Temperature

Upper body sweat mapping provides evidence of relative sweat redistribution towards the periphery following hot-dry heat acclimation

--Manuscript Draft--

Manuscript Number:	KTMP-2018-0045R1
Article Type:	Research Paper
Corresponding Author:	Caroline J. Smith, PhD Appalachian State University Boone, NC UNITED STATES
First Author:	Caroline J. Smith, PhD
Order of Authors:	Caroline J. Smith, PhD
	George Havenith
Manuscript Region of Origin:	UNITED STATES
Abstract:	Purpose: Produce a detailed upper-body sweat map and evaluate changes in gross and regional sweating rates (RSR) and distribution following heat acclimation (HA). Methods: Six male participants (25±4 yrs) completed six consecutive days of HA (45°C,20% rh) requiring 90 minutes of intermittent exercise to maintain a rectal temperature (Tre) increase of 1.4°C. RSR were measured at 55% (Intensity-1; I1) and 75% 〖V O〗_2max(Intensity-2; I2) on the upper-body pre- and post-HA using a modified absorbent technique. Results: By design, work rate increased from day one to six (n.s.) of HA, and heart rate (HR), Tre, and skin temperature (Tsk) were similar between days. Gross sweat loss (GSL) increased (656±77 to 708±80g.m-2.h-1; P<0.001) from day one to six. During pre- and post-acclimation experiments, relative workloads were similar for both intensities (Pre-I1 54±3, Post-I1 57±5 %VO2max; Pre-I2 73±4, Post-I2 76±7 %VO2max). GSL was significantly higher post-HA (Pre 449±90 g.m-2.h-1, Post 546 g.m-2.h-1; P<0.01). Highest RSR were observed on the central back both pre and post acclimation at I1 (pre 854±269 post 1178±402g.m-2.h-1) and I2 (pre 1221±351 post 1772±396 g.m-2.h-1). Absolute RSR increased significantly in 12 (I1) to 14 (I2) of the 17 regions. Ratio data indicated significant relative RSR redistribution following HA, with the relative back contribution to whole-body sweat loss decreasing, chest staying the same and the arms increasing. Conclusions: Hot-dry HA significantly increased GSL in aerobically trained males at I2 only. Absolute RSR significantly increased in I1 and I2, with a preferential relative redistribution towards the periphery of the upper body.

Upper body sweat mapping provides evidence of relative sweat redistribution towards the periphery following hot-dry heat acclimation

Caroline J. Smith[1,2] and George Havenith[1]

[1] Environmental Ergonomics Research Center, Loughborough University Design School, Loughborough, UK.

[2] Department of Health & Exercise Science, Appalachian State University, Boone, NC.

Corresponding Author

Caroline J. Smith, Ph.D.

Department of Health and Exercise Science,

Appalachian State University,

Boone, NC. USA

Phone: 828-265-8652

Fax: 8282623138

Email: smithcj7@appstate.edu

ABSTRACT

Purpose: Produce a detailed upper-body sweat map and evaluate changes in gross and regional sweating rates (RSR) and distribution following heat acclimation (HA). **Methods:** Six male participants (25±4 yrs) completed six consecutive days of HA (45°C,20% rh) requiring 90 minutes of intermittent exercise to maintain a rectal temperature (T_{re}) increase of 1.4°C. RSR were measured at 55% (Intensity-1; I1) and 75% $\dot{V}O_{2max}$(Intensity-2; I2) on the upper-body pre- and post-HA using a modified absorbent technique. **Results:** By design, work rate increased from day one to six (n.s.) of HA, and heart rate (HR), T_{re}, and skin temperature (T_{sk}) were similar between days. Gross sweat loss (GSL) increased (656±77 to 708±80g.m^{-2}.h^{-1}; P<0.001) from day one to six. During pre- and post-acclimation experiments, relative workloads were similar for both intensities (Pre-I1 54±3, Post-I1 57±5 %VO_{2max}; Pre-I2 73±4, Post-I2 76±7 %VO_{2max}). GSL was significantly higher post-HA (Pre 449±90 g.m^{-2}.h^{-1}, Post 546 g.m^{-2}.h^{-1}; P<0.01). Highest RSR were observed on the central back both pre and post acclimation at I1 (pre 854±269 post 1178±402g.m^{-2}.h^{-1}) and I2 (pre 1221±351 post 1772±396 g.m^{-2}.h^{-1}). Absolute RSR increased significantly in 12 (I1) to 14 (I2) of the 17 regions. Ratio data indicated significant relative RSR redistribution following HA, with the relative back contribution to whole-body sweat loss decreasing, chest staying the same and the arms increasing. **Conclusions:** Hot-dry HA significantly increased GSL in aerobically trained males at I2 only. Absolute RSR significantly increased in I1 and I2, with a preferential relative redistribution towards the periphery of the upper body.

Keywords: sweating, technical absorbent, regional, sweat mapping, relative redistribution

ABBREVIATIONS

BL, **Baseline**

GSL, **Gross sweat loss**

HA, **Heat acclimation**

HR, **Heart rate**

I1 **Intensity 1**

I2 **Intensity 2**

rh, **Relative humidity**

RSR, **Regional sweating rate**

Ta **Ambient temperature**

T_{core}, **Core temperature**

T_{sk}, **Skin Temperature**

T_{re}, **rectal temperature**

INTRODUCTION

The ability of an individual to dissipate heat is of fundamental importance during exercise and exposure to hot environments, with evaporation of sweat being the greatest avenue of heat loss from the body (1). Physiological responses to both acute and chronic heat exposure have been well documented, with beneficial thermal and cardiovascular adaptations occurring following repeated exposure. Classic hallmarks of heat acclimation (HA) include, 1) a reduced absolute core temperature (T_{core}) threshold for sweating, 2) increased sweating rate for a given absolute T_{core} (gain) due to increased thermosensitivity and output per gland, 3) increased maximal sweating rate, 4) greater maximum skin wettedness, 4) increased tolerance as evidenced by a reduced heart rate, cardiac output and core temperature for a given workload, and 5) an improvement in exercise performance (2-10). Whilst there is a consensus supporting these beneficial adaptations, there are discrepancies in the literature regarding the existence of regional sweating adjustments, namely peripheral relative redistribution of sweating, and linked potential alterations in cooling efficiency. Traditionally, many studies have utilized change in whole body mass to estimate whole body (gross) sweat loss throughout heat acclimation regimens. Fewer studies have examined regional sweating rate (RSR) changes, with between 1-4 small (1-4 cm^2) local sweat sites typically measured and inconsistent conclusions being drawn regarding potential redistribution of sweating patterns following acclimation (5, 11-13). This is not surprising considering the large variation in RSR both between and within body regions (14-19), making selection of the specific measurement site important. Measurement of a single small 'central' and single 'peripheral' site provides minimal information and limits conclusions that can be drawn, highlighting the need for detailed sweating data over a large surface area of the body to truly assess alterations in sweating rate and distribution following HA.

Most studies have observed a significant increase in both gross sweat loss (GSL) and RSRs following heat acclimation (1, 11, 13, 20), with a primary focus on absolute sweating rates. Limited consideration has been given to sweat distribution changes, in which RSR relative to the average sweating rate over all sites measured is evaluated. Several studies have examined a small number of RSR sites and extrapolated to larger body regions, and calculated RSR as a percentage of total sweating. When considered in this manner, several studies support a central to peripheral relative redistribution (13, 20, 21), whilst others reported an increase in sweating rates across the body with no shift in sweating patterns (11, 12). Some of this discrepancy results from difficulty in direct comparison of sweating rates between studies, owing to differing environmental conditions (hot humid vs. dry), acclimation protocols and durations, varied exercise modes and intensities, participant selection, sweat measurement techniques, and limited measurement sites being generalized to larger body regions. This approach makes a true assessment of absolute quantity and distribution shifts difficult. Our laboratory previously published detailed regional 'sweating body maps' using a modified absorbent technique, covering up to 83% body surface area (SA; 1.6 m^2 of 1.92 m^2 total body SA in male athletes) (14). This study demonstrated that due to the large variation in sweating rates within regions, small sweat capsules may not capture what is happening across that region. Using this modified absorbent technique to produce pre and post acclimation sweat maps will allow simultaneous measurement of more sites and over a larger body surface area than is possible with capsule techniques, allowing greater insight into absolute RSRs and distribution following heat acclimation.

The primary aim of this study was to produce detailed sweating maps of the upper body, with the secondary aim of investigating alterations in regional sweating rates and distribution over multiple central (torso) and peripheral (arms) sites in young, trained male athletes following six consecutive days of 'constant thermal strain' exercise-heat acclimation in a hot-dry environment (45°C, 20% rh). It was hypothesized that a significant increase in both gross sweat loss and absolute regional sweating rates would occur at all sites measured. Furthermore, it was hypothesized that the relative increase in contribution to total body sweat rate would be greater at peripheral upper body versus central sites, leading to increasing uniformity of sweat coverage.

MATERIALS AND METHODS

Participants

Six aerobically trained male athletes completed the HA regimen and sweat mapping experimentation (25 ± 4 years, 178.6 ± 3.8 cm, 75.12 ± 4.8 kg, 1.94 ± 0.1 m^2, 12.4 ± 5.4% body fat, 64.9 ± 14.9 $ml.kg^{-1}.min^{-1}$ predicted $VO_{2\ max}$). All experimental procedures were approved by the Loughborough University Ethics Committee and conformed to the guidelines set forth by the Declaration of Helsinki. Procedures were fully explained to all participants before informed verbal and written consent were obtained and a health-screening questionnaire completed. All participants trained a minimum of 8 hours per week, were free from cardiovascular and metabolic diseases (self-reported), were not taking any medications that could conceivably alter thermoregulatory function and were not heat acclimated as determined by self-reported information confirming no exposure to heat within 3 months prior to the study.

Preliminary Session

Participants attended the Environmental Ergonomics Research Center (EERC) for a preliminary session involving anthropometric measurements of height, body weight, and body dimensions used for the production of individualized absorbent pads. Skinfolds were measured at 7 sites and body fat percentage calculated based on a population specific equation for male athletes (22). $\dot{V}O_{2max}$ was estimated from a submaximal fitness test (23) based on the Åstrand-Ryhming method (24) . All participants completed four, five minute (min) exercise intensities on a treadmill (h/p/cosmos mercury 4.0 h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) in thermoneutral conditions (18°C, 30%rh).

Sweat Pad Preparation and Application

The modified absorbent technique utilized to calculate RSRs and produce body sweat maps has previously been described (14, 15, 25). Briefly, hygroscopic material (Tech Absorbents product 2164) was used to produce custom-made pads individually sized to each participant based on anthropometric measurements. All pads were individually weighed (Sartorius YACOILA, Sartorius AG, Goettingen, Germany. Precision 0.01g) inside labelled airtight bags and stored until testing. Immediately prior to testing, pads were attached to custom-sized plastic sheeting (28 pads per exercise intensity) for efficient application to the skin surface and to prevent sweat evaporation during measurement periods. Pads were maintained in contact with the skin in their appropriate positions using a custom-made, rapidly removable, long sleeve stretch t-shirt. Sweat pads were additionally placed at the base of the neck (anterior and posterior), and under the armpits to avoid sweat run down and contamination of adjacent pads. These pads were discarded and were not used in RSR calculations. Upon completion of the protocol, all pads were re-weighed, and SA calculated from the dry weight of each pad and the weight per unit of surface area of the material. RSRs were calculated in grams per meter square of body surface area per hour ($g.m^{-2}.h^{-1}$) based on the weight change of the pad, the pad SA, and the duration of application to the skin. To minimize the effect of the pads on the overall thermal state of the body, sweat mapping was only conducted on the torso and arms and sample periods were limited to 5 minutes.

Body Sweat Mapping Protocol

Body sweat mapping experiments were conducted in the EERC in a climate-controlled room maintained at 25.7±0.4°C, 46.6±8.0 % rh, prior to and following a 6-day HA protocol (described below). Subjects were instructed to refrain from strenuous exercise and consume 20 ml.kg body weight of water within 24 hours prior to testing. Upon arrival at the laboratory, participants were provided with shorts and t-shirt before being weighed. Baseline values of heart rate (HR, Polar Electro Oy, Kempele, Finland), sublingual temperature, and body core temperature ($T_{core,}$ ingestible core temperature pill), were recorded with participants in a seated position. HR was recorded at 15 second intervals throughout the protocol, and T_{core} was measured using a VitalSense ® Integrated Physiological Monitoring System (Mini Mitter Co., Inc., Bend, Oregon, USA). Participants swallowed a Vitalsense™ ingestible temperature pill 5 hours before testing, which wirelessly tracked and recorded T_{core} up to four times per minute. Baseline skin temperature (T_{sk}) was recorded via Infra-red imaging (Thermacam B2, FLIR Systems Ltd., West Malling, Kent, UK) of nude, dried skin, and repeated before and after each pad application, and immediately following cessation of the exercise protocol.

Following collection of baseline data, participants completed a 60 min training run on a treadmill (1% incline) involving two exercise intensities (30 min per intensity). A target HR of 125-135 and 150-160 beats per minute (bpm) were achieved for intensity 1 (I1) and intensity 2 (I2), equating to ~55 and ~75% of $VO_{2\ max}$, respectively. RSRs were measured for each exercise intensity via application of the customized hygroscopic pads for a period of 5 min, first after 30 (I1) and then after 60 (I2) min of the protocol, as described above. Running was resumed during the 5 min sampling periods at the respective workloads. For IR images and pad application, subjects briefly dismounted the treadmill, with a total transition time of less than 3 min. To ensure sweat collection occurred for the 5 min sample periods only, participants removed their t-shirt before thoroughly drying their skin with a towel immediately prior to pad application. Evaporation of sweat from the pads was prevented during sweat measurement due to their hygroscopic properties, their impermeable backing, and by their attachment to custom-made polyethylene sheeting necessary for their application to the body. To prevent participant dehydration during the protocol, *ad libitum* water consumption was permitted, and recorded for necessary adjustments of GSL. Following completion of the protocol, body weight and sublingual temperature were recorded.

Heat Acclimation Protocol

On arrival at the laboratory participants changed into shorts and body weight was obtained (Mettler Toledo kcc150, 150 kg, resolution 1g. Mettler Toledo, Leicester. UK.). Water bottles were labelled and weighed prior to and following testing on an electronic scale to monitor fluid consumption throughout testing, and were stored inside a cool box in the environmental chamber. Participants self-inserted a rectal thermistor (Grant Instruments, Cambridge, England) 10cm beyond the anal sphincter for measurement of T_{core} during the HA protocol. Thermistors (Grant Instruments, Cambridge, England) were attached to four skin sites (upper arm, chest, thigh and lower leg) for measurement of local T_{sk} and calculation of weighted mean T_{sk}(26). The skin and rectal thermistors were attached to an Eltek/Grant 10-bit, 1000 series squirrel data logger (Grant Instruments, Cambridge, England) for data collection. Participants were fitted with a polar heart rate monitor and watch (Polar Electro Oy, Kempele, Finland) which recorded HR at 5 second intervals. Participants were asked to sit in a thermoneutral preparation room for 15 min prior to entering the environmental chamber to obtain resting, baseline data.

Before commencing the acclimation regimen, the cycle ergometer was adjusted, and a level of resistance was established which could be maintained throughout the first exercise period, and that was sufficient to elicit a 1.4°C T_{core} rise. Three 50cm diameter fans (JS Humidifiers plc, Littlehampton, UK) were mounted in a linear arrangement on a wooden frame, 1 meter in front of the bike. This enabled an equal distribution of wind over the height of the body, with an air velocity of 1.0 $m{\cdot}s^{-1}$. Daily calibration of air velocity was performed using a hot wire anemometer (model TSI Alnor 8455. TSI Instruments Ltd, UK. Range 0.125-50 m·s-1.) at the position of the cycle ergometer seat. T_{core}, T_{sk}, ambient temperature (T_a), relative humidity (rh) and HR were recorded at one min intervals, and manual readings recorded every five min. The HA regime was based on the Fox constant strain technique (27, 28), involving intermittent exercise in 45°C and 20% rh (hot-dry) to achieve and maintain a 1.4°C elevation in T_{core} above baseline. Participants completed a 90 min exposure involving three, 20 min bouts of submaximal cycling, interspersed with 10 min rest periods. Resistance was adjusted to achieve the desired increase in T_{core} or at the request of the participant. If T_{core} exceeded a 1.4°C increase from baseline or approached 39°C participants interrupted exercise and sat on the cycle ergometer to limit any further elevation, until T_{core} started to drop.

Following each daily 90-min heat exposure, all equipment was removed, and participants were re-weighed wearing only their shorts. Measurements of T_{core} and HR were repeated, and participants were advised they could leave the laboratory when values approached those observed pre-exposure.

Data and Analysis

Gross and Regional Sweating Data

GSL during all HA days and sweat mapping experiments was calculated based on the weight change of each semi-nude participant during testing, adjusted for fluid intake and clothing weight, and corrected for respiratory and metabolic mass losses (1), based upon work described by Livingston et al.(29) and Kerslake ((30) Pp. 121), respectively. A two-way repeated measures ANOVA was performed to analyze regional differences within each intensity, pre and post HA. Similarly to prior sweat mapping studies, right-left differences in RSR and changes with exercise intensity and HA were analyzed using paired samples t-tests, both with and without Bonferroni correction to evaluate the risk of Type I versus that of Type II error. Both corrected and uncorrected data are presented due to the exploratory nature of the study and the large number of regions studied (31). Due to the highly stringent nature of the Bonferroni correction, and small sample size, some regions which may be significant in studies involving a smaller number of areas, may fail to meet significance and should be considered alongside the uncorrected analysis. Sweating maps are presented using median values to present an 'average sweater' versus use of mean RSR values that illustrate the 'average amount of sweat produced', the latter being more easily affected by outliers. Both values are presented to provide insight into the data distribution. One-way repeated measures ANOVAs were performed to analyze differences in all outcome variables throughout the 6 day HA protocol, and post hoc comparisons were conducted both with and without Bonferroni correction.

In addition to the absolute RSR data, individual's RSR values were normalized for the area weighted sweating rate of all (n) zones measured to standardize RSR data over all participants, before calculating means, medians, etc.

$$RSR_{norm,i} = \frac{RSR_i}{\left\{\frac{\sum_{j=1}^{j=n}\left(area_j * RSR_j\right)}{\sum_{j=1}^{j=n}\left(area_j\right)}\right\}} \qquad (1)$$

With $RSR_{norm,i}$ = normalized local sweat rate of zone i (non-dimensional; 0=no sweat, 1=average, 2=double than average sweat rate over all zones)

RSR_i = measured sweat rate in zone i in $g.m^{-2}.h^{-1}$

n=total number of tested zones

RSR_j=regional sweat rate of zone j in $g.m^{-2}.h^{-1}$

$area_j$=surface area of zone j

This allows easy identification of 'high' and 'lower' sweat regions regardless of absolute values, and any alterations of the distribution of sweat produced and any alteration in the contribution of a certain area to whole body sweat rate with exercise intensity and/or HA. The same analysis was performed on the normalized ratio RSR data as previously outlined for the absolute data. Statistical analysis was performed using SPSS (IBM SPSS, version 24, Armonk, N.Y. USA) and the significance level was set at an alpha level of $p<0.05$.

Regional Skin Temperature Data

A one-way repeated measures ANOVA and post hoc pairwise comparisons were performed on all regional T_{sk} data for separate time points during sweat mapping experiments. A series of paired t-tests were used to analyze changes in T_{sk} between measurement periods, and corrected for multiple comparisons (Bonferroni). A within subject analysis was performed to examine potential correlations between regional T_{sk} and RSR. Pearson's r correlation coefficients were produced for RSR and both pre and post pad application T_{sk} at each exercise intensity due to significant differences between measurement periods.

RESULTS

By design of the constant thermal strain acclimation protocol, T_{core} and T_{sk} were similar between HA days (P>0.05), and cardiovascular strain (HR) during the work bouts decreased slightly (P<0.05). Work performed (kJ) on acclimation days to elicit the target T_{core} increased from day one to six in five (+21%, p=0.01) out of six (+11%, p>0.05) participants (Table 1). GSL increased significantly from day one to six of acclimation (P<0.001), representing an average increase of 14.2 ± 2.3%.

Gross Sweat Loss and Metabolic Rate

During pre and post HA body mapping experiments relative workloads (to achieve the target HR) were similar for I1 and I2, suggesting no change in fitness level, but GSL was significantly higher following acclimation at I2 (Table 2). Figure 1 illustrates the similarity in metabolic rate ($W.Kg^{-1}$) between pre- and post HA experiments at both I1 and I2, but highlights divergent GSL results depending on workload. Pre- versus post HA GSL was similar at I1 but the higher metabolic load at I2 resulted in a significantly higher post HA GSL. This picture was the same when metabolic rate is expressed in Watts.

Regional Sweating Rates

Pre and post acclimation regional sweating maps for I1 and I2 are illustrated in Figure 2. Following analysis of right-left RSR data, it was decided to group corresponding right-left pads producing a total of 17 grouped R-L regions for further analysis, due to any significant right-left differences being present in only a small number of the 28 individual zones sampled. RSR were highest on the central back during both pre and post acclimation tests at I1 (median values: pre 864 vs. post 1178 $g.m^{-2}.h^{-1}$) and I2 (pre 1268 vs. post 1772 $g.m^{-2}.h^{-1}$) for the regions tested. Pre HA, the lowest RSR were observed on the anterior and posterior upper arms and the anterior lower torso at I1 and I2. Post acclimation, though absolute values increased, the same areas sweated least, with posterior arms increasing more than anterior. Absolute RSR increased in all zones (R-L grouped data), significantly at 12 of the 17 regions tested at I1 and 14 regions at I2 (Table 3). Detailed descriptive statistics and comparisons of all absolute RSR pre- and post HA, and regional sudomotor sensitivity may be viewed in the Supplemental Digital Content 1 for exercise intensity 1 (see Table 1, SDC 1) and intensity 2 (see Table 2, SDC 1). Normalized regional sweating ratio data for individual zones (Fig. 3) showed no clear shift of sweating rate distribution to the periphery, only a significant reduction in relative sweating rate on the back at I1 following acclimation. I2 individual zone ratio values on the other hand significantly decreased at the lateral upper back ($p<0.01$) and increased at the anterior and posterior upper arm, and anterior lower arm ($p<0.05$) versus pre-acclimation values (Table 3). To further evaluate relative redistribution of sweating, both absolute and normalized RSR were area weighted and grouped into ‘central’ (whole excl.

shoulders, front and back torso excl. shoulders) and ‘peripheral’ (whole, anterior and posterior arms) regions. As expected, absolute RSRs increased with acclimation in all grouped areas and at both work intensities ($P<0.001$). For the normalized grouped data, (Fig.4), the sweat ratio (local/average sweat rate) decreased for the back torso ($p<0.05$), did not change significantly for the front torso, and increased for the arms, whole and both front and back ($p<0.05$), with acclimation. This was observed for both intensities. Accordingly, a significant interaction between acclimation and regional sweating ratio change was present at both intensities ($P<0.05$), indicating that not all RSR increased in the same manner, supporting an increase in absolute RSR and an alteration in relative distribution of sweat with heat acclimation towards a greater contribution from the periphery.

Skin Temperature

Sweat mapping regional T_{sk} data (Table 4) were grouped into corresponding right-left regions due to limited significant differences (post HA: BL, posterior upper torso $p < 0.05$; post I1, posterior lower torso $p < 0.05$; all non-significant following Bonferroni correction). T_{sk} was compared at the beginning and end of each exercise intensity, and prior to and following pad application to assess the influence of pad application itself on regional T_{sk}.

Exercise Intensity: During Pre HA testing, no significant changes in regional T_{sk} occurred during I1, but seven of the 13 regions significantly decreased during I2. During post HA testing, one region significantly increased and two regions significantly decreased during I1 (Table 4), and T_{sk} at 11 of the 13 regions significantly decreased during I2. Overall, the largest increase in T_{sk} was observed during I2 at the anterior medial lower torso in both pre and post HA data, increasing 1.8°C and 2.2°C, respectively. The smallest pre HA T_{sk} change was observed during I1 at the anterior lateral lower torso, rising by 0.3°C, versus the anterior lower arm during post HA testing, rising 1.1°C. Despite the larger increases in regional T_{sk} during post HA sweat mapping, the large inter-individual variation resulted in only one significant difference being present between experiments (pre I2: anterior medial upper torso).

Pad Application: During pre HA testing, T_{sk} increased significantly at 11 of the 13 regions during the 5 minute I1 pad application period (only 3 out of 13 regions following Bonferroni correction), and only three regions during I2 pad application (one region following Bonferroni correction). During post HA testing, a significant increase in 9 out of 13 regions occurred during both I1 and I2 pad application. The mean increase of all regions at I1 was 0.9 ± 0.4°C and 1.7 ± 0.5°C for pre and post acclimation respectively, and 1.1 ± 0.4°C and 2.2 ± 0.6°C I2. Notably, significant increases in T_{sk} associated with pad application were not consistent across exercise intensities or pre/post HA testing, suggesting a limited impact.

DISCUSSION

The present study provides the most detailed regional sweating rate data of the upper body following heat acclimation currently available. The main findings from the regional sweating data were 1) sweating rates increased in all zones (most reaching significance) following 6 days of hot-dry heat acclimation using a clamped-hyperthermia (constant thermal strain) protocol, 2) the ranking of high to low sweat producing regions remained similar pre and post acclimation, and 3) the contribution of peripheral sweating rates to whole body sweat rate increased relatively more than for central regions, leading to a more uniform sweat distribution. Overall, these data provide evidence of a preferential relative redistribution of sweating from central to peripheral regions following hot-dry acclimation. An important secondary finding highlights significant increases in

GSL at higher workloads following HA (increased gain), that are not observed at lower workloads. Classic hallmarks of acclimation were observed, including a physiologically relevant increase in workload of 21% in 5 out of 6 participants, required to elicit the target 1.4°C T_{core} rise and a concomitant, significant increase of 14% in GSL to compensate for this higher heat production on day 6 versus day 1 of HA.

Regional variation in sweating rates over the body are well documented, yet little consensus exists regarding how RSRs change with HA. In the present study, a relative RSR redistribution was observed post-HA, that was more pronounced at the higher workload (Figure 3 and 4). When simply considering absolute high and low RSR regions, our data are consistent with prior sweat mapping data (14, 15), and other groups using varied measurement techniques (16, 17, 32, 33). At both intensities, RSR were highest at the central back, with a medial to lateral decrease across both the anterior and posterior torso at I1 and I2 during both pre- and post-acclimation testing. The lowest RSR were consistently observed on the arms, with lowest values on the upper arms at both intensities. Importantly, despite a significant increase in absolute RSRs, the magnitude of this increase varied between sites. Normalized ratio sweating data were used to assess relative changes in the contribution of a zone's RSR to overall body sweat production, both for individual (Table 3) and for grouped zones (Fig. 4). For individual zones, limited statistical support was observed for relative peripheral redistribution at I1, but was evident at I2. When zones were grouped as front torso / back torso / front arms / rear arms (Fig. 4), clear significant changes were observed with the greatest increase on the arms and the strongest decrease in relative sweat rate on the back. No change was observed on the chest. This preferential relative redistribution of sweating on the upper limbs suggests a shift towards a more uniform distribution and thus improved distribution of skin wettedness (10, 34), potentially leading to higher evaporative efficiency.

In conjunction with the RSR data, an intensity-dependent increase in GSL following HA was evident only at I2. The present data (Fig. 1) supports our prior findings (14, 15) and those of others (35), indicating a strong relation between sweating rates and metabolic heat production (Fig. 1 remains similar, whether expressed in $W.Kg^{-1}$; $W.m^{-2}$; or W). However, as in our earlier studies (14, 15) the relation differs depending on intensity, despite similar evaporative requirements, and in the present study also between pre- and post-HA sweat mapping experiments. Improved sweating responses following HA are well documented, but this latter result appears to tease out an HA-related augmentation of sweating responses that is dependent on heat production levels. Intensity-dependent differences in GSL have previously been reported by Gagnon and Kenny (36), who observed sex-related differences in sudomotor function only to occur above certain heat loss requirements. In the present study, both significant HA-dependent increases in GSL and a more pronounced upper body peripheral redistribution of local sweating were observed at a higher workload, indicating the importance of heat production levels when determining physiological differences or adaptations. A recent study by Jay and colleagues provides support for an HA-induced peripheral redistribution in RSR, but highlights the importance of compensability (37). Pre and post HA T_{core} responses in their experiments were similar during exercise in compensable conditions, regardless of HA status, but greater GSL, RSR and reduced T_{core} rise were observed post HA in uncompensable conditions. Using ventilated capsules at two sites (arm, chest), peripheral (arm) RSR were higher in both instances, but the increase was greater in uncompensable conditions, coupled with an increased torso (central) RSR that was not observed under compensable conditions. In relation to the present study which provided more extensive RSR sites, the compensable conditions during sweat mapping experiments may explain the similarity in pre- versus post HA T_{core} data and limited peripheral redistribution at I1. As uncompensable conditions are approached (i.e. the higher workload), significantly greater post-HA RSR and GSL are observed, with evidence of peripheral redistribution. Emerging support for HA-induced thermoregulatory adjustments evident only during exercise stress in uncompensable conditions may contribute to explaining discrepancies in the literature.

The present data indicate increases in GSL that are much smaller than increases in total sweating loss captured by the sum of all patches. Post HA GSL increased 10% at I1, yet SA weighted GSL for the torso and arms together increased 68%. There are two possible causes. The first, described in our earlier studies and confirmed by Morris et al. (38), is that GSL is measured over the whole 30 min period, integrating periods where sweating begins, with periods where sweating rate will have increased markedly. The sample period for the patches occurs during steady state, only capturing the highest sweating rate for that period. In addition, it may suggest that the increase in areas not covered with pads is lower than in the regions measured, but this is difficult to tease out from the first consideration. The biggest surface area not measured is the legs, thus suggesting that RSR on the legs may increase less than the average for the torso and arm regions following HA.

It is important to note that in its broadest sense 'redistribution' implies that something is transferred from one location to another, with absolute decreases in one area facilitating increases elsewhere. This was not the case here, with RSR increasing in all areas. Discussing only absolute changes in RSR and drawing conclusions from these regarding redistribution does not provide a complete picture. Similarly, expressing a relative increase as a percentage or fraction increase for a zone (11) (e.g. RSR_{chest} post-HA/ RSR_{chest} pre-HA) can be misleading, as the same absolute change would suggest a higher percentage increase for the low sweat zone. In the present study, the terms **'relative redistribution'** and **'relative increase/decrease'** are used to more appropriately reflect relative changes in RSR as a proportion of whole body sweating rate. For this purpose, 'relative' values are expressed as the RSR in relation to the average whole body sweating rate (equation 1). Logically, an increase in this value reflects a bigger contribution to overall body sweating rate and allows evaluation of relative shifts of contribution. When considering HA studies, this highlights the importance of normalized ratio sweating data, with different approaches to data analysis and use of definitions leading to varied interpretation.

A central to peripheral 'redistribution' in RSR following HA was initially reported by Hofler (21), and later supported by Shvartz (13). Hofler (21) calculated the percentage contribution of four body segments to overall sweating output following HA to dry and humid heat. Results varied depending on the environmental conditions (35 days, hot-dry (n=3) versus hot-wet (n=5)), with humid heat exposure eliciting a significant relative redistribution towards the upper limbs. Hofler reported a decrease in absolute RSR on the legs with a similar pre- and post HA relative distribution, an increase in both absolute and relative RSR on the arms, and varied absolute changes in torso RSR. A relative decrease of the contribution of torso sweating rates to the overall sweat output, and redistribution towards the upper limbs (after >9 days HA) support the present findings. Notably, the preferential torso to limb redistribution observed during humid-heat HA, suggests specificity of sweating responses to the environmental conditions (evaporation capacity), providing further support for greater post HA sweating responses during uncompensable conditions (37). Limitations to Hofler's data should be considered, including the limited sites and surface area used to extrapolate body segment sweating rates (2-6, 4cm diameter Plexiglas rings per region), and different environmental conditions (hot-dry, hot humid) and protocols (exposures ranging 2hrs/day to continuous 'living', and HA protocols ranging 20-35 days) utilized for individual participants. Similar results were observed by Shvartz (13), whereby absolute RSRs measured using sweat capsules (4cm^2), increased proportionally more on the arms following a 15 day HA protocol, however, absolute arm RSR were consistently higher than the chest and torso which is inconsistent with most other data from a range of laboratories (12, 20). Similarly to the present data, there was a discrepancy between magnitude of increases in GSL following HA and greater increases in RSR at the locations measured, reinforcing that RSRs, dependent on the total surface area measured, may not reflect GSL changes with HA. This further highlights the unique data provided by the present body sweat maps, allowing a broader and more detailed picture of RSR alterations versus more traditional approaches.

More recently, Poirier and colleagues (20), observed an increase in GSL following 10 days of hot-dry HA (35°C, 20% rh) and some evidence of RSR redistribution. Local forearm sweating rates increased significantly during the 2nd and 3rd exercise bouts, yet similar pre- and post-HA values were observed on the chest and upper back throughout the protocol. Notably, RSR were measured using the ventilated capsule technique (~3.8 cm^2) and did not include sites on the lower torso, legs, or forehead. These data support the current findings and other investigators (13, 21), clearly demonstrating that individual location or small area RSR do not necessarily reflect increases in GSL or the larger region.

A number of studies have focused on other aspects of HA, but upon secondary analysis of these data, we find that they do in fact support the redistribution theory. For example, Inoue et al (5) investigated the effects of heat acclimation and aerobic fitness on RSR in both younger and older males. Since sweating distribution *per se* was not the primary focus, we reevaluated the data presented and calculated both absolute changes following HA and relative RSR changes in proportion to all sites measured (relative redistribution). An absolute increase in RSR was observed at all sites in the young males following 8 days of fixed intensity exercise acclimation (43°C, 30% rh), with greater relative increases at peripheral (forearm, thigh) versus central sites (chest, back). Based on our new calculations from their data (5), peripheral sites remained the lowest absolute sweat regions following acclimation, but values increased by ~100% on the forearm and thigh compared to ~47% and ~11% on the chest and back, respectively. The latter two calculations are consistent with observation from our own data that the back increases relatively less with HA than the chest (Fig. 3). This is one of only a limited number of studies that has measured peripheral sweating at multiple limb sites, providing some indication of a true peripheral relative redistribution, and not simply 'upper limb' redistribution.

In contrast, Patterson and colleagues, reported an absence of peripheral sweating redistribution (3.15 cm^2 capsules) following 3 weeks (16 exposures) of humid HA (11). Unacclimated males underwent a controlled-hyperthermia protocol (40°C, 60% rh) involving 90 min cycling/day, 6 days per week to elicit a target T_{core} of 38.5°C. Despite the authors arguing against relative peripheral redistribution, their data may in fact support an increase in upper limb redistribution with RSR. In absolute terms, forearm RSR increased 122% from day 1 to 22 of HA, versus 85% on the scapula and 105% on the chest. However, redistribution towards the lower limbs (thighs) was not evident, with an increase of only 45% by day 22. Lower limb RSR were not measured in the present study, but a comparison of GSL and SA weighted GSL provides agreement with Patterson et al (11), whereby a smaller increase on areas not covered by pads (i.e. legs) indicates an absence of lower limb relative redistribution. Interpretation of data from Patterson and colleagues (11) is problematic when only considering absolute increases (%) due to a regional percentage increase being related to the zone's RSR rather than the whole body SR, as in the present data. When we recalculated their data, considering either RSR in relation to GSL or proportionally to all sites measured (normalized ratio values), the forearm showed the greatest relative increase (from 0.80 to 1.0 ratio following HA), followed by the chest (0.90 to 1.0). The relative scapula sweating rate remained similar from day 1 to 22 of HA (1.0 ratio value), whilst the thigh showed a relative decrease (from 1.0 to 0.73). Unfortunately, given the small areas tested, we cannot accurately calculate relative contributions in the same way as in the present paper and this interpretation needs to be considered with caution.

Other studies have noted no improvement in GSL (5, 12, 28), or RSR and/or peripheral redistribution for reasons that are not fully clear (12). Explanations include an insufficient stimulus for acclimation to occur, associated with lower workloads and compensable conditions (39, 40), and non-consecutive HA days allowing potential decay in the physiological responses (41-43). A 6-day controlled hyperthermia protocol with intermittent exercise, adapted by Havenith and van Middendorp (28) based on the work of Fox (39), was selected in the present study to ensure maintained physiological strain and optimal acclimation (44). This is reported as the minimum number of days required to achieve sudomotor adjustments (11), although others have suggested >10-14 days are necessary for more complete adaptation (41, 45), particularly in untrained populations. The ‘partial acclimation’ possessed by athletes allowed a short HA regimen, owing to higher baseline sweat rates versus sedentary individuals, and more rapid acclimation (41, 42, 46). Discrepancy still surrounds optimal HA procedures, and rate of decay (41, 47, 48), which may be explored further in several extensive review articles (42-44, 49). GSL did increase in all participants throughout heat acclimation for a similar T_{core} rise but was similar on days 5 and 6 (14.2 ± 2.3% increase on day 6 vs day 1), representing a classic hallmark of heat acclimation. Considering the high RSR, which may be near maximal following HA, a relative redistribution of sweating towards the arms may be an efficient way to maximize evaporative heat loss.

Limitations

Due to the use of a modified absorbent method in the present study, the entire body surface could not be measured in a single test without potential alterations in the thermal state of the body and manipulation of RSR. Changes in RSR on the head, legs, feet and hands were therefore not assessed. As such, the ratio values calculated to observe distribution shifts only considered RSR on the regions measured, i.e. torso and arms. Further, this technique does not allow for continuous measurement of sweating rates or onset thresholds. Investigators requiring such measurements should consider ventilated capsules as a more suitable approach, whilst acknowledging its drawback of measuring only a small surface area at limited body sites. RSR measured with the modified absorbent technique correlate highly with the ventilated capsule method during steady state, but may yield lower RSR values during non-steady state (e.g. in the early stages of exercise), making the use of ventilated capsules more appropriate under such conditions (38). Finally, sweat gland activation was not measured or output per gland calculated in the present study but may be considered (50). The origin of the increases in RSR can therefore not be established.

CONCLUSIONS

Finally, these data are in agreement with literature reporting HA-induced increases in GSL and RSR, but with a preferential relative peripheral redistribution which was more pronounced at higher workloads. The modified absorbent technique provides a novel approach to the simultaneous measurement of sweating rates over multiple sites covering a large skin surface area. Careful consideration of absolute changes versus relative redistribution of sweating must be recognized to gain accurate insights into physiological adjustments with HA.

The present upper body sweat maps provide the most detailed regional sweating data covering the largest skin surface area currently available following heat acclimation. Controlled hyperthermia (constant thermal strain) exercise-heat acclimation in a hot-dry environment elicited a significantly increased gross sweat loss that was evident only at a higher exercise intensity and increased regional sweating rates in most regions. Lower sweating regions at the periphery (arms) showed a greater increase in contribution to overall sweat rate compared to the increases in higher sweating regions (torso), leading to a preferential relative redistribution of sweating towards the periphery mainly from the back torso to the arms (note that legs were not measured). The HA-associated higher uniformity of sweat distribution is stronger at the higher work intensity. Sweating patterns were consistent with prior body sweat mapping studies, showing highest and lowest regional sweat rates on the central back versus the anterior lower torso and arms, respectively. These sweat maps provide a unique assessment of local sweating rates which may help inform researchers on the most appropriate measurements sites when only a minimal number of sites are possible to be captured (i.e. capsules). Further, these data have important applications for thermophysiological modeling requiring detailed physiological data on responses to HA and for garment design, which consider evaporative cooling and moisture management.

Acknowledgements

This research was co-funded by the Adidas Futures Team, Germany, and the Environmental Ergonomics Research Centre, Loughborough University, UK. The authors would like to thank Dr. Simon Hodder for his assistance with data collection, and Dr. Gavin Williams for production of sweat mapping images.

Disclosure of Potential Conflicts of Interest

The authors were fully responsible for the conduct of the trial and the data. The authors declare that there are no conflicts of interest.

References

1. Havenith G, Fiala D. Thermal Indices and Thermophysiological Modeling for Heat Stress. Compr Physiol. 2015;6(1):255-302. Epub 2016/01/13. doi: 10.1002/cphy.c140051. PubMed PMID: 26756633.
2. Lorenzo S, Halliwill JR, Sawka MN, Minson CT. Heat acclimation improves exercise performance. Journal of applied physiology (Bethesda, Md : 1985). 2010;109(4):1140-7. Epub 2010/08/21. doi: 10.1152/japplphysiol.00495.2010. PubMed PMID: 20724560; PubMed Central PMCID: PMCPMC2963322.
3. Havenith G. Individualized model of human thermoregulation for the simulation of heat stress response. Journal of applied physiology (Bethesda, Md : 1985). 2001;90(5):1943-54. Epub 2001/04/12. doi: 10.1152/jappl.2001.90.5.1943. PubMed PMID: 11299289.
4. Wyndham CH, Rogers GG, Senay LC, Mitchell D. Acclimization in a hot, humid environment: cardiovascular adjustments. Journal of applied physiology. 1976;40(5):779-85. Epub 1976/05/01. doi: 10.1152/jappl.1976.40.5.779. PubMed PMID: 931906.
5. Inoue Y, Havenith G, Kenney WL, Loomis JL, Buskirk ER. Exercise- and methylcholine-induced sweating responses in older and younger men: effect of heat acclimation and aerobic fitness. International journal of biometeorology. 1999;42(4):210-6. Epub 1999/05/08. PubMed PMID: 10232057.
6. Nielsen B, Hales JR, Strange S, Christensen NJ, Warberg J, Saltin B. Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. J Physiol. 1993;460:467-85. Epub 1993/01/01. PubMed PMID: 8487204; PubMed Central PMCID: PMCPMC1175224.
7. Sawka MN, Young AJ, Cadarette BS, Levine L, Pandolf KB. Influence of heat stress and acclimation on maximal aerobic power. Eur J Appl Physiol Occup Physiol. 1985;53(4):294-8. Epub 1985/01/01. PubMed PMID: 4039255.
8. Sato F, Owen M, Matthes R, Sato K, Gisolfi CV. Functional and morphological changes in the eccrine sweat gland with heat acclimation. Journal of applied physiology. 1990;69(1):232-6. doi: 10.1152/jappl.1990.69.1.232. PubMed PMID: 2203723.
9. Candas V, Libert JP, Vogt JJ. Sweating and sweat decline of resting men in hot humid environments. Europ J Appl Physiol. 1983;50(2):223-34. doi: 10.1007/bf00422161.
10. Ravanelli N, Coombs GB, Imbeault P, Jay O. Maximum Skin Wettedness after Aerobic Training with and without Heat Acclimation. Med Sci Sports Exerc. 2018;50(2):299-307. Epub 2017/10/11. doi: 10.1249/mss.0000000000001439. PubMed PMID: 28991042.
11. Patterson MJ, Stocks JM, Taylor NA. Humid heat acclimation does not elicit a preferential sweat redistribution toward the limbs. American journal of physiology Regulatory, integrative and comparative physiology. 2004;286(3):R512-8. Epub 2003/10/28. doi: 10.1152/ajpregu.00359.2003. PubMed PMID: 14578114.
12. Cotter JD, Patterson MJ, Taylor NAS. Sweat distribution before and after repeated heat exposure. Europ J Appl Physiol. 1997;76(2):181-6. doi: 10.1007/s004210050232.
13. Shvartz E, Bhattacharya A, Sperinde SJ, Brock PJ, Sciaraffa D, Van Beaumont W. Sweating responses during heat acclimation and moderate conditioning. Journal of applied physiology: respiratory, environmental and exercise physiology. 1979;46(4):675-80. Epub 1979/04/01. doi: 10.1152/jappl.1979.46.4.675. PubMed PMID: 457545.
14. Smith CJ, Havenith G. Body mapping of sweating patterns in male athletes in mild exercise-induced hyperthermia. Eur J Appl Physiol. 2011;111(7):1391-404. Epub 2010/12/15. doi: 10.1007/s00421-010-1744-8. PubMed PMID: 21153660.
15. Smith CJ, Havenith G. Body mapping of sweating patterns in athletes: a sex comparison. Med Sci Sports Exerc. 2012;44(12):2350-61. Epub 2012/07/20. doi: 10.1249/MSS.0b013e318267b0c4. PubMed PMID: 22811031.

16. Cotter JD, Patterson MJ, Taylor NAS. The topography of eccrine sweating in humans during exercise. Europ J Appl Physiol. 1995;71(6):549-54. doi: 10.1007/bf00238559.
17. Machado-Moreira CA, Smith FM, van den Heuvel AMJ, Mekjavic IB, Taylor NAS. Sweat secretion from the torso during passively-induced and exercise-related hyperthermia. Eur J Appl Physiol. 2008;104(2):265-70. doi: 10.1007/s00421-007-0646-x.
18. Machado-Moreira CA, Caldwell JN, Mekjavic IB, Taylor NA. Sweat secretion from palmar and dorsal surfaces of the hands during passive and active heating. Aviat Space Environ Med. 2008;79(11):1034-40. Epub 2008/11/13. PubMed PMID: 18998484.
19. Machado-Moreira CA, Wilmink F, Meijer A, Mekjavic IB, Taylor NAS. Local differences in sweat secretion from the head during rest and exercise in the heat. Eur J Appl Physiol. 2008;104(2):257-64. doi: 10.1007/s00421-007-0645-y.
20. Poirier MP, Gagnon D, Kenny GP. Local versus whole-body sweating adaptations following 14 days of traditional heat acclimation. Applied Physiology, Nutrition, and Metabolism. 2016;41(8):816-24. doi: 10.1139/apnm-2015-0698.
21. Hofler W. Changes in regional distribution of sweating during acclimatization to heat. Journal of applied physiology. 1968;25(5):503-6. Epub 1968/11/01. doi: 10.1152/jappl.1968.25.5.503. PubMed PMID: 5687355.
22. Jackson AS, Pollock ML. Generalized equations for predicting body density of men. Br J Nutr. 1978;40(3):497-504. Epub 1978/11/01. PubMed PMID: 718832.
23. Epstein Y, Stroschein LA, Pandolf KB. Predicting metabolic costs of running with and without backpack loads. Eur J Appl Physiol. 1987;56(5):495-500.
24. Whaley MH, Brubaker PH, Otto RM, Armstrong LE. ACSM's guidelines for exercise testing and prescription. Philadelphia, Pa.: Lippincott Williams & Wilkins; 2006. 70-5 p.
25. Havenith G, Fogarty A, Bartlett R, Smith CJ, Ventenat V. Male and female upper body sweat distribution during running measured with technical absorbents. Eur J Appl Physiol. 2008;104(2):245-55. doi: 10.1007/s00421-007-0636-z.
26. Ramanathan NL. A New weighting system for mean surface temperature of the human body. Journal of applied physiology. 1964;19:531-3. Epub 1964/05/01. PubMed PMID: 14173555.
27. Fox RH. A review of studies on the physiology of heat stress. Army Personnel Research Committee Report 68/A1 Ministry of Defence UK. 1968.
28. Havenith G, Van Middendorp H. Determination of the individual state of acclimatization. IZF report 1986-27. . TNO Institute for Perception. Soesterberg, Netherlands. Pp. 24., 1986. https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/10942
29. Livingstone SD, Nolan RW, Cain JB, Keefe AA. Effects of working in hot environments on respiratory air temperature. Eur J Physiol Occup Physiol. 1994;69(2):98-101.
30. Kerslake D. The stress of hot environments: Cambridge University Press. ; 1972. p 121.
31. Bender R, Lange S. Multiple test procedures other than Bonferroni's deserve wider use. BMJ. 1999;318(7183):600-1. Epub 1999/02/26. PubMed PMID: 10037651; PubMed Central PMCID: PMC1115040.
32. Hertzman AB. Individual differences in regional sweating. Journal of applied physiology. 1957;10(2):242-8. Epub 1957/03/01. doi: 10.1152/jappl.1957.10.2.242. PubMed PMID: 13428653.
33. Weiner JS. The regional distribution of sweating. The Journal of Physiology. 1945;104(1):32-40. doi: 10.1113/jphysiol.1945.sp004103.
34. Candas V, Libert JP, Vogt JJ. Influence of air velocity and heat acclimation on human skin wettedness and sweating efficiency. Journal of applied physiology. 1979;47(6):1194-200. doi: 10.1152/jappl.1979.47.6.1194. PubMed PMID: 536289.
35. Cramer MN, Jay O. Explained variance in the thermoregulatory responses to exercise: the independent roles of biophysical and fitness/fatness-related factors. Journal of applied physiology

(Bethesda, Md : 1985). 2015;119(9):982-9. Epub 2015/09/01. doi: 10.1152/japplphysiol.00281.2015. PubMed PMID: 26316511; PubMed Central PMCID: PMCPMC4628991.
36. Gagnon D, Kenny GP. Sex differences in thermoeffector responses during exercise at fixed requirements for heat loss. Journal of applied physiology (Bethesda, Md : 1985). 2012;113(5):746-57. Epub 2012/07/17. doi: 10.1152/japplphysiol.00637.2012. PubMed PMID: 22797311.
37. Jay O, Imbeault P, Ravanelli N, editors. The Sweating and Core Temperature Response to Compensable and Uncompensable Heat Stress Following Heat Acclimation. FASEB JOURNAL; 2018: FEDERATION AMER SOC EXP BIOL 9650 ROCKVILLE PIKE, BETHESDA, MD 20814-3998 USA.
38. Morris NB, Cramer MN, Hodder SG, Havenith G, Jay O. A comparison between the technical absorbent and ventilated capsule methods for measuring local sweat rate. Journal of applied physiology (Bethesda, Md : 1985). 2013;114(6):816-23. Epub 2013/01/12. doi: 10.1152/japplphysiol.01088.2012. PubMed PMID: 23305986.
39. Fox RH, Goldsmith R, Kidd DJ, Lewis HE. Acclimatization to heat in man by controlled elevation of body temperature. J Physiol. 1963;166:530-47. Epub 1963/05/01. PubMed PMID: 13959046; PubMed Central PMCID: PMCPMC1359351.
40. Regan JM, Macfarlane DJ, Taylor NA. An evaluation of the role of skin temperature during heat adaptation. Acta Physiol Scand. 1996;158(4):365-75. Epub 1996/12/01. doi: 10.1046/j.1365-201X.1996.561311000.x. PubMed PMID: 8971258.
41. Pandolf KB, Burse RL, Goldman RF. Role of Physical Fitness in Heat Acclimatisation, Decay and Reinduction. Ergonomics. 1977;20(4):399-408. doi: 10.1080/00140137708931642.
42. Taylor NAS. PRINCIPLES AND PRACTICES OF HEAT ADAPTATION. Journal of the Human-Environment System. 2000;4(1):11-22. doi: 10.1618/jhes.4.11.
43. Daanen HAM, Racinais S, Périard JD. Heat Acclimation Decay and Re-Induction: A Systematic Review and Meta-Analysis. Sports medicine (Auckland, NZ). 2018;48(2):409-30. Epub 2017/11/11. doi: 10.1007/s40279-017-0808-x. PubMed PMID: 29129022.
44. Tyler CJ, Reeve T, Hodges GJ, Cheung SS. The Effects of Heat Adaptation on Physiology, Perception and Exercise Performance in the Heat: A Meta-Analysis. Sports Medicine. 2016;46(11):1699-724. doi: 10.1007/s40279-016-0538-5.
45. Horowitz M. Do Cellular Heat Acclimation Responses Modulate Central Thermoregulatory Activity? Physiology. 1998;13(5):218-25. doi: 10.1152/physiologyonline.1998.13.5.218.
46. Sunderland C, Morris JG, Nevill ME. A heat acclimation protocol for team sports. British journal of sports medicine. 2008;42(5):327-33. Epub 2008/05/08. doi: 10.1136/bjsm.2007.034207. PubMed PMID: 18460609.
47. Casadio JR, Kilding AE, Siegel R, Cotter JD, Laursen PB. Periodizing heat acclimation in elite Laser sailors preparing for a world championship event in hot conditions. Temperature (Austin). 2016;3(3):437-43. Epub 2017/03/30. doi: 10.1080/23328940.2016.1184367. PubMed PMID: 28349083; PubMed Central PMCID: PMCPMC5079264.
48. Ashley CD, Ferron J, Bernard TE. Loss of heat acclimation and time to re-establish acclimation. J Occup Environ Hyg. 2015;12(5):302-8. Epub 2015/01/27. doi: 10.1080/15459624.2014.987387. PubMed PMID: 25621940.
49. Périard JD, Travers GJS, Racinais S, Sawka MN. Cardiovascular adaptations supporting human exercise-heat acclimation. Autonomic Neuroscience. 2016;196:52-62. doi: https://doi.org/10.1016/j.autneu.2016.02.002.
50. Gerrett N, Amano T, Inoue Y, Havenith G, Kondo N. The effects of exercise and passive heating on the sweat glands ion reabsorption rates. Physiological Reports. 2018;6(5):e13619. doi: 10.14814/phy2.13619. PubMed PMID: PMC5828933.

Figure Legends

Figure 1. Absolute gross sweat loss (GSL; $g.h^{-1}$) and metabolic rate ($W.Kg^{-1}$) at exercise intensity 1 (I1) and intensity 2 (I2) during pre and post heat acclimation (HA) sweat mapping experiments. * indicates $p<0.05$

Figure 2. Absolute pre- and post-acclimation regional median sweat rates of the torso and arms in male athletes at exercise intensity 1 and 2. Image created by Gavin Williams.

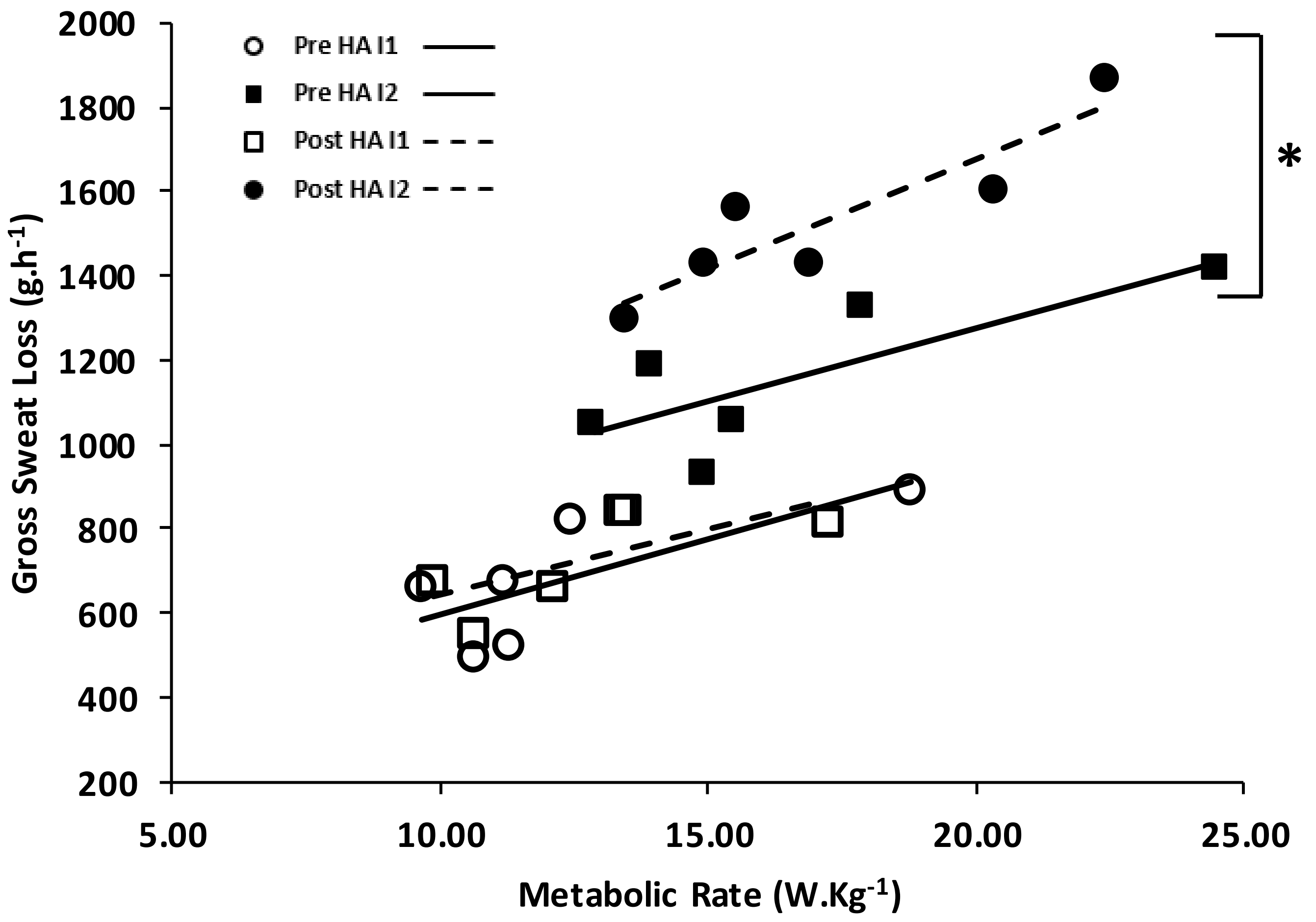
Figure 3. Normalized pre-and post-acclimation regional median sweat rates of the torso and arms in male athletes at exercise intensity 1 and 2. Image created by Gavin Williams.

Figure 4. Individual normalized pre- and post- heat acclimation sweating rates for central (torso) versus peripheral (arms) regions at intensity 1 (I1) and intensity 2 (I2). * indicates $p<0.05$

List of Supplemental Digital Content

Supplemental Digital Content 1.pdf

Figure 1


Pre HA I1
Pre HA I2
Post HA I1
Post HA I2
*
Gross Sweat Loss (g.h-1)
2000
1800
1600
1400
1200
1000
800
600
400
200
5.00
10.00
15.00
20.00
25.00
Metabolic Rate (W.Kg-1)

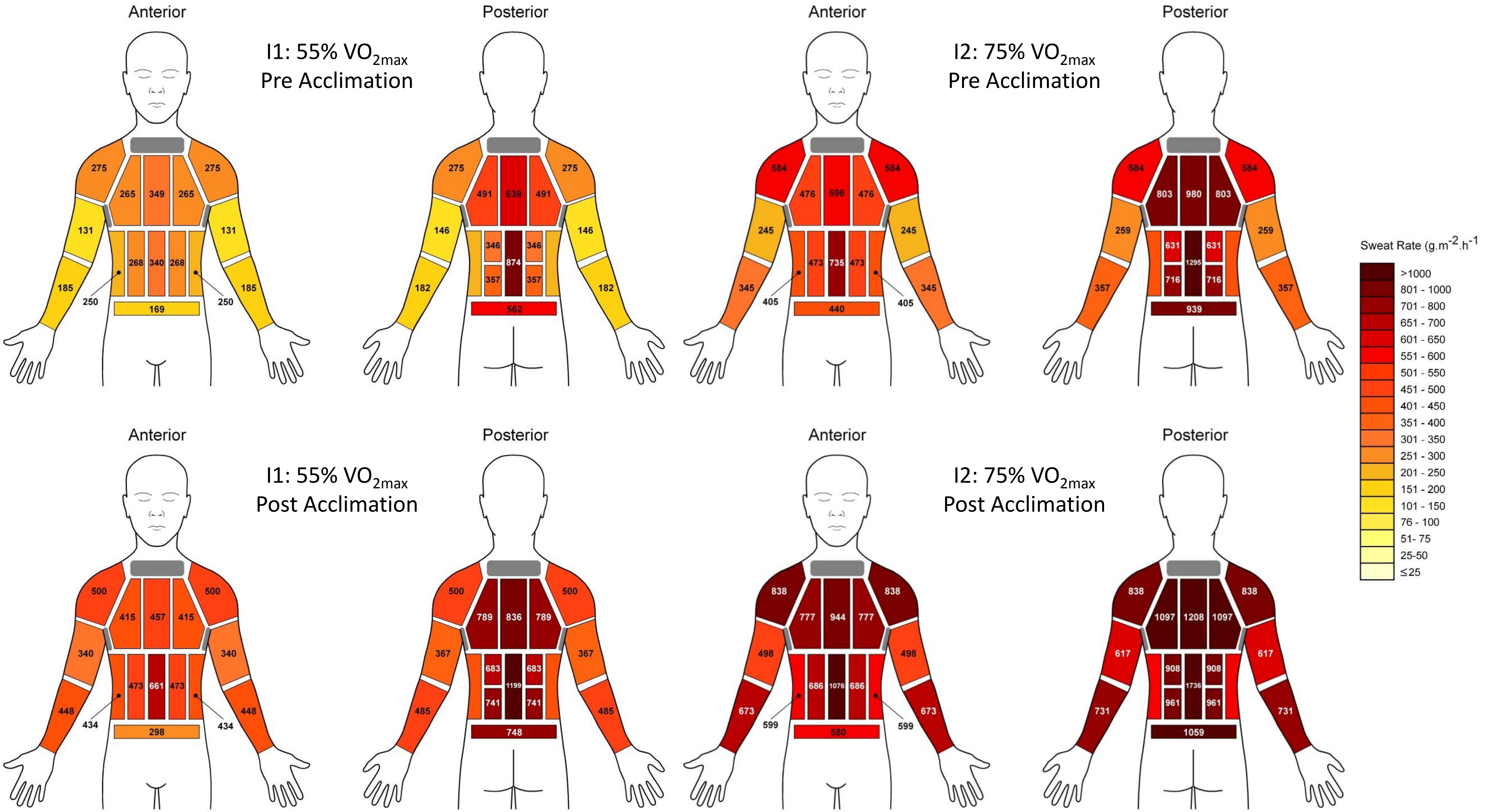

Anterior
Posterior
I1: 55% VO2max
Pre Acclimation
275 275
265 349 265
131 131
268 340 268
185 185
250 250
169
275 275
491 639 491
146 146
346 346
874
357 357
182 182
562
Anterior
Posterior
I2: 75% VO2max
Pre Acclimation
584 584
476 596 476
245 245
473 735 473
345 345
405 405
440
584 584
803 980 803
259 259
631 631
1295
716 716
357 357
939
Anterior
Posterior
I1: 55% VO2max
Post Acclimation
500 500
415 457 415
340 340
473 661 473
448 448
434 434
298
500 500
789 836 789
367 367
683 683
1199
741 741
485 485
748
Anterior
Posterior
I2: 75% VO2max
Post Acclimation
838 838
777 944 777
498 498
686 1076 686
673 673
599 599
580
838 838
1097 1208 1097
617 617
908 908
1736
961 961
731 731
1059
Sweat Rate (g.m-2.h-1
>1000
801 - 1000
701 - 800
651 - 700
601 - 650
551 - 600
501 - 550
451 - 500
401 - 450
351 - 400
301 - 350
251 - 300
201 - 250
151 - 200
101 - 150
76 - 100
51- 75
25-50
≤25

Figure 1.

Figure 3

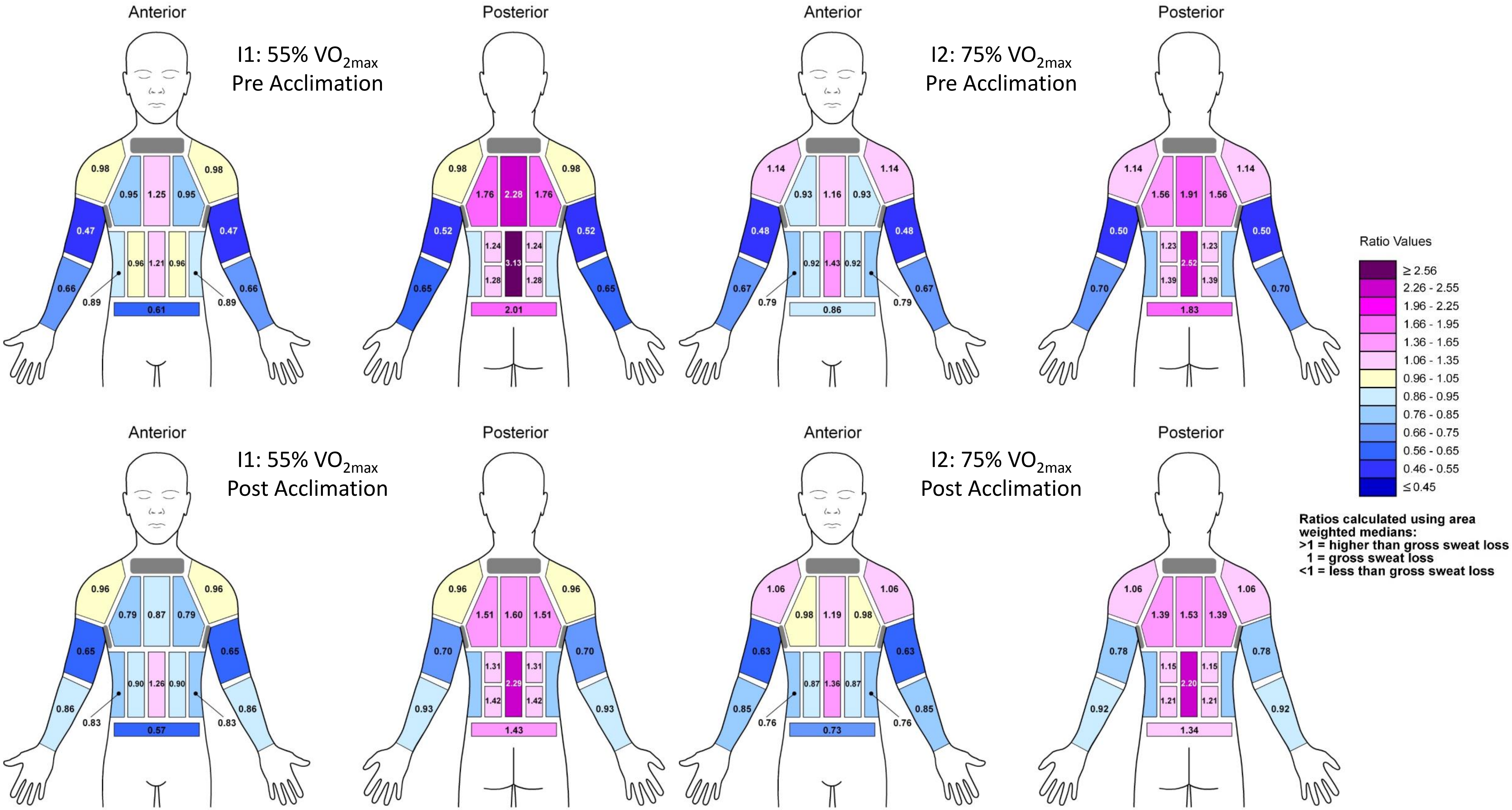


Figure 2.

Figure 4

Click here to access/download;Figure;Figure 4_R1.pptx

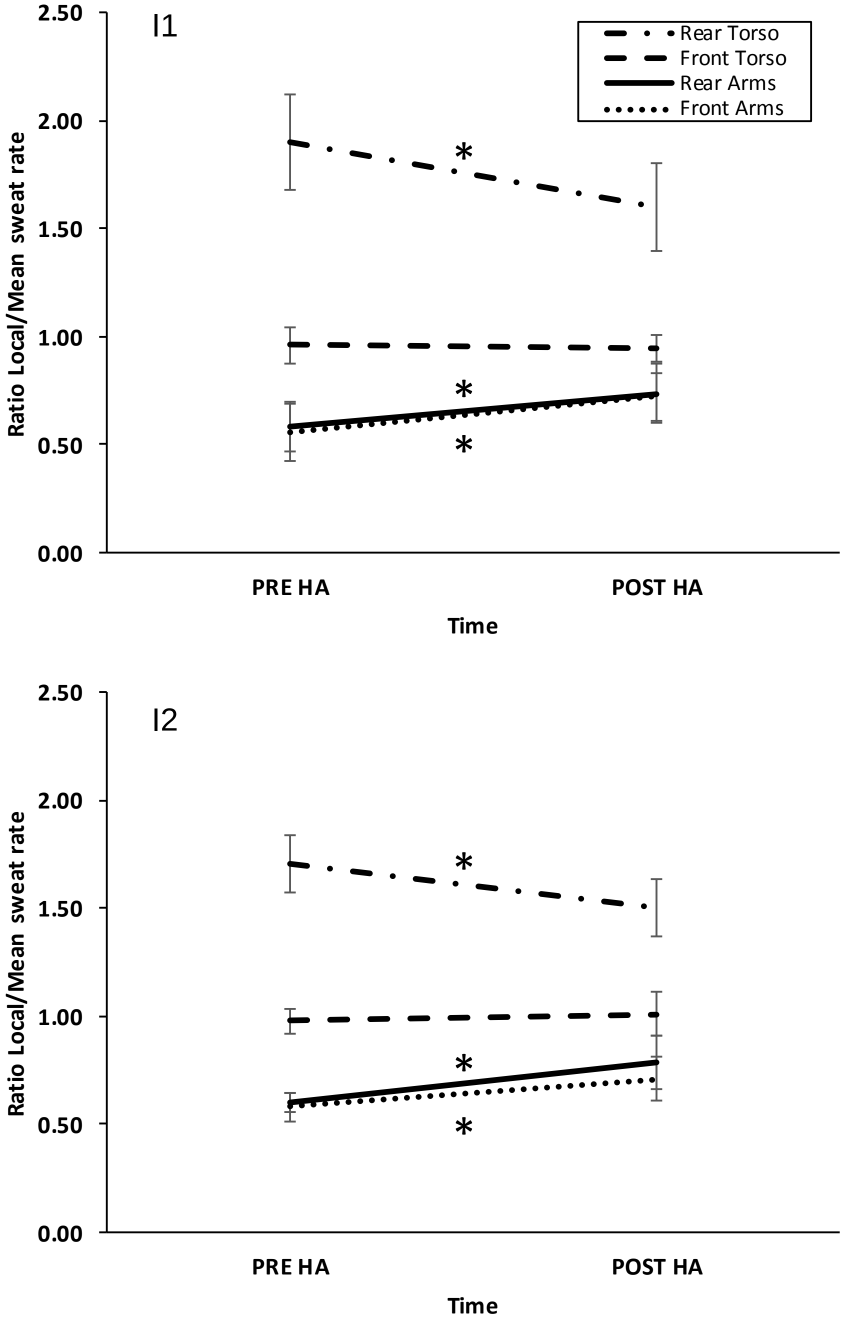


Table 1. Physiological data (mean ± SD) on days 1 and 6 of heat acclimation (HA).

HA	**Gross Sweat Loss ($g.m^{-2}.h^{-1}$)**	**Final T_{core} (ºC)**	**Final mean T_{sk} (ºC)**	**Av. Exercise HR (bpm)**	**Av. Exercise Metabolic Rate (W)**	**Av. Work Performed (Kj)**
Day 1	621 ± 73	38.4 ± 0.2	37.4 ± 0.7	141 ± 9	659 ± 135	2374 ± 485
Day 6	708 ± 80***	38.5 ± 0.3	37.3 ± 0.4	136 ± 9	763 ± 155	2746 ± 558

*Significant versus day 1: *** $p<0.001$.* Heart rate (HR) and metabolic rate data are averages of all three exercise bouts completed during each heat acclimation session. Final core temperature (T_{core}) and mean skin temperature (T_{sk}) were the average values recorded during the final minute of the protocol.

Table 2. Physiological data (mean ± SD) during pre and post heat acclimation (HA) sweat mapping experimentation. Surface area weighted gross sweat loss (SA weighted GSL) was calculated from regional sweat rates for the surface area covered by pads only.

	Time Point	**Baseline**	**Intensity 1**	**Intensity 2**
T_{core} (°C)	Pre HA	37.1 ± 0.3	38.0 ± 0.2	38.4 ± 0.3
	Post HA	36.9 ± 0.4	37.6 ± 0.3	37.9 ± 0.1
Heart Rate (bpm)	Pre HA	65 ± 11	136 ± 2	156 ± 3
	Post HA	58 ± 7	132 ± 3*	157 ± 4
Work Rate (%VO_{2max})	Pre HA	-	54 ± 3	73 ± 4
	Post HA	-	57 ± 5	76 ± 7
Gross sweat loss ($g.m^{-2}.h^{-1}$)	Pre HA	-	350 ± 83	599 ± 97
	Post HA	-	376 ± 56	795 ± 121**
SA Weighted GSL ($g.m^{-2}.h^{-1}$)	Pre HA	-	312 ± 102	521 ± 108
	Post HA	-	517 ± 153**	807 ± 174**

Significantly different versus pre HA values: * P<0.05; ** P<0.01

Table 3

Table 3. Significance level of pre versus post heat acclimation regional sweating rates. Gray shading indicates a significant decrease whilst no shading indicates a significant increase.

	Intensity 1		**Intensity 2**	
	Absolute data ($g.m^{-2}.h^{-1}$)	**Normalised ratio data**	**Absolute data ($g.m^{-2}.h^{-1}$)**	**Normalised ratio data**
shoulders	*	-	***#	-
lat upper chest	**$	-	*	-
med upper chest	-	-	-	-
lat mid chest	*	-	*	-
med mid chest	**	-	-	-
sides	**#	-	**$	-
ant lower	-	-	**	-
lat upper back	-	*	***#	**
med upper back	*	**	**	-
lat mid upper back	**$	-	**#	-
lat mid lower back	*	-	*	-
med mid back	-	-	**	-
pos lower back	-	-	-	-
ant upper arm	**	*	**$	**
pos upper arm	**	-	**$	*
ant lower arm	**#	-	**	-
pos lower arm	**	-	**#	**$

Significance level for uncorrected data: *P ≤ 0.05; **P ≤ 0.01; ***P ≤ 0.001; Significance level following Bonferroni correction: # P ≤ 0.05; ## P ≤ 0.01; ### P ≤ 0.001; $ 0.1 > P ≥ 0.05

Table 4

Table 4. Pre and post heat acclimation (HA) regional skin temperature during sweat mapping experiments at 5 measurement periods: baseline (BL), pre I1 pad application (Pre I1), post I1 pad application (Post I1), pre I2 pad application (Pre I2), and post I2 pad application (Post I2). Significant changes within regions from the previous measurement period are indicated by the symbols listed below the table. A significant decrease is indicated by grey shading ( ).

		Skin Temperature (°C)									
		Pre-HA					**Post HA**				
Region		**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**	**BL**	**Pre I1**	**Post I1**	**Pre I2**	**Post I2**
Torso	anterior medial upper	31.3	32.3	32.7*	32.9	33.5	33.4	31.8	33.1	31.5**#	33.2
	anterior lateral upper	31.6	31.7	32.2*	31.7*	32.8	32.9	31.3	32.8	30.5***##	32.9
	anterior medial lower	30.4	31.0	31.7**#	30.0**#	31.8	32.1	30.1	32.0	28.9***#	31.9*
	anterior lateral lower	30.7	32.0	32.3*	31.6*	32.5	32.7	31.2	32.7*	30.2**#	32.4
	posterior medial upper	31.9	32.4	33.4*	33.7	34.5	33.1	32.7	34.6**#	33.0**#	35.2***##
	posterior lateral upper	32.0	31.6	33.0**$	32.7*	34.0	32.8	31.5**#	34.2***##	32.0**#	35.0***##
	posterior medial lower	30.6	32.2	33.3***##	33.5	34.2	32.6	32.7	34.7***##	32.9***##	35.1***###
	posterior lateral lower	30.2	31.4	32.6**#	32.3*	33.5	31.7	31.3	33.8***##	31.4***##	34.4***###
	sides	30.6	31.5	32.5*	31.5*	32.9**#	32.0	31.0	32.8**$	30.7**#	33.3**#
Arms	anterior upper	32.4	31.8	32.9*	31.5*	32.7*	33.1	31.2	32.4	30.8**#	32.8*
	posterior upper	31.6	31.9	32.9	31.8	32.9*	31.0	31.0*	32.6**$	31.8	33.5**$
	anterior lower	31.4	31.7	33.0*	32.1	33.1	32.4	30.7**	32.1**#	30.8**	32.0
	posterior lower	31.7	31.9	32.8	32.5	33.0	31.7	31.0	32.2*	31.7	33.3**#
	Unweighted Mean	**31.0 ± 3.0**	**31.7 ± 1.5**	**33.3 ± 1.8**	**32.1 ± 1.5**	**33.0 ± 1.1**	**31.7 ± 0.6**	**31.1 ± 0.4**	**32.2 ± 1.0**	**31.7 ± 1.0**	**33.2 ± 1.4**

No correction: *P < 0.05; **P < 0.01; ***P < 0.001;
Bonferroni correction: # P < 0.05; ## P < 0.05; ### P < 0.001; $ 0.1 > P ≥ 0.05

Supplemental Digital Content 1

Table 1. Descriptive statistics for all regions sampled at intensity 1 pre and post heat acclimation (HA) and statistical comparison of sweating rates within each region pre and post heat acclimation for both absolute and normalized data, corrected and uncorrected for multiple comparisons.

		Surface area	Absolute sweating data ($g.m^{-2}.h^{-1}$) Pre HA					Post HA					Normalised ratio data Pre HA		Post HA		Pearson's r GSL and RSR		Significance level of pre vs. post HA comparison		Sudomotor sensitivity ($g.m^{-2}.h^{-1}.°C^{-1}$)	
	n	cm^2	min	max	median	mean	SD	min	max	median	mean	SD	Median	IQR	Median	IQR	Pre	Post	Absolute data	Normalised ratio data	Pre	Post
shoulders	6	655	320	175	315	165	335	145	385	210	175	165	0.98	0.28	0.96	0.07	0.66	0.68	*	-	350	300
lat upper chest	6	320	197	324	265	265	49	302	576	415	442	108	0.95	0.23	0.79	0.17	0.36	0.47	**$	-	295	592
med upper chest	6	175	224	444	349	342	89	277	936	457	508	249	1.25	0.56	0.87	0.38	0.41	0.61	-	-	388	652
lat mid chest	6	315	233	479	268	297	91	314	638	473	472	119	0.96	0.04	0.90	0.18	0.86	0.62	*	-	298	676
med mid chest	6	165	177	823	340	395	238	393	919	661	674	216	1.21	0.63	1.26	0.34	0.68	0.66	**	-	378	944
sides	6	335	108	552	250	285	149	248	722	434	449	175	0.89	0.24	0.83	0.17	0.84	0.82	**#	-	278	620
ant lower chest	6	145	30	405	169	192	126	97	598	298	327	172	0.61	0.25	0.57	0.34	0.61	0.15	-	-	188	426
lat upper back	6	385	445	970	491	562	201	477	902	789	729	168	1.76	0.15	1.51	0.18	0.87	0.51	-	*	546	1127
med upper back	6	210	500	1148	639	710	236	508	1582	836	928	393	2.28	0.23	1.60	0.48	0.97	0.88	*	**	710	1194
lat mid upper back	6	175	151	616	346	375	158	379	884	683	631	211	1.24	0.10	1.31	0.22	0.78	0.49	**$	-	384	975
lat mid lower back	6	165	253	785	357	405	198	296	1086	741	694	297	1.28	0.37	1.42	0.10	0.85	0.20	*	-	397	1058
med mid back	6	178	537	1237	874	864	248	552	1667	1199	1178	402	3.13	1.52	2.29	1.02	-0.26	0.14	-	-	971	1713
pos lower back	6	144	326	1059	562	623	297	408	1439	748	860	391	2.01	0.52	1.43	0.66	0.21	0.66	-	-	624	1069
ant upper arm	6	652	68	212	131	139	48	145	553	340	344	142	0.47	0.09	0.65	0.19	0.95	0.80	**	*	146	486
pos upper arm	6	658	75	271	146	152	65	149	468	367	342	114	0.52	0.04	0.70	0.25	0.92	0.49	**	-	162	524
ant lower arm	6	570	110	393	185	215	107	198	624	448	424	160	0.66	0.24	0.86	0.08	0.96	0.72	**#	-	206	640
pos lower arm	6	567	137	442	182	227	116	183	562	485	427	150	0.65	0.22	0.93	0.09	0.97	0.54	**	-	202	693

A decrease in median sweating rate ratio between pre and post heat acclimation is indicated by *grey shading* in the pre vs. post comparison column. Sudomotor sensitivity for all regions tested are presented, calculated as changes in regional sweating rate divided by change in T core (ΔT core) for intensity 1.

For conversion of absolute sweating rates (in $g\ m^{-2}\ h^{-1}$) to other units: divide by 600 to get $mg.cm^{-2}.min^{-1}$, or by 10,000 to get $ml.cm^{-2}.h^{-1}$

Level of significance with no correction for multiple comparisons: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, - no significant difference.
Level of significance following Bonferroni correction: # $p < 0.05$, ## $p < 0.05$, ### $p < 0.0001$, $ $0.1 > p > 0.05$, - no significant difference.

Table 2. Descriptive statistics for all regions sampled at intensity 2 pre and post heat acclimation (HA) and statistical comparison of sweating rates within each region pre and post heat acclimation for both absolute and normalized data, corrected and uncorrected for multiple comparisons.

			Absolute sweating data ($g.m^{-2}.h^{-1}$)										Normalised ratio data				Pearson's r		Significance level of pre vs. post HA comparison		Sudomotor sensitivity			
		Surface area	Pre HA					Post HA					Pre HA		Post HA		GSL and RSR				($g.m^{-2}.h^{-2}.°C^{-1}$)		($mg.cm^{-2}.min^{-1}.°C^{-1}$)	
	n	cm^2	min	max	median	mean	SD	min	max	median	mean	SD	Median	IQR	Median	IQR	Pre	Post	Absolute data	Normalised ratio data	Pre	Post	Overall Pre	Overall Post
shoulders	6	670	403	941	584	614	198	660	1183	838	873	186	1.14	0.26	1.06	0.27	0.82	0.68	***#	-	673	2095	0.79	1.45
lat upper chest	6	335	365	579	476	477	79	485	1170	777	797	224	0.93	0.29	0.98	1.01	-0.09	0.75	*	-	528	1207	0.61	1.33
centre ant upper	6	175	350	790	596	561	154	391	2205	944	1043	611	1.16	0.43	1.19	1.19	0.15	0.88	-	-	616	1626	0.72	1.74
lat mid chest	6	335	238	599	473	454	137	585	888	686	708	107	0.92	0.04	0.87	0.90	0.58	0.40	*	-	513	710	0.58	1.18
centre ant mid	6	170	268	1000	735	711	276	698	1214	1076	1030	181	1.43	0.30	1.36	1.27	0.61	0.09	-	-	987	1385	0.91	1.72
sides	6	350	233	755	405	454	195	480	1060	599	674	225	0.79	0.24	0.76	0.81	0.86	0.90	**$	-	389	550	0.58	1.12
ant lower	6	150	99	688	440	387	220	362	705	580	549	150	0.86	0.47	0.73	0.70	0.62	0.55	**	-	678	938	0.50	0.91
lat pos upper	6	395	666	1127	803	841	186	996	1393	1097	1125	139	1.56	0.17	1.39	1.40	0.78	0.83	***#	**	781	1027	1.08	1.88
centre pos upper	6	215	617	1515	980	1036	336	1058	2042	1208	1367	374	1.91	0.56	1.53	1.77	0.96	0.96	**	-	852	1240	1.33	2.28
lat pos M-U	6	185	337	838	631	607	173	687	1331	908	940	236	1.23	0.06	1.15	1.20	0.72	0.85	**#	-	713	749	0.78	1.57
lat pos M-L	6	172	312	1065	716	696	248	647	1311	961	963	250	1.39	0.53	1.21	1.16	0.57	0.22	*	-	897	733	0.89	1.61
centre pos mid	6	175	765	1647	1295	1268	316	1325	2411	1736	1772	396	2.52	0.45	2.20	2.02	0.12	-0.19	**	-	1052	1791	1.63	2.95
pos lower	6	145	484	1483	939	932	328	359	1906	1059	1123	645	1.83	0.47	1.34	1.26	0.69	0.76	-	-	942	1036	1.19	1.87
ant upper arm	6	649	176	302	245	247	42	308	709	498	513	148	0.48	0.10	0.63	0.64	0.74	0.83	**$	**	284	527	0.32	0.86
pos upper arm	6	654	193	338	259	260	52	301	806	617	589	178	0.50	0.07	0.78	0.75	0.80	0.72	**$	*	282	833	0.33	0.98
ant lower arm	6	569	280	457	345	357	69	393	919	673	655	222	0.67	0.09	0.85	0.82	0.80	0.67	**	-	401	750	0.46	1.09
pos lower arm	6	573	260	491	357	367	87	415	973	731	703	222	0.70	0.15	0.92	0.87	0.72	0.64	**#	**$	438	818	0.47	1.17

A decrease in median sweating rate ratio between pre and post heat acclimation is indicated by *grey shading* in the pre vs. post comparison column. Sudomotor sensitivity for all regions tested are presented, calculated as changes in regional sweating rate divided by change in *T* core (ΔT core) for intensity 2 and overall (entire testing period with I1 and I2 combined).

For conversion of absolute sweating rates (in $g\ m^{-2}\ h^{-1}$) to other units: divide by 600 to get $mg.cm^{-2}.min^{-1}$, or by 10,000 to get $ml.cm^{-2}.h^{-1}$

Level of significance with no correction for multiple comparisons: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, - no significant difference.
Level of significance following Bonferroni correction: # $p < 0.05$, ## $p < 0.05$, ### $p < 0.0001$, $ $0.1 > p > 0.05$, - no significant difference.