

Sweat secretion from the torso during passively-induced and exercise-related hyperthermia

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Abstract Thermal sweating from the human torso accounts for about half of the whole-body sweat secretion, yet its intra-segmental distribution has not been thoroughly examined. Therefore, the aim of the current study was to provide a detailed description of the distribution of eccrine sweating within the torso during passively-induced (water-perfusion garment: 40°C) and progressively increasing, exercise-related thermal strain (36°C, 60% relative humidity). Sudomotor function was measured in ten males using ventilated sweat capsules (3.16 cm²) attached to twelve sites on the ventral (four), lateral (three) and dorsal (four) torso, and upper shoulder surfaces. Sweating increased asymptotically in all sites, with the final core temperature averaging 39.7°C (±0.1) and heart rates being 181 b min⁻¹ (±2). During exercise, the mean torso sweat rate averaged 1.35 mgcm⁻²min⁻¹, with sweating from the lateral torso surfaces generally being the lowest. Each of the between-site comparisons with the lateral torso differed significantly ($P < 0.05$), except for comparisons with the chest ($P = 0.051$) and shoulder ($P > 0.05$). The intra-segmental differences between the lateral torso and the chest, abdomen, upper- and lower-back areas were significantly accentuated during exercise. From these data, it is evident that the torso is another region that does not have a uniform distribution of thermally-induced sweating. Thus, it is no longer acceptable for researchers, modellers, sweating

manikins engineers or clothing manufacturers to assume that the sweat rates for all local sites within any body segment are equivalent.

Keywords Eccrine sweat glands · Regional sweating · Sudomotor · Thermoregulation

Introduction

The regulation of body temperature relies upon autonomic and behavioural mechanisms for producing, conserving and dissipating heat, and these responses are activated or inhibited, depending upon information arising from central and peripheral thermoreceptors. In hot conditions, body temperatures increase, particularly that of the skin, and when air temperature exceeds skin temperature, evaporative cooling becomes the main avenue for heat loss. Thermal sweat is produced by eccrine sweat glands located across almost the entire body surface. However, sweat flow is variable among body segments (Weiner 1945; Hertzman 1957; Cotter et al. 1995), and there is now a growing body of knowledge to show that sweat secretion also varies within body segments (Taylor et al. 2006; Havenith et al. 2007a, b; Machado-Moreira et al. 2007a; Taylor and Machado-Moreira 2007). In the current study, differences in the local distribution of thermal sweating within the torso are explored.

Segmental differences in sudomotor function have been reported during rest and exercise with regard to sweat gland densities, secretion rates, sensitivity to core and skin temperature changes, and the sudomotor thresholds (Weiner 1945; Hertzman et al. 1952; Park and Tamura 1992; Cotter et al. 1995; Cotter and Taylor 2005). In general, sweat gland densities are higher at the forehead, hand and foot, and lower on the thigh and leg, with the arms and trunk

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displaying intermediate densities (Thompson 1954; Szabo 1962, 1967; Knip 1969; Hwang and Baik 1997). A caudal-to-rostral pattern of sweat onset has been demonstrated for resting subjects (Randall and Hertzman 1953), with higher thermal sweat secretions usually observed at the forehead during resting and exercising states (Cotter et al. 1995; Machado-Moreira et al. 2007b). These generalisations are well accepted, but there is a paucity of knowledge concerning differences in sweat secretion within body segments.

The chest and back appear to have equivalent eccrine sweat gland densities (Ogata 1935; Szabo 1962; Knip 1969). However, while a greater sweat secretion has been reported for the ventral surface of the torso (Weiner 1945), another report demonstrated higher sweating from the dorsal area (Park and Tamura 1992). Since the torso represents about 40% of the total body surface area, and accounts for about 50% of the whole-body sweat secretion (Weiner 1945), then a clear understanding of the inter-site variations in thermal sweating within the torso is of considerable importance to thermal physiologists, thermal modellers and manikin engineers, and also to those within the clothing industry. However, the intra-segmental distribution of sweat secretion within the torso has not, to the best of our knowledge, been thoroughly examined until very recently (Havenith et al. 2007a, b; Machado-Moreira et al. 2007a).

Accordingly, the aim of the current study was to provide a detailed description of the distribution of thermal sweating within the torso during passively-induced and exercise-related thermal strain. Thermal loading was applied at rest using passive heating (water-perfusion garment), and then using incremental cycling in hot-humid conditions. Intra-segmental sudomotor differences were quantified using ventilated sweat capsules attached to 12 sites on the ventral, lateral, dorsal and upper shoulder surfaces of the torso.

Methods

Subjects

Sweating distribution was investigated in ten healthy, physically-active males [26.7 years (SD 4.7); 75.5 kg (SD 8.5); 1.78 m (SD 0.07)] using a climate-controlled chamber. Subjects wore a whole-body, water-perfusion suit supplied with heated water during the entire trial. Procedures were approved by the Human Research Ethics Committee (University of Wollongong), and fully explained to the subjects prior to their provision of written, informed consent.

Procedures

Following a preparatory period, in which subjects were equipped with core and skin thermistors, heart rate monitor

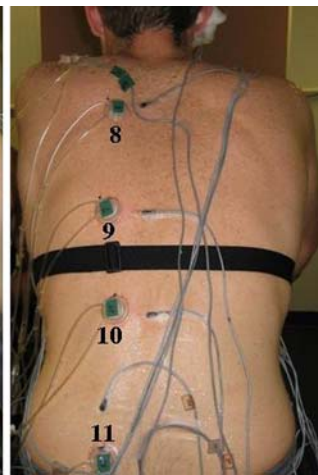
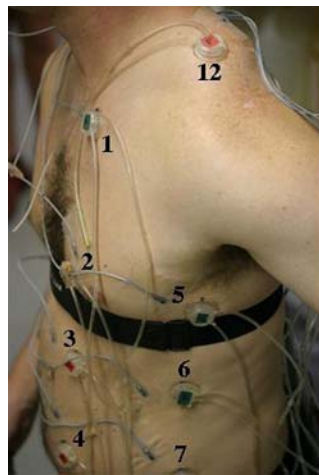
and sweat capsules, and dressed in the water-perfusion suit, subjects were exposed to a resting, passive heat load for 50 min. This heating was achieved using the combined influences of a heated climate-controlled chamber (36°C, 60% relative humidity, wind speed < 0.5 m s⁻¹) and a heated water-perfusion suit (40°C: Cool Tubesuit, Med-Eng, Ottawa, Canada; 38-L water bath: Type VFP, Grant Instruments, UK), which received water at 0.3 L min⁻¹ (Delta Wing pump, Med-Eng, Ottawa, Canada). At the completion of this resting phase, the upper half of the perfusion suit was removed, and subjects were moved to an electronically-braked ergometer (Lode Excalibur Sport; Groningen, Netherlands), and commenced cycling at 50 W (60 rev min⁻¹, 15 min). Subsequently, the work rate was increased 25 W every 15 min. Exercise was concluded when the core temperature exceeded 39.5°C for 2 min ($N = 2$) or at volitional fatigue ($N = 8$). On average, exercise lasted 66.3 min (range 52–85 min).

Measurements

Local sweat rates (mg cm⁻² min⁻¹) from twelve sites on the left side of the torso were evaluated. Ventilated capsules (3.16 cm²) were placed on two chest sites (Fig. 1, sites 1 and 2), two abdominal sites (sites 3 and 4), three lateral sites (sites 5, 6 and 7), two upper-back sites (sites 8 and 9), two lower-back sites (sites 10 and 11), and on the upper shoulder (*trapezius*; site 12). Capsules were glued to the skin (Collodion U.S.P., Mavidon Medical Products, FL, USA). Pre-capsular airflow was independently regulated at 600 ml min⁻¹, with inlet relative humidity maintained at 12% by passing room air for all capsules over a common, saturated lithium chloride solution. The humidity of the post-capsular air was measured using capacitance hygrometers, which formed parts of a sweat data acquisition system (Clinical Engineering Solutions, NSW, Australia), with inlet and exhaust air temperatures and humidities sampled at 1-s intervals from six channels (DAS1602, Keithley Instruments, Inc., Cleveland, OH, USA), and used to compute local sweat rates (Taylor et al. 1997). Hygrometer calibration, using saturated salt solution standards, preceded experimentation.

Sweat rates from only six locations could be measured simultaneously. Thus, the remaining sweat capsules were ventilated with room air to avoid moisture accumulation on the skin below each capsule. During passive heat loading (rest), sweat secretion from six sites was examined: upper chest (Fig. 1, site 1), lower abdomen (site 4), upper- and lower-lateral sites (sites 5 and 7), upper back (site 8) and lower back (site 11). During cycling, capsules were connected to the sweat system in an alternating pattern. To control this rotation pattern, and to ensure that measurements were taken in a balanced order, two trial sequences

Fig. 1 Sweat capsule placement on the torso skin surfaces. Also shown are the two experimental sequences used to ensure that these sites were evaluated in a balanced order



Sequence A	Sequence B	Torso sites
1	2	
4	3	
5	12	
7	6	
8	9	
11	10	

Sites names:

- 1: Upper chest
- 2: Lower chest
- 3: Upper abdomen
- 4: Lower abdomen
- 5: Upper lateral
- 6: Middle lateral
- 7: Lower lateral
- 8: Upper back 1
- 9: Upper back 2
- 10: Lower back 1
- 11: Lower back 2
- 12: Shoulder

were established, with five subjects participating in each sequence (Fig. 1). Subsequently, 5 min prior to each work rate increase, the sites of sweat measurement were changed so that the six remaining sites were now connected to the sweat system. These changes took approximately 2 min to be completed, and this rotation pattern was continued until the trial terminated.

Body temperatures were recorded at 5-s intervals using a data logger (1206 Series Squirrel, Grant Instruments Pty Ltd., Cambridge, UK). Auditory canal (insulated) and rectal temperatures (10 cm beyond the anal sphincter; Edale instruments Ltd., Cambridge, UK) were measured, with the former used as the primary core temperature index. Skin temperatures were measured at the forehead, chest, scapula, upper arm, forearm, dorsal hand, thigh and calf, and an area-weighted summation of these temperatures was used to calculate mean skin temperature (ISO 9886 1992). In addition, local skin temperatures were measured adjacent to each sweat capsule. Thermistors were calibrated in a stirred water bath against a certified reference thermometer (Dobros total immersion, Dobbie Instruments, Sydney, Australia). Heart rate was also recorded every 5 s (Vantage NV Sports Tester, Polar Electro Oy, Kempele, Finland).

Analysis

Local sweat rates were evaluated using data obtained from the 2-min periods immediately before switching sweat capsules, and immediately prior to each increase in work rate. Changes in local sweat rates and auditory canal temperature, observed across the first 45 min of exercise, were used to determine local sudomotor sensitivities (gain: $\text{mg cm}^{-2} \text{min}^{-1} \text{ } ^\circ\text{C}^{-1}$; after Taylor et al. 2006). Between-site differences in sudomotor responses were assessed using one-way analyses of variance, followed by Tukeys *HSD* post hoc tests. In addition, two-way analyses of variance were performed to compare localised sweat rates over the first 45 min of exercise. *Alpha* was set at the 0.05 level for

all analyses. Data are presented as means with standard errors of the means (\pm SEM) and standard deviations (SD).

Results

The passive heat load, and the incremental cycling protocols caused significant increases in body core temperature and heart rate ($P < 0.05$; Table 1), with the mean core temperature at the end of each trial being 39.7°C (± 0.1 ; moderately to profoundly hyperthermic) and the corresponding heart rate was 181 b min^{-1} (± 2), representing 92% of the age-predicted maximal heart rate for these subjects. When averaged across all sites over the entire exercise duration, the mean torso sweat rate was $1.35 \text{ mg cm}^{-2} \text{ min}^{-1}$.

Sweat rates from all sites within the torso increased during passive heating ($P < 0.05$), except for the lateral torso ($P = 0.07$) and chest ($P = 0.10$). During incremental cycling, further elevations in sweat rate occurred ($P < 0.05$). Since the sweating responses within the chest (two sites), abdomen (two sites), upper- and lower-back (two sites each), and the lateral torso (three sites) surfaces

Table 1 Body core temperatures and heart rates at the beginning and at end of 50 min of passive heating at rest (36°C , 60% relative humidity; water-perfusion suit: 40°C), and during incremental cycling

Work rate (W)	N	Core temperature ($^\circ\text{C}$)	Heart rate (b min^{-1})
Rest (start)	10	37.1 (0.1)	83 (3)
Rest (end)	10	37.3 (0.1)	90 (3)
50	10	37.3 (0.1)	107 (3)
75	10	37.6 (0.1)	128 (4)
100	10	38.0 (0.1)	151 (5)
125	9	38.6 (0.1)	170 (5)
150	3	39.0 (0.1)	178 (1)
175	2	39.7 (0.1)	181 (2)

Data are means with standard errors of the means

did not differ significantly ($P > 0.05$), these localised data were combined to provide six torso areas for subsequent analyses: chest, abdomen, upper back, lower back, lateral torso and upper shoulder. At the end of passive heating (48–50 min), and immediately before commencing exercise, these local sweat rates were: chest $0.32 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.07); abdomen $0.35 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.05); upper back $0.59 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.11); lower back $0.56 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.08); lateral torso $0.38 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.09); shoulder $0.51 \text{ mg cm}^{-2} \text{ min}^{-1}$ (± 0.13).

Within each of these six torso areas, sweating increased asymptotically during exercise (Fig. 2), and it was apparent that sweating from the lateral torso surfaces was generally the lowest at each work rate, with each of the between-site comparisons being significant ($P < 0.05$), except for comparisons with the chest ($P = 0.051$) and upper shoulder ($P > 0.05$). Other significant main effects existed for comparisons between abdomen sweating and that of the upper- and lower-back areas ($P < 0.05$). Significant site by time interactions were evident for comparisons between the lateral area and each of the other torso sites ($P < 0.05$), except for the shoulder ($P > 0.05$). Thus, the intra-segmental differences in sweat rate between the lateral torso and the chest, abdomen, upper- and lower-back areas were accentuated during incremental exercise. These differences existed in the presence of generally uniform local skin temperatures (maximal inter-site difference $< 1.6^\circ\text{C}$) for the exercise period from 40 to 45 min (Table 2), although the abdomen was significantly cooler than all other torso sites ($P < 0.05$).

To obtain an integrated assessment of the differences in these local sweat rates during exercise, data were averaged over the entire exercise duration (Fig. 3). From these data, the following descending rank order for sweat rates within

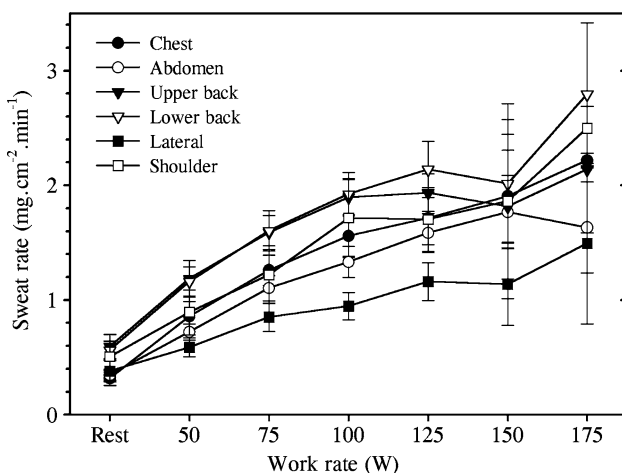


Fig. 2 Local sweat rates from six torso sites following 50 min of passive heating (rest), and then during incremental cycling in the heat (36°C , 60% relative humidity; water-perfusion suit 40°C). Data were averaged over the second half (7.5 min) of each work rate, and are presented as means with standard errors of the means

Table 2 Intra-segmental differences in sudomotor sensitivity and local skin temperatures of the torso during incremental cycling in the heat (36°C , 60% relative humidity; water-perfusion suit 40°C)

Torso sites	Sudomotor sensitivity ($\text{mg cm}^{-2} \text{ min}^{-1} \text{ }^\circ\text{C}^{-1}$)	Skin temperature ($^\circ\text{C}$)
Lower back	1.92 (0.34)	36.6 (0.1)*
Upper back	1.87 (0.28)	36.8 (0.1)***
Shoulder ($N = 8$)	1.21 (0.22)	37.0 (0.1)
Chest	1.75 (0.31)	36.6 (0.1)
Abdomen	1.41 (0.24)	35.5 (0.1)**
Lateral	0.76 (0.18)	36.2 (0.1)*

Sudomotor sensitivities were derived from changes in local sweat rates and auditory canal temperature, computed across 45 min of exercise. Skin temperatures were derived from the period 40–45 min of exercise. Data are means with standard errors of the means. The local abdominal skin temperature was significantly cooler than all other sites ($P < 0.05$). * Significantly different from shoulder, ** significantly different from the other sites ($P < 0.05$), *** significantly different from lateral sites ($P < 0.05$)

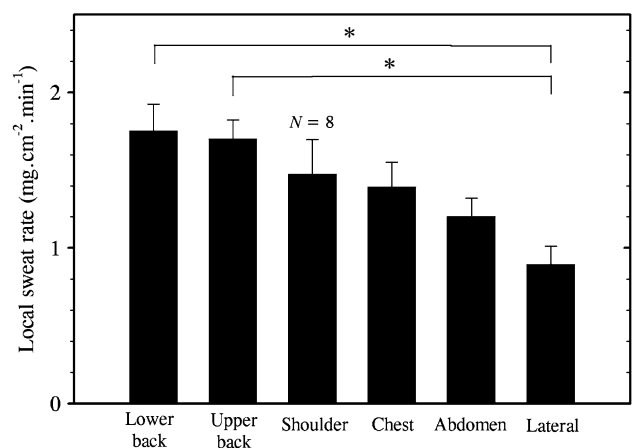


Fig. 3 Averaged sweat rates for six torso skin surfaces. Data are means with standard errors of the means, collected from 10 subjects (8 for the shoulder) during incremental cycling in the heat (36°C , 60% relative humidity; water-perfusion suit: 40°C) and averaged across the entire exercise phase (66.3 min; range: 52–85 min). * Significantly different from the sites identified by either end of the horizontal lines ($P < 0.05$)

the torso was derived: lower back, upper back, shoulder, chest, abdomen and lateral surface. The low sweat flow from the lateral torso surface is highlighted by these inter-site comparisons, with secretion from this lateral area representing only 50% of that observed at the lower-back, 53% of that at the upper back, 61% of shoulder sweating, 64% of that at the chest and 74% of the abdomen sweat secretion. However, whilst the sweat rate of the lateral area remained significantly lower than that observed for the upper- and lower-back sites ($P < 0.05$), significant differences were not observed for the other intra-torso comparisons ($P > 0.05$).

Local sudomotor sensitivities were determined for each of the six torso skin surfaces over the first 45 min of exercise. Although the sensitivity of the lateral area was 1.6–2.5 times less than that observed at the other sites, and displayed considerable variability among subjects, no significant between-site differences were apparent for sudomotor sensitivity among the torso skin surfaces (Table 2).

Discussion

We have known for many years that sweat secretion varies among body segments (Weiner 1945; Hertzman 1957; Cotter et al. 1995). However, the results of the current project add 12 more local sites to the growing body of experimental evidence that highlights clear intra-segmental variations in human eccrine sweating across a broad range of thermal loads (Taylor et al. 2006; Machado-Moreira et al. 2007b; Taylor and Machado-Moreira 2007). Two principal observations from this project are worth emphasising. First, the lateral torso surfaces displayed the lowest thermal sweat response, and differences between this site and those from the ventral and dorsal areas of the torso became more pronounced as exercise progressed. Second, sweating was more profuse from the dorsal surface of the torso than from the abdominal surface, with the most prolific sweat secretion coming from the lower part of the back.

With the exception of Havenith et al. (2007a, b), only a few researchers have previously studied more than two torso sites when investigating the inter-segmental distribution of sweating (Weiner 1945; Hertzman 1957; Park and Tamura 1992). Since these projects primarily focussed upon the whole-body sweat distribution, none used the methodological detail currently employed. Weiner (1945; $N = 3$) suggested that dorsal torso sites secreted less sweat than the ventral surfaces, with the highest torso sweat secretion coming from the upper chest. Weiner (1945) also observed a tendency for sweating to diminish on the more caudal areas of the trunk, and a lower thermal sweating in the axilla. Our data do not concur with most of these observations, with the lower back having the highest average sweat rate, and there was no consistent evidence of reduced sweating at either the lower ventral or dorsal torso sites (Fig. 3). Furthermore, Park and Tamura (1992) observed greater evaporative rates from the dorsal torso skin surfaces than from the chest and abdominal areas.

There are several possible methodological explanations for these diverse observations. Among these, the sample size used by Weiner (1945), which was frequently small during that era, is inadequate for the provision of such descriptive information. When sample sizes are small, the probability of obtaining unrepresentative data increases, and this is probably also the case with the frequently cited data

of Szabo (1962, 1967) for inter-segmental differences in sweat gland densities. In addition, Weiner (1945) used cotton pledgets pressed against the skin to collect sweat from within a sealed ring (38.5 cm²) that was lightly pressed against the skin surface. Variations of this technique have been shown to be very reliable (Havenith et al. 2007b). However, if adequate care is not taken, data can become contaminated due to unwanted evaporation, though this was probably prevented by Weiner (1945). The more likely possibility is that reactive errors could be introduced into the measurement by the elevation in local skin temperature and the accumulation of sweat within the collection ring. Since these sealed containers were designed to prevent evaporation, it is possible that, in taking these measurements, one could elevate local skin temperature, and thereby heighten local sweating, or suppress sweating due to localised hydro-meiosis. The extent and variability of these possible influences is uncertain. Of course, ventilated sweat capsules also introduce measurement artefacts, since these maintain an artificially dry skin surface, and this state does not always exist during daily activities, particularly when clothed.

Hertzman (1957; $N = 5$) previously observed a lower sweat secretion at sites located along the axillary line, thus matching the current data, and possibly also those reported by Weiner (1945). When these observations are considered together with the large individual variability, the lower thermal sweat secretion and the lower sudomotor sensitivity observed for the lateral surface of the torso, they are consistent with the sudomotor function of these skin surfaces behaving in a similar manner to that observed for the glabrous (non-hairy) surfaces of the body.

It is always a possibility that differences in the density of the active eccrine sweat glands, or glandular flow, may explain variations in sweat secretion. Certainly, this may be so for some inter-segmental comparisons, but this is not universally the case (Taylor et al. 2006; Taylor and Machado-Moreira 2007). However, within a body segment, one may anticipate more uniform gland counts, and this is precisely what occurs within the torso (Table 3), even though it has a large surface area.

Conclusion

The current experiment has provided a comprehensive evaluation of inter-site variations in sudomotor function within the torso using ventilated sweat capsules. From these data, and those presented by Havenith et al. (2007b), it is concluded that the torso has a non-uniform distribution of thermally-induced sweating. Sweat secretion is greater for the dorsal torso surface, with the lower back being the most profuse, and the lateral surfaces the least profuse sweating areas. Indeed, the lateral sites of the torso behave

Table 3 Intra-segmental differences in eccrine sweat gland densities for the human torso. The numbers in the right column refer to the number of data sets obtained from the literature (with superscript citations provided below) and from which the mean glandular densities (middle column) were derived

Torso sites	Gland density (glands cm ⁻²)	Data sets
Abdomen	115	16 ^(1, 3–10)
Upper back (scapula)	104	16 ^(1–5, 7–10)
Axilla	103	3 ⁽¹⁾
Chest	102	16 ^(1, 3–10)
Lower back (lumbar)	101	13 ^(3–8, 10)
Chest (sternal)	90	2 ⁽¹⁾
Abdomen (umbilicus)	81	2 ⁽¹⁾
Chest (mammary)	21	2 ⁽¹⁾

¹ Hwang and Baik (1997; male and female cadavers), ² Willis et al. (1973), ³ Knip (1972; Hindu males and females, and Bushmen), ⁴ Roberts et al. (1970; Caingang Indians), ⁵ Knip (1969; Dutch males and females), ⁶ Szabo (1967; Caucasians), ⁷ Ojikutu (1965; African, American Negro and Syrian/Iranian), ⁸ Thompson (1954; Caucasians and Africans), ⁹ Kawahata (1950; Filipino), ¹⁰ Ogata (1935; Korean)

somewhat similarly to the glabrous (non-hairy) skin surfaces, and perhaps it should be considered to be an intermediate zone, between glabrous and non-glabrous skin, at least with regard to eccrine sweat gland function. We have previously demonstrated that the intra-segmental sweat rates of the foot are not equivalent (Taylor et al. 2006), and we have now demonstrated that a non-uniform sweat distribution also occurs within the head (Machado-Moreira et al. 2007b) and the torso. Furthermore, our laboratory has recently completed experiments involving the hands, arms and legs (Taylor and Machado-Moreira 2007), in which these non-uniform secretion patterns were again evident. Therefore, when taken collectively, these facts force one to conclude that it is no longer acceptable for researchers, modellers, sweating manikins engineers or clothing manufacturers to assume that the sweat rates for all local sites within any body segment are equivalent.

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