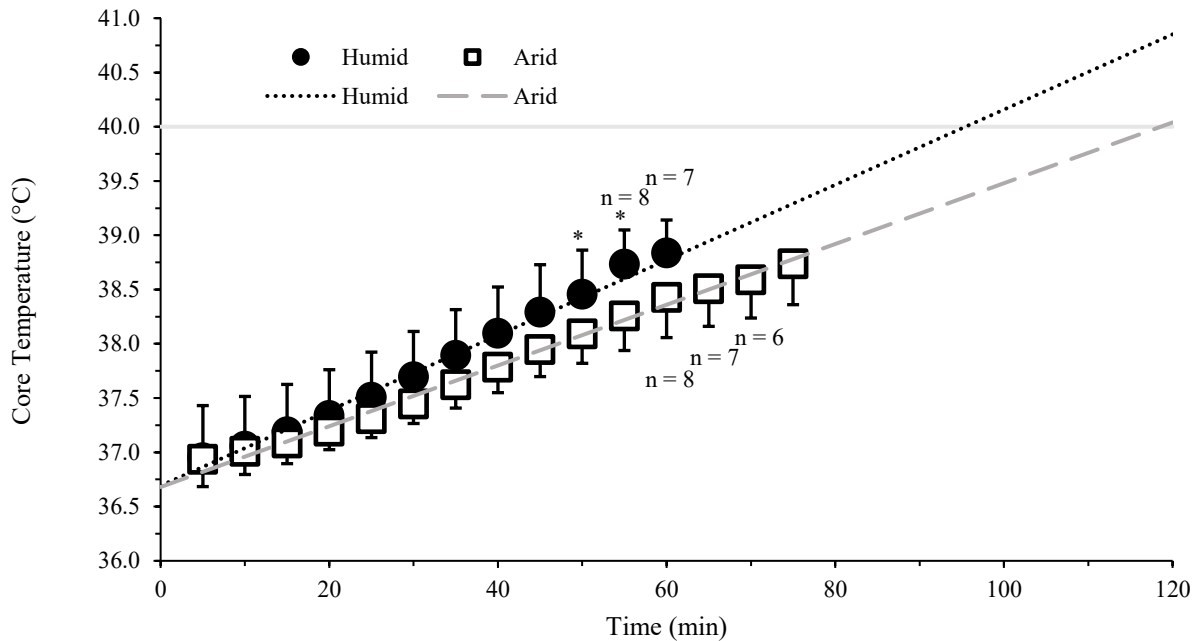
Figure 4: Rectal temperature during a simulated pack march in either a humid (33°C, 78% RH) or arid (44°C, 21% RH) environment. Trendlines display the predicted means based on recorded data, only for when $n = 9$. Data are plotted as mean ± standard deviation for $n = 9$ unless otherwise stated (data are stopped once $n < 6$ and is noted when it changes). *$p < .05$ between conditions at individual time-points.

restrained beyond this threshold (Goforth & Kazman, 2015; Smith et al., 2016). Indeed, reducing core temperature below 40°C rapidly after exercise drastically reduces the mortality risk (Casa et al., 2012). However, in real-world military contexts, heat stress is often not alleviated and rectal temperature continues to rise even after the cessation of exercise, placing soldiers in danger, even if exercise is stopped (Giesbrecht et al., 2007; Smith et al., 2017). In the humid environment a 40°C rectal temperature would have been seen only 20 min after the average termination time, highlighting the imminent danger of exercise in humid environments. However, it should be noted that the 95 min mark where rectal temperature is calculated to reach 40°C in the humid condition falls outside of the 95% confidence interval (Table 1), suggesting internal cues can help reduce risk by terminating exercise in both environmental conditions. Therefore, when operating in these environments, particularly humid environments, continuous physiological monitoring of soldiers may be valuable to ensure activities are conducted safely (Buller et al., 2018; Parsons et al., 2019; Tharion et al., 2013), as is understanding methods for rapidly cooling individuals (Carter et al., 2007; Casa et al, 2012; Epstein et al., 2012).

The strength of the relationships between rectal temperature and performance is strengthened by the ethical termination of trials when core temperature exceeded 39.3°C, although, as mentioned above, internal cues such as central fatigue likely also lead to test termination (Nybo & Nielsen, 2001, Tucker et al., 2004). The stronger relationship between rectal temperature slope and performance in the humid environment may also be explained by this, where 56% of heat-stress tests were terminated due to high core temperature, compared to only 44% in the arid environment.

Nonetheless, this ethical limit was put in place as it was deemed unsafe for core temperature to rise any further, and is the point where physical activity should be restrained in the field, if possible (Goforth & Kazman, 2015; Taylor et al., 1997). High rates of rise in core temperature have previously been identified to increase hyperthermia risk and heat-illness symptoms (Armstrong et al., 2010; Maughan et al., 2012), highlighting the desire for a reduced rate of rise in core temperature (Hunt et al., 2016). Therefore, to prioritise safety, core temperature should be monitored. Although less practical, the ability to monitor core temperature during exercise, either using a heat tolerance test prior to departure or real-time monitoring of soldiers in the field (Buller et al., 2018; Epstein et al., 2017), provides a much stronger predictor of performance (Table 2).

The arid environment induced a higher skin temperature (Table 1), likely through heat gain from the environment that occurs when temperatures exceed 35°C (Nadel, 1979). This is in line with recent findings from Lei et al (2020) which showed that, at a constant absolute humidity, elevating temperature increases skin temperature, without affecting other thermoregulatory variables. In the current study however, core temperature was increased in the humid condition as absolute humidity in the humid environment was 4 times greater than in the arid environment. The elevation in skin temperature impairs heat loss as it minimises the core-to-skin temperature gradient (Chou et al., 2018). The lower humidity in the arid environment facilitates heat loss (Akerman et al., 2016), explaining the lower rectal temperature despite a higher skin temperature. The higher

Table 2: Regression analysis predicting walking time (TTE) using baseline and exercising predictors for a simulated heat-stress pack march in humid (33°C, 78% RH) and arid (44°C, 21% RH) environments. Data are displayed as standardised (β) or unstandardised (B) coefficients with a 95% confidence interval.

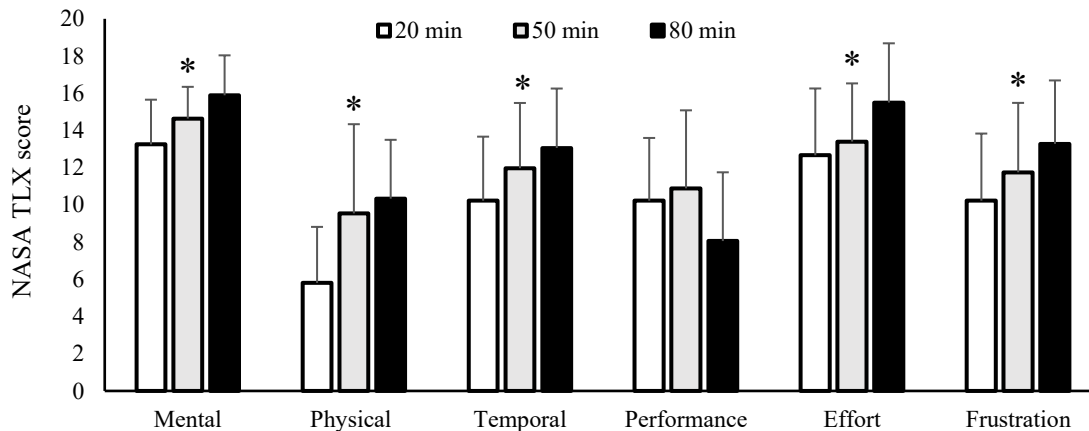|	Humid		Arid	
	β	B	β	B
Baseline Characteristics				
Aerobic Fitness	.18 (-.55, .75)	0.4 (-1.5, 2.2)	.58 (-.13, .90)	2.1 (-0.5, 4.7)
Resting Rectal Temperature (°C)	-.31 (-.80, .44)	-9 (-32, 15)	-.15 (-.74, .57)	-15 (-103, 74)
Resting Skin Temperature (°C)	-.28 (-.80, .47)	-5 (-21, 11)	-.30 (-.80, .46)	-9 (-36, 17)
Resting Heart Rate (b.min^{-1})	-.23 (-.78, .51)	-0.2 (-1.0, 0.6)	.18 (-.55, .75)	0.3 (-1.2, 1.8)
Body Fat (mm)	-.19 (-.79, .59)	-0.1 (-0.5, 0.3)	-.39 (-.86, .43)	-0.4 (-1.3, 0.5)
Body Mass (kg)	.39 (-.37, .84)	0.5 (-0.5, 1.5)	.15 (-.57, .74)	0.3 (-1.7, 2.3)
USG	-.30 (-.80, .46)	-0.5 (-2.3, 1.1)	.18 (-.60, .78)	0.6 (-2.5, 3.7)
HSP70 (ng/mL)	-.14 (-.74, .58)	-0.03 (-0.08, 0.03)	-.40 (-.84, .36)	-0.01 (-0.05, 0.06)
Exercising Characteristics				
Rectal Temperature Slope	-.73 (-.94, -.12)	-32 (-59, -5)	-.54 (-.89, .19)	-36 (-86, 14)
Skin Temperature Slope	-.24 (-.78, .51)	-4 (-20, 12)	-.56 (-.89, .16)	-19 (-43, 6)
Heart Rate Slope	-.61 (-.91, .08)	-0.6 (-1.3, 0.1)	-.23 (-.78, .51)	-0.4 (-1.8, 1.0)
Sweat Rate	.74 (.07, .95)	22 (-4, 49)	.48 (-.26, .87)	31 (-19, 80)
Fluid Consumption Rate	.40 (-.36, .84)	16 (-17, 49)	-.35 (-.82, .41)	-14 (-49, 21)
Thermal Sensation Change	-.65 (-.92, .02)	-5 (-11, 0)	-.80 (-.96, -.30)	-13 (-21, -4)
Sleepiness Change	-.79 (-.95, -.26)	-5 (-9, -2)	-.87 (-.97, -.48)	-10 (-15, -5)
RPE Change	.17 (-.56, .75)	1 (-6, 9)	-.37 (-.83, .39)	-4 (-13, 5)

Figure 5: Pooled responses from both humid and arid heat-stress tests to the NASA task-load index following completion of a cognitive battery. *indicates a significant effect of time, regardless of the environment.

skin temperature in the arid environment likely explains the stronger relationship with performance, which was of moderate strength, compared to only a weak relationship in the humid environment. Furthermore, skin temperature may directly influence the perceptual relationships with performance, which were among the strongest predictors of performance in both environments (Table 2), consistent with previous findings (Flouris & Schlader, 2015; Schlader et al., 2013). Whether the higher skin temperature in the arid environment partially explains the stronger relationships between perceptual changes and performance in the arid environment, however, is uncertain as a lack of perceptual differences existed between environments (Table 1). Perceptions are produced by the brain integrating numerous physiological signals to generate behavioural responses to help cope with environmental stress (Fleming & James, 2014; Morante & Brotherhood, 2008; Periard et al., 2014; Schlader et al., 2011). Therefore, as a response to exercise becoming uncompensable, thermoregulatory behaviour leads to the termination of the test (Cheung & McLellan, 1998; Gonzalez-Alonso et al., 1999; Pimental et al., 1987). Thereby having a lower skin temperature could delay the rate at which perceptual feelings worsen, allowing prolonged performance before voluntary termination, although there were only marginally more voluntary terminations in the arid environment. The absence of relationship between rating of perceived exertion and performance may highlight military mental toughness, hypothesised to place individuals in danger as they disregard internal cues to cease exercise (Buller et al., 2018; Epstein et al., 2012; Howe & Boden, 2007; Parsons et al., 2019). If valid, overcoming these internal cues exacerbates the danger of these environments as continuing to exercise further elevates core temperature which can ultimately be fatal (Parsons et al., 2019). Understanding that in these environments the accumulated heat gain from both endogenous and exogenous sources, and not simply exercise intensity alone, is the primarily cause of fatigue and casualties, may help develop monitoring strategies (Macpherson, 1962). The data in the current study found that directly addressing heat in perceptual monitoring, by enquiring of

how hot or sleepy individuals are feeling, provides an indication of how much longer an individual can safely exercise for.

4.3. Cardiovascular

A higher heart rate was seen during the heat-stress test in the humid environment (Table 1). In the humid environment, cardiovascular variables were better predictors of performance, whereas baseline aerobic fitness was a better predictor in the arid environment (Table 2). Furthermore, fitter individuals are known to be able to tolerate a higher core temperature (Cheung & McLellan, 1998), therefore the withdrawal of participants due to having a high core temperature, which occurred more frequently in the humid environment, limits aerobic fitness influencing the time to exhaustion.

During exercise, elevations in cardiac output, facilitated by an increase in heart rate, are required to ensure both cutaneous and skeletal muscle circulations receive adequate blood supply (Cramer & Jay, 2016; Gonzalez-Alonso & Calbet, 2003). A larger underlying blood volume facilitates higher stroke volume and a more widespread distribution of blood, allowing heat loss while maintaining performance (Gonzalez-Alonso et al., 1998; Taylor, 2000). A greater blood volume may be more important in humid environments as sweat evaporation is restricted by high humidity (Maughan et al., 2012), thereby causing insensible fluid loss, where dehydration occurs without beneficial heat loss (Eichna, 1943; King et al., 2016; Taylor, 2017). As central blood volume declines a greater strain is placed on the cardiovascular system (Charkoudian, 2016; Gonzalez-Alonso et al, 1998), limiting peripheral blood flow. As the perfusion of cutaneous circulations is reduced, heat transfer becomes limited, thereby causing increases in core temperature (Casa et al., 2012; Gonzalez-Alonso et al., 1998; Kenefick et al., 2010; Nadel et al., 1980). Alternatively, a greater reliance may be placed on convective heat loss mechanisms, thereby requiring an increased cardiac output to elevate cutaneous blood flow (Chou et al., 2018; Kenney et al., 2014; Tebeck et al., 2019), shown by an elevated heart rate in the humid environment (Table 1). The importance of limiting the

cardiovascular demand is further illustrated by the strong ability of the change in heart rate to predict performance (Table 2). When the cardiovascular system can no longer increase cardiac output to support perfusion of both skeletal muscle and cutaneous circulations blood flow is reduced, first to cutaneous, and then to skeletal muscle circulations (Gonzalez-Alonso & Calbet, 2003; Gonzalez-Alonso et al., 2008; Kenney et al., 2014). Without the muscular blood flow to sustain oxygen requirements for exercising muscle intensity is reduced (Tucker et al., 2004), which in this experiment meant test termination. Heart rate monitoring is one of the simplest real-time monitoring methods available (Eggenberger et al., 2018), and by assessing the rate of rise in heart rate it allows evasive steps to be taken to prevent exhaustive limits being reached by the individual.

4.4. Sweat Rate

No differences in sweat rate were seen between the environments, although evaporated sweat was significantly reduced in the humid environment (Table 1), likely due to the vapour pressure gradient being reduced by the humidity, preventing sweat evaporation (Maughan et al., 2012). As sweat is unable to evaporate, core temperature rises (McLellan & Aoyagi, 1996; Sawka et al., 1993), underlying the elevated rectal temperature in the humid condition (Figure 4), whereas the evaporation of sweat in the arid environment would have helped maintain a lower rectal temperature (Figure 4) (McLellan et al., 1992). Sweat rate changes were closely linked to performance in both environments (Table 2). In the humid environment sweat rate strongly predicted performance (Table 2), while evaporated sweat rate had a weak negative relationship. This suggests sweating facilitates performance, but only if the sweat evaporates. If sweat does not evaporate then heat is not lost from the body, and water loss merely adds to dehydration (Cheung & McLellan, 1998; Taylor, 2017). Conversely, despite conditions favouring the evaporation of sweat, the arid environment had only a moderately strong relationship between sweat rate and performance, (Table 2). As sweat could more readily evaporate, it is likely that this was not a limiting factor, and therefore other variables were more directly linked to performance.

4.5. Metabolic

The metabolic strain during the heat stress test was greater in the humid environment, illustrated by larger oxygen uptake and carbon dioxide production. The greater pack weight in the humid environment likely accounts for some of this difference as more muscular work is required to carry the pack (Knapik, 1997). Indeed, the relatively greater $\dot{V}O_2$ in the humid environments occurred close to the expected relative value based on load carrying energy expenditure predictions (Pandolf et al., 1977). Furthermore, lighter individuals are known to have a greater relative metabolic demand when carrying heavy absolute loads (Bilzon et al., 2001). Therefore, the increased oxygen requirement from the additional relative workload likely creates a strong relationship between body mass and performance, as this would also add to metabolic heat production (Table 2).

No relationship was found between HSP70 and performance (Table 2), although most participants showed minimal plasma concentrations that were often below the detection limit of the ELISA assay. Low serum concentrations of HSP70 are not uncommon, especially at rest (Njemini et al., 2011; Walsh et al., 2001), with some studies reporting wide variations in concentrations between individuals (Lee et al., 2015). It is acknowledged that the practicality of measuring HSP70 in a real-world military context is limited due to the cost, invasiveness and laboratory expertise required to obtain results. Therefore, based on these constraints, the large variability, and our non-significant findings, HSP70 does not appear to be a worthwhile or accessible measure for predicting soldier performance in the heat.

4.6. Cognitive

Minimal changes in cognitive performance existed both within and between environments. Many of the tasks used in the cognitive assessments were relatively simple, which have been shown to be largely unaffected by heat (Hancock & Vasmatzidis, 2003; Mazloumi et al., 2014). However, research has shown load carriage (Caldwell et al., 2011; Eddy et al., 2015) and physical fatigue (Vrijkotte et al., 2016) to impair simple cognitive processes. Despite the self-reported mental demand of tasks increasing across the trial (Figure 5), no differences in cognitive performance existed. It is possible participants felt more strained when doing the tasks, but could still allocate sufficient cognitive resources to the task to complete them accurately (Lambourne & Tomporowski, 2010). In real-world military contexts, soldiers may experience greater thermal stress, physical fatigue and more complex tasks, which could impair cognition.

4.7. Conclusion

While physiological responses to military specific physical activity in humid and arid environments share many similarities, significant differences do exist and should be accounted for. Specifically, the expected environmental parameters and gear loadout of the humid environment appeared to increase heat production, while also impairing cooling due to limited sweat evaporation resulting in increased core temperature and heart rate, which lead to impairments in soldier performance. While many physiological variables predicted performance, perceptual variables were the strongest predictors. The lack of relationship between the difficulty of exercise and performance suggests monitoring questions should focus on the heat, not the exercise, to ensure soldier safety and wellbeing. Understanding the dangers of heat and improving coping mechanisms and monitoring strategies will help minimise soldier casualties.

Conflict of Interest

The authors declare no conflict of interests.

References

Akerman, A. P., Tipton, M., Minson, C. T., & Cotter, J. D. (2016). Heat stress and dehydration in adapting for performance: Good, bad, both, or neither? *Temperature, 3*(3), 412-436.

Amos, D., Hansen, R., Lau, W-M., & Michalski, J. T. (2000). Physiological and cognitive performance of soldiers conducting routine patrol and reconnaissance operations in the tropics. *Military Medicine, 165*(12): 961-966.

Ashworth, E. T., Cotter, J. D., & Kilding, A. E. (2021). Impact of elevated core temperature on cognition in hot environments within a military context. *European Journal of Applied Physiology, 121*(4), 1061-1071.

Aoyagi, Y., McLellan, T. M., & Shephard, R. J. (1995). Effects of 6 versus 12 days of heat acclimation on heat tolerance in lightly exercising men wearing protective clothing. *European Journal of Applied Physiology and Occupational Physiology, 71*(2-3), 187-196.

Armed Forces Health Surveillance Branch. (2019). Update: Heat illness, active component, U.S. Armed Forces, 2018. *Medical Surveillance Monthly Report.*

Armstrong, L. E., Johnson, E. C., Casa, D. J., Ganio, M. S., McDermott, B. P., Yamamoto, L. M., Lopez, R. M., & Emmanuel, H (2010). The American Football uniform: Uncompensable heat stress and hyperthermic exhaustion. *Journal of Athletic Training, 45*(2), 117-127.

Bergeron, M. F., Bahr, R., Bartsch, P., Bourdon, L., Calbet, J. A., Carlsen, K. H., Castagna, O., Gonzalez-Alonso, J., Lundby, C., Maughan, R. J., Millet, G., Mountjoy, M., Racinais, S., Rasmussen, P., Singh, D. G., Subudhi, A. W., Young, A. J., Soligard T., & Engebretsen, L. (2012). International Olympic Committee consensus statement on thermoregulatory and altitude challenges for high-level athletes. *British Journal of Sports Medicine, 46*(11), 770-779.

Bilzon, J. L. J., Allsopp, A. J., & Tipton, M. J. (2001). Assessment of physical fitness for occupations encompassing load-carriage tasks. *Occupational Medicine, 51*(5), 357-361.

Boffey, D., Harat, I., Gepner, Y., Frosti, C. L., Funk S., & Hoffman, J. R. (2019). The Physiology and Biomechanics of Load Carriage Performance. *Military Medicine, 184*(1-2), 83-90

Brzoska, M., & Fröhlich, C. (2016). Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development, 5*(2), 190-210.

Buller, M. J., Welles, A. P., & Friedl, K. E. (2018). Wearable physiological monitoring for human thermal-work strain optimization. *Journal of Applied Physiology, 124*(2), 432-441.

Buono, M., Martha, S., & Heaney, J. (2009). Peripheral sweat gland function is improved with humid heat acclimation. *Journal of Thermal Biology, 34*(3), 127-130.

Caldwell, J. N., Engelen, L., van der Henst, C., Patterson, M. J., & Taylor, N. A. (2011). The interaction of body armor, low-intensity exercise, and hot-humid conditions on physiological strain and cognitive function. *Military Medicine, 176*(5), 488-493.

Carter, J., Rayson, M., Wilkinson, D., Richmond, V., & Blacker, S. (2007). Strategies to combat heat strain during and after firefighting. *Journal of Thermal Biology, 32*(2), 109-116.

Carter, R. 3rd, Cheuvront, S. N., Williams, J. O., Kolka, M. A., Stephenson, L. A., Sawka M. N., & Amoroso, P. J. (2005). Epidemiology of hospitalizations and deaths from heat illness in soldiers. *Medicine & Science in Sports & Exercise, 37*(8), 1338-1344.

Casa, D. J., Armstrong, L. E., Kenny, G. P., O'Connor, F. G., & Huggins, R. A. (2012). Exertional heat stroke: new concepts regarding cause and care. *Current Sports Medicine Reports, 11*(3), 115-123.

Charkoudian, N. (2016). Human thermoregulation from the autonomic perspective. *Autonomic Neuroscience, 196*, 1-2.

Che Muhamed, A. M., Atkins, K., Stannard, S. R., Mündel, T., & Thompson, M. W. (2016) The effects of a systematic increase in relative humidity on thermoregulatory and circulatory responses during prolonged running exercise in the heat. *Temperature (Austin), 3*(3), 455-464.

Cheung, S. S., & McLellan, T. M. (1998). Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *Journal of Applied Physiology (1985), 84*(5), 1731-1739.

Chou, T. H., Allen, J. R., Hahn, D., Leary, B. K., & Coyle, E. F. (2018). Cardiovascular responses to exercise when increasing skin temperature with narrowing of the core-to-skin temperature gradient. *Journal of Applied Physiology (1985), 125*(3), 697-705.

Cramer, M., & Jay, O. (2016). Biophysical aspects of human thermoregulation during heat stress. *Autonomic Neuroscience, 196*, 3-13.

Dorman, L. E., & Havenith, G. (2009). The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology, 105*(3), 463-470.

Eddy, M. D., Hasselquist, L., Giles, G., Hayes, J. F., Howe, J., Rourke, J., Coyne, M., O'Donovan, M., Batty, J., Brunye T. T., & Mahoney, C. R. (2015). The effects of load carriage and physical fatigue on cognitive performance. *PLoS One, 10*(7), e0130817.

Eggenberger, P., MacRae, B. A., Kemp, S., Bürgisser, M., Rossi R. M., & Annaheim, S. (2018). Prediction of core body temperature based on skin temperature, heat flux, and heart rate under different exercise and clothing conditions in the heat in young adult males. *Frontiers in Physiology, 9,*1780.

Eichna, L. W., Bean, W. B., & Ashe, W. F. (1943). *Operations at high temperatures: Studies of men in simulated jungle (humid) heat.* Army Medical Research Lab, Fort Knox, KY.

Ely, B. R., Ely, M. R., Cheuvront, S. N., Kenefick, R. W., DeGroot, D. W., & Montain, S. J. (2009). Evidence against a 40°C core temperature threshold for fatigue in humans. *Journal of Applied Physiology, 107*(5), 1519-1525.

Epstein, Y., Druyan, A., & Heled, Y. (2012). Heat injury prevention--a military perspective. *Journal of Strength and Conditioning Research*, *26* (Suppl 2), S82-86.

Epstein, Y., Shapiro, Y., Moran, D., Heled, Y., & Yanovich, R. (2017). Use of a Heat Tolerance Test (HTT) within the Israel Defense Force (IDF). *Journal of Science and Medicine in Sport, 20*, S57-S58.

Evans, J. D. (1996). *Straightforward statistics for the behavioral sciences.* Thomson Brooks/Cole Publishing Co.

Fleming, J., & James, L. J. (2014). Repeated familiarisation with hypohydration attenuates the performance decrement caused

by hypohydration during treadmill running. *Applied Physiology, Nutrition and Metabolism, 39*(2), 124-129.

Flouris, A. D., & Schlader, Z. J. (2015). Human behavioral thermoregulation during exercise in the heat. *Scandinavian Journal of Medicine & Science in Sports, 25* (Suppl 1), 52-64.

Forster, M. (1951). A long-range jungle operation in Malaya—1951. *Journal of the Royal Army Medical Corps, 97*, 328-339.

Gerson, N., & Goodman, S. (2007). *National Security and the Threat of Climate Change.* The CNA Coprporation.

Giesbrecht, G. G., Jamieson, C., & Cahill, F. (2007). Cooling hyperthermic firefighters by immersing forearms and hands in 10 degrees C and 20 degrees C water. *Aviation, Space & Environmental Medicine, 78*(6), 561-567.

Goforth, C. W., & Kazman, J. B. (2015). Exertional heat stroke in navy and marine personnel: A hot topic. *Critical Care Nurse, 35*(1), 52-59.

Gonzalez-Alonso, J., & Calbet, J. A. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation, 107*(6), 824-830.

Gonzalez-Alonso, J., Calbet, J. A., & Nielsen, B. (1998). Muscle blood flow is reduced with dehydration during prolonged exercise in humans. *Journal of Physiology, 513,* 895-905.

Gonzalez-Alonso, J., Crandall, C. G., & Johnson, J. M. (2008). The cardiovascular challenge of exercising in the heat. *Journal of Physiology, 586*(1), 45-53.

Gonzalez-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology (1985), 86*(3), 1032-1039.

Gonzalez, R. R., Pandolf, K. B., & Gagge, A. P. (1974). Heat acclimation and decline in sweating during humidity transients. *Journal of Applied Physiology, 36*(4), 419-425.

Haisman, M. (1972). Energy expenditure of soldiers in a warm humid climate. *British Journal of Nutrition*, *27*(2), 375-381.

Hancock, P. A., & Vasmatzidis, I. (2003). Effects of heat stress on cognitive performance: the current state of knowledge. *International Journal of Hyperthermia, 19*(3), 355-372.

Hargreaves, M. (2008). Physiological limits to exercise performance in the heat. *Journal of Science & Medicine in Sport, 11*(1), 66-71.

Hocking, C., Silberstein, R. B., Lau, W. M., Stough, C., & Roberts, W. (2001). Evaluation of cognitive performance in the heat by functional brain imaging and psychometric testing. *Comparative Biochemistry & Physiology, Part A: Molecular and Integrative Physiology, 128*(4), 719-734.

Howe, A. S., & Boden, B. P. (2007). Heat-related illness in athletes. *American Journal of Sports Medicine, 35*(8), 1384-1395.

Humphreys, M. (2005). Natural resources, conflict, and conflict resolution:Uncovering the mechanisms. *Journal of Conflict Resolution, 49*(4), 508-537.

Hunt, A. P., Billing, D. C., Patterson, M. J., & Caldwell, J. N. (2016). Heat strain during military training activities: The dilemma of balancing force protection and operational capability. *Temperature (Austin), 3***,** 307-317.

Jeukendrup, A. E., & Wallis, G. A. (2005). Measurement of substrate oxidation during exercise by means of gas exchange measurements. *International Journal of Sports Medicine, 26*(Suppl 1), S28-37

Johnson, R. F., Knapik, J. J., & Merullo, D. J. (1995). Symptoms during load carrying: effects of mass and load distribution during a 20-km road march. *Perceptual & Motor Skills, 81*(1), 331-338.

Kase, S. R., Frank, E. R., & Schoelles, M. J. (2009). Serial subtraction errors revealed. *Proceedings of the 31st Annual Conference of the Cognitive Science Society (pp. 1551-1556), Amsterdam, Netherlands, Cognitive Science Society.*

Kenefick, R. W., Cheuvront, S. N., Palombo, L. J., Ely, B. R., & Sawka, M. N. (2010). Skin temperature modifies the impact of hypohydration on aerobic performance. *Journal of Applied Physiology (1985), 109*(1), 79-86.

Kenney, W. L., Stanhewicz, A. E., Bruning, R. S., & Alexander, L. M. (2014). Blood pressure regulation III: what happens when one system must serve two masters: temperature and pressure regulation? *European Journal of Applied Physiology, 114*(3), 467-479.

King, M. A., Clanton, T. L., & Laitano, O. (2016). Hyperthermia, dehydration, and osmotic stress: unconventional sources of exercise-induced reactive oxygen species. *American Journal of Physiology - Regulatory Integrative and Comparative Physiology, 310*(2), R105-114.

Knapik, J. K., Ang, P., Bensel, C., Meiselman, H., Hanlon, W., & Johnson, W. (1997). Soldier performance and strenuous road marching: Influence of load mass and load distribution. *Military Medicine, 162*(1), 62-67.

Koubi, V. (2019). Climate change and conflict. *Annual Review of Political Science, 22*(1), 343-360.

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: a meta-regression analysis. *Brain Research, 1341*, 12-24.

Larsen, B., Netto, K., & Aisbett, B. (2011). The effect of body armor on performance, thermal stress, and exertion: a critical review. *Military Medicine, 176*(11), 1265-1273.

Leahy, S., Toomey, C., McCreesh, K., O'Neill, C., & Jakeman, P. (2012). Ultrasound measurement of subcutaneous adipose tissue thickness accurately predicts total and segmental body fat of young adults. *Ultrasound in Medicine & Biology, 38*(1), 28-34.

Lee, B. J., Mackenzie, R. W. A., Cox, V., James, R. S., & Thake, C. D. (2015). Human monocyte heat shock protein 72 responses to acute hypoxic exercise after 3 days of exercise heat acclimation. *BioMed Research International, 2015,* 849809.

Lee, J. K., Nio, A. Q., Lim, C. L., Teo, E. Y., & Byrne, C. (2010). Thermoregulation, pacing and fluid balance during mass participation distance running in a warm and humid environment. *European Journal of Applied Physiology, 109*(5), 887-898.

Lei, T. H., Schlader, Z. J., Che Muhamed, A. M., Zheng, H., Stannard, S. R., Kondo, N., Cotter, J. D., & Mündel, T. (2020) Differences in dry-bulb temperature do not influence moderate-duration exercise performance in warm environments when vapor pressure is equivalent. *European Journal of Applied Physiology, 120*(4), 841-852.

Macpherson, R. K. (1962). The Assessment of the thermal environment. A review. *British Journal of Industrial Medicine, 19*(3), 151-164.

Maughan, R. J., Otani, H., & Watson, P. (2012). Influence of relative humidity on prolonged exercise capacity in a warm environment. *European Journal of Applied Physiology, 112*(6), 2313-2321.

Mazloumi, A., Golbabaei, F., Mahmood Khani S., Kazemi, Z., Hosseini, M., Abbasinia, M., & Farhang Dehghan, S. (2014). Evaluating effects of heat stress on cognitive function among workers in a hot industry. *Health Promotion Perspectives, 4*(2), 240-246.

McLellan, T. M. (2001). The importance of aerobic fitness in determining tolerance to uncompensable heat stress. *Comparative Biochemistry and Physiology, Part A: Molecular and Integrative Physiology, 128*(4), 691-700.

McLellan, T. M., & Aoyagi, Y. (1996). Heat strain in protective clothing following hot-wet or hot-dry heat acclimation. *Canadian Journal of Applied Physiology, 21*(2), 90-108.

McLellan, T. M., Meunier, P., & Livingstone, S. (1992). Influence of a new vapor protective clothing layer on physical work tolerance times at 40 degrees C. *Aviation, Space & Environmental Medicine, 63*(2), 107-113.

Marfell-Jones, M., Olds, T., Stewart, A., & Carter, L. (2006). International standards for anthropometric assessment. *International Society for the Advancement of Kinanthropometry.*

Morante, S. M., & Brotherhood, J. R. (2008). Autonomic and behavioural thermoregulation in tennis. *British Journal of Sports Medicine, 42*(8), 679-685.

Nadel, E. R. (1979). Control of sweating rate while exercising in the heat. *Medicine & Science in Sports, 11*(1), 31-35.

Nadel, E. R., Fortney, S. M. & Wenger, C. B. (1980). Effect of hydration state of circulatory and thermal regulations. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology, 49*(4), 715-721.

Njemini, R., Bautmans, I., Onyema, O. O., van Puyvelde, K., Demanet, C., & Mets, T. (2011). Circulating heat shock protein 70 in health, aging and disease. *BMC Immunol, 12,* 24.

Nybo, L., & Nielsen, B. (2001). Hyperthermia and central fatigue during prolonged exercise in humans. *Journal of Applied Physiology, 91*(3), 1055-1060.

Pandolf, K. B., Givoni, B., & Goldman, R. F. (1977). Predicting energy expenditure with loads while standing or walking very slowly. *Journal of Applied Physiology, 43*(4), 577-581.

Parsons, I. T., Stacey, M. J., & Woods, D. R. (2019). Heat adaptation in military personnel: Mitigating risk, maximizing performance. *Frontiers in Physiology, 10,* 1485.

Periard, J. D., Racinais, S., Knez, W. L., Herrera, C. P., Christian, R. J., & Girard, O. (2014). Thermal, physiological and perceptual strain mediate alterations in match-play tennis under heat stress. *British Journal of Sports Medicine, 48*(Suppl 1), 32-38.

Pimental, N. A., Cosimini, H. M., Sawka, M. N., & Wenger, C. B. (1987). Effectiveness of an air-cooled vest using selected air temperature and humidity combinations. *Aviation, Space & Environmental Medicine, 58*(2), 119-124.

Ramanathan, N. (1964). A new weighting system for mean surface temperature of the human body. *Journal of Applied Physiology, 19*(3), 531-533.

Reuveny, R. (2007). Climate change-induced migration and violent conflict. *Political Geography, 26*(6), 656-673.

Sawka, M., Wenger, C. B., Young, A. J., & Pandolf, K. B. (1993). *Physiological responses to exercise in the heat.* Nutritional Needs in Hot Environments: Applications for Military Personnel in Field Operations. Institute of Medicine (US), Washington DC.

Schlader, Z. J., Perry, B. G., Jusoh, M. R., Hodges, L. D., Stannard, S. R., & Mundel, T. (2013). Human temperature regulation when given the opportunity to behave. *European Journal of Applied Physiology, 113*(5), 1291-1301.

Schlader, Z. J., Simmons, S. E., Stannard, S. R., & Mundel, T. (2011). Skin temperature as a thermal controller of exercise intensity. *European Journal of Applied Physiology, 111*(8), 1631-1639.

Smith, M., Withnall, R., & Boulter, M. (2017). An exertional heat illness triage tool for a jungle training environment. *Journal of the Royal Army Medical Corps, 164*(4), 287-289

Smith, P. J. (2007). Climate change, mass migration and the military response. *Orbis, 51*(4), 617-633.

Smith, R., Jones, N., Martin, D., & Kipps, C. (2016). 'Too much of a coincidence': identical twins with exertional heatstroke in the same race. *British Medical Journal Case Reports*. Published Online. https://doi.org/10.1136/bcr-2015-212592

Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology, 37*(1), 153-156.

Taylor, N., Patterson, M., Regan, J., & Amos, D. (1997). *Heat acclimation procedures: preparation for humid heat exposure.* Defence Science and Technology Organisation, Melbourne, Victoria.

Taylor, N. A. S. (2000). Principles and practices of heat adaptation. *Journal of the Human-Environment System, 4*(1), 11-22.

Taylor, N. A. S. (2015). Overwhelming physiological regulation through personal protection. *Journal of Strength and Conditioning Research, 29*, S111-S118.

Taylor, N. A. S. (2017). Heat adaptation within a military context. *Journal of Science and Medicine in Sport, 20*, S56.

Tebeck, S. T., Buckley, J. D., Bellenger, C. R., & Stanley, J. (2019). Differing physiological adaptations induced by dry and humid short-term heat acclimation. *International Journal of Sports Physiology and Performance*, 1-24.

Tharion, W., Buller, M., Potter, A., Karis, A., Goetz, V., & Hoyt, R. (2013). Acceptability and usability of an ambulatory health monitoring system for use by military personnel. *IIE Transactions on Occupational Ergonomics and Human Factors, 1*(4), 203-214.

Tucker, R., Rauch, L., Harley Y. X., & Noakes, T. D. (2004). Impaired exercise performance in the heat is associated with an anticipatory reduction in skeletal muscle recruitment. *European Journal of Physiology, 448*(4), 422-430.

Veltmeijer, M. T., Eijsvogels, T. M., Thijssen, D. H., & Hopman, M. T. (2015). Incidence and predictors of exertional hyperthermia after a 15-km road race in cool environmental conditions. *Journal of Science & Medicine in Sport, 18*(3), 333-337.

Vrijkotte, S., Roelands, B., Meeusen, R., & Pattyn, N. (2016). Sustained military operations and cognitive performance. *Aerospace Medicine & Human Performance, 87*(8), 718-727.

Wagner, D. R. (2013). Ultrasound as a tool to assess body fat. *Journal of Obesity, 2013*, 280713.

Walsh, R. C., Koukoulas, I., Garnham, A., Moseley, P. L., Hargreaves, M., & Febbraio, M. A. (2001). Exercise increases serum Hsp72 in humans. *Cell Stress Chaperones, 6*(4), 386-393.

Yaglou, C. P., & Minard, D. (1957). Control of heat casualties at military training centers. *AMA Archives of Industrial Health, 16*(4), 302-316.