Evaporative heat loss insufficient to attain heat balance at rest in individuals with a spinal cord injury at high ambient temperature

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ABSTRACT

The aim of the study was to determine whether climatic limits for achieving heat balance at rest are affected by spinal cord injury (SCI). Twenty-three males (8 able-bodied (AB), 8 with paraplegia (PP) and 7 with tetraplegia (TP)) rested in 37°C and 20% relative humidity (RH) for 20 mins. With the ambient temperature held constant, RH was increased by 5% every 7 mins, until gastrointestinal temperature (T_{gi}) showed a clear inflection or increased by >1°C. T_{gi}, skin temperatures, perceptual responses and metabolic energy expenditure were measured throughout. Metabolic heat production (AB: 123 (21) W, PP: 111 (15) W, TP: 103 (29) W) and required rate of evaporative cooling for heat balance ($E_{req,}$ AB: 113 (20) W, PP: 107 (17) W, TP: 106 (29) W) were similar between groups (p = 0.22 and p = 0.79). Compared to AB, greater increases in T_{gi} were observed in TP (p = 0.01), with notable increases in mean skin temperature (T_{sk}) for TP and PP (p = 0.01). A T_{gi} inflection point was demonstrated by 7 AB, only 3 out of 8 PP and none of TP. Despite metabolic heat production (and E_{req}) being similar between groups evaporative heat loss was not large enough to obtain heat balance in TP, linked to a shortfall in evaporative cooling potential. Although PP possess a greater sweating capacity, the continual increase in T_{gi} and T_{sk}, in most PP, while lower than for TP, implies that latent heat loss for PP is also insufficient to attain heat balance.

NEW AND NOTEWORTHY

In the absence of convective heat loss, at temperatures around 37ºC, evaporative heat loss is insufficient to attain heat balance at rest in individuals with paraplegia and tetraplegia. This finding was directly linked to a shortfall in evaporative cooling potential compared to required evaporative cooling. In this environment, both individuals with paraplegia and tetraplegia cannot subjectively determine the magnitude of their thermal strain, thus perceptual responses should not be relied upon for this population group.

Keywords: Tetraplegia, Paraplegia, Heat Balance, Passive Heat, Heat loss

INTRODUCTION

To prevent an accumulation of heat within the body and maintain a stable core temperature (T_{core}), individuals primarily rely on evaporative heat loss in warm and hot environments. Over a wide range of environments, T_{core} is able to equilibrate at levels proportional to metabolic rate known as the “prescriptive zone” (27), whilst being independent of ambient conditions. At thermal environments above this prescriptive zone T_{core} is forced out of equilibrium resulting in a continuous rise in T_{core} and the attainment of a critical environmental limit (23).

Individuals with a spinal cord injury (SCI) have a complete or partial loss of central control of the sympathetic nervous system, resulting in a loss of sweating capacity and vasomotor control below the lesion level. The higher the lesion level the smaller the body surface area of sensate skin (14, 29) resulting in a reduction in sweating capacity and hence evaporative heat loss potential. Most of the SCI literature investigating thermoregulation has involved exercise. Although these studies, typically using upper body exercise, have not matched heat production between groups, the premise of the exercise used within these studies was to replicate sporting scenarios or provide an appropriate exercise stimulus for this population group (13, 33, 34). However, to gain a deeper understanding of the effects an SCI has on heat dissipation, studies need to be conducted at rest too (i.e. removing the additional metabolic heat production from exercise), in environments considered compensable for the able-bodied (AB).

The lesion level of an individual with an SCI, determining the amount of remaining sympathetic innervation, is likely to play an important role in the dissipation of heat through sweating and the subsequent attainment of heat balance. An impairment or loss of motor and/or sensory function of the cervical segments of the spinal cord results in tetraplegia (TP). Whereas, an impairment or loss of motor and/or sensory function of the thoracic, lumbar or sacral segments of the spinal cord results in paraplegia (PP). Both individuals with PP and TT have a lower body surface area of sensate skin than AB individuals, with the amount of sensate skin related to an individual's lesion level. Thus, TP have a lower body surface area of sensate skin than PP. While all groups may be able to attain heat balance within a "prescriptive zone", it is expected that PP and TP may reach a critical thermal environmental limit prior to AB, i.e. a leftward shift in temperature and/or relative humidity (RH) of the prescriptive zone, with the size of the shift related to their lesion level.

The aim of this study was to determine the effect the lesion level of an SCI has on the attainment of a critical environmental limit. Experimental sessions were conducted at rest, in hot conditions (37°C) using a stepwise increase in RH, based on the experimental design of previous studies (5, 21–23). The experimental design aimed to minimise heat loss from dry heat loss by removing the skin to air temperature gradient and then progressively reducing the water vapour pressure gradient from the skin to the environment, increasing the thermal stress of the environment and hindering evaporative heat loss. Based on sweat rate capacity data from pilot work, all groups were expected to have sufficient thermoregulatory capacity in the climate chosen as the starting point of the protocol. It was hypothesised that critical environmental limits would occur at high RH for AB. Whereas, in individuals with PP and TP it was hypothesised that heat balance would be attained initially but a critical environmental limit would be reached prior to AB, with TP potentially experiencing a continual increase in T_{core} from the early stages of the protocol.

MATERIALS AND METHODS

Participants. Twenty-three recreationally active male participants, consisting of eight AB individuals, eight individuals with PP (T3-T12) and seven individuals with TP (C5/6-C6/7) volunteered for the study. In PP, five had complete and three had incomplete injuries, whilst in TP two had complete and five had incomplete injuries (Table 1). An individual with a complete injury has no motor and/or sensory function preserved in the lowest sacral segments of the spinal cord (S4-S5), whilst a motor or sensory incomplete injury refers to the preservation of motor and/or sensory function in the lowest sacral segments (S4-S5, (24)). Health and heat tolerance questionnaires were completed by all participants. All procedures were approved by the University Ethical Advisory Committee and conformed to the principles defined in the Declaration of Helsinki. Participants were fully informed of the experimental protocols before providing written consent to participate.

Insert Table 1 here

Procedures. Participants were instructed to refrain from alcohol, caffeine and strenuous exercise 24 h prior to testing. All trials were conducted at the same time of day to negate circadian variation. Prior to arrival at the laboratory, participants ingested a telemetric pill (HQ Inc, Palmetto, Florida), for the measurement of gastrointestinal temperature (T_{gi}), 6-8 hours prior to experimental sessions to avoid the influence of ingested food or fluid on the temperature reading, in accordance with previous recommendations (6).

Upon arrival at the laboratory, skinfold measurements (Harpenden Skinfold Callipers, Baty International, West Sussex, UK) were taken from the biceps, triceps, subscapular and suprailliac sites to calculate a sum of skinfolds (mm). Body fat percentage, using the Durnin and Wormsley four site method, plus fat and fat free mass were calculated using age dependent equations (9). To standardise clothing, all participants were given a pair of shorts and a short-sleeved t-shirt to wear during testing. Participants wore their own socks and sports shoes, with an estimated clo value of 0.4 for the overall clothing ensemble (including wheelchair). Prior to instrumentation, euhydration was confirmed for all participants (urine specific gravity <1.025, Meta Scientific Ltd, Surrey, UK) and participants were weighed (Mettler Toledo KCC 150, Leicester, UK, accuracy ± 5g, resolution 1g) before entering the climatic chamber (T.I.S.S. Peak Performance, Series 2009).

Skin temperature was measured throughout the protocol at 10 sites using iButtons (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA), which were applied to the forehead and on the right side of the body at the forearm, upper arm, chest, abdomen, upper back, thigh, calf, hand and foot. Mean skin temperature (T_{sk}) was calculated in accordance with the formula by Ramanathan (35).

During the protocol, PP and TP remained in their own daily wheelchair, whilst AB remained seated in a similar wheelchair provided. The climatic chamber was initially set at 37°C and 20% RH (water vapour pressure in the ambient air (P_a) = 1.26 kPa). Participants were informed that the RH would increase during the protocol but were not told the initial starting RH or when the RH was being increased. Participants sat for an initial 20 min stabilisation period, after which the RH was increased by 5% steps (ΔP_a = 0.314 kPa) every 7 minutes, whilst the ambient temperature was kept constant (37.2°C ± 0.2°C throughout all trials). By the end of the 7 minutes the climatic chamber had just reached the desired humidity resulting in a steady ramp in humidity. Air velocity was measured as 0.12 ± 0.07 $m \cdot s^{-1}$ throughout all trials. Based on sweat rate capacity data from pilot work, all groups were expected to have sufficient thermoregulatory capacity during the stabilisation period. The ambient temperature and RH inside the climatic chamber were measured next to the participant (Testo 435, Testo AG, Germany). Participants were withdrawn from the climatic chamber after a clear inflection point in T_{gi} had been observed (critical RH limit, (26)), or T_{gi} increased by 1°C from the initial value upon entering the chamber (Figure 1).

Insert Figure 1

Heart rate (HR, Polar PE 4000, Kempele Finland) and T_{gi} were measured throughout. Perceptual measures of thermal comfort, thermal sensation and wetness sensation were taken during the last minute of each step increase in RH. The thermal sensation scale comprised of categories ranging from 0 (“unbearably cold”) to 8 (“unbearably hot”) in 0.5 increments (42). The thermal comfort scale ranged from 1 (“comfortable”) to 4 (“very uncomfortable”) in increments of 1 (12). The wetness sensation scale ranged from 0 (“dry”) to 6 (“dripping wet”) in increments of 1 (modified scale from (15)).

Fluid balance. Participants could drink water *ad libitum,* except during the last minute of each 7 min stage to prevent interference with respiratory measures. Fluid consumption was recorded and was kept at the same temperature of the chamber to prevent any cooling effect of the fluid on the participant. Upon removal from the climatic chamber and towel drying their skin, if required, participants were re-weighed and provided another urine sample, which was analysed for urine specific gravity. The towel was subsequently weighed and any sweat trapped in the towel added to the participant’s end weight. Sweat loss was adjusted for respiratory mass loss (Table 3). In addition to the percentage change in body mass ($(\text{Mass}_{pre} - \text{Mass}_{post}) / \text{Mass}_{pre} \cdot 100$), the change in body mass adjusted for fluid consumed (total mass loss) was also calculated ($(\text{Mass}_{pre} - \text{Mass}_{post})$ + fluid consumed).

Ventilatory data and heat balance calculations. Expired gas was recorded continuously throughout the test using a calibrated online gas analysis system in breath by breath mode (Metamax, Cortex Biophysik GmbH, Leipzig, Germany). Saturated water vapour pressure (P_{sa}), saturated skin vapour pressure (P_{sk}) and P_a were calculated using the following equations (30).

$$P_{sa}(kPa) = \frac{e^{(18.956-(4030.18 \div T_a + 235))}}{10} \tag{1}$$

$$P_{sk}(kPa) = \frac{e^{(18.956-(4030.18 \div T_{sk} + 235)}}{10} \tag{2}$$

$$P_a(kPa) = (\Phi \cdot 0.01) \cdot P_{sa} \tag{3}$$

Where: T_a is the ambient temperature (°C) and Φ is the relative humidity.

Metabolic energy expenditure (M) was obtained from minute-average values for $\dot{V}O_2$ in litres per minute and respiratory exchange ratio (RER) collected with the metabolic cart. Metabolic energy expenditure was calculated using the equation below:

$$M\ (\mathrm{W}) = V\dot{O}_2\ \frac{\left(\frac{RER - 0.7\ \cdot \mathrm{e}_c}{0.3}\right) + \left(\frac{1 - RER\ \cdot e_f}{0.3}\right)}{60} \cdot 1000 \tag{4}$$

Where: e_c is the caloric equivalent per litre of oxygen for the oxidation of carbohydrates (21.13 kJ), and e_f is the caloric equivalent per litre of oxygen for the oxidation of fat (19.62 kJ). Since the rate of external work (W) was assumed to be zero (i.e. any work on surrounding objects was negligible), metabolic heat production (M-W) was taken to be equal to metabolic energy expenditure. Dry heat exchange (radiative (R) and convective (C)),evaporative (E_{res}) and convective respiratory heat exchange (C_{res}) and required rate of evaporative cooling (E_{req}) were calculated using the following equations. E_{res} enabled the calculation of mass loss via the respiratory system (M_{res}).

$$\text{Dry (W)} = \frac{T_{sk} - T_a}{I_{cl} + \left(\frac{f_{cl}}{h_{c} + h_r}\right)} \cdot \text{BSA} \tag{5}$$

$$f_{cl} = 1.0 + 0.31 \cdot I_{cl} \tag{6}$$

$$C_{res} + E_{res}\,\text{(W)} = (0.0014 \cdot \text{M} \cdot (34 - T_a) + 0.0173 \cdot \text{M} \cdot (5.87 - P_a)) \tag{7}$$

$$M_{res}\,(\text{g}\cdot\text{h}^{-1}) = E_{res} \cdot \frac{3600}{2430} \tag{8}$$

$$E_{req}\,\text{(W)} = \text{M} - \text{W} - (\text{C} + \text{R} + C_{res} + E_{res}) \tag{9}$$

Where: I_{cl} is the intrinsic clothing insulation (estimated to be 0.4 clo) and f_{cl} is the clothing area factor, which is the ratio of the clothed surface area of the body to the nude surface area of the body. h_c is the convective heat transfer coefficient (estimated at 3.1 $\text{W}\cdot\text{m}^{-2}\,\text{K}^{-1}$ when air velocity is less than 0.2 $\text{m}\cdot\text{s}^{-1}$), (28) and h_r is the radiative heat transfer coefficient (estimated at 4.7 $\text{W}\cdot\text{m}^{-2}\,\text{K}^{-1}$) for typical indoor conditions, (1). Body surface area (BSA) was calculated using the Dubois formula (8).

Statistical analyses. All data were analysed using the Statistical Package for Social Sciences (version 19, SPSS Chicago, IL) and are presented as mean (SD). An *a priori* power analysis, conducted in G*Power 3.1, revealed a minimum sample size of 6 participants was required per group, with 90% power and an α of 5%, based on findings from (31). Given the heterogeneity of the population group, additional participants were recruited to increase statistical power.

Delta HR, T_{gi}, T_{sk} and individual skin temperatures were calculated as the change from the last minute of the 20 min stabilisation period. Statistical analysis was conducted for repeated measures up to 65% RH (n = 23), thereafter several participants from PP and TP were removed due to a ≥ 1°C change in T_{gi} or the participant had reached a critical RH limit. To account for the reduced number of participants tested at 70-90% RH, predicted lines were calculated for the change in T_{gi} and T_{sk} to indicate the expected trend (Figure 2). To calculate the predicted delta data the difference between each time point for each remaining individual were calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH where dropouts were present. For ventilatory data and the heat balance calculations, data from two AB participants were excluded due to missing data as a result of equipment error.

For all groups a critical RH was determined grapically from the raw data. A line was drawn between the data points of T_{gi} starting from an initial equilibirum phase. When the T_{gi} slope started to deviate upward from the equilibrium slope, a second line was drawn from the point of deviation from the first line. The RH before the point at which the second line deviated from the first was defined as the critical RH, a method previously used in (23).

Distribution and normality of data were assessed using the Shapiro–Wilk test. For data violating normality and homogeneity assumptions, logarithmic or square-root conversions were applied. For one way analysis of variance (ANOVA), if these conversions failed to correct the skew and heterogeneity, a Kruskal-Wallis test was used. To analyse any between group differences at both the start and at 65% RH a one way ANOVA was used, whilst for between group differences during the protocol a mixed method ANOVA was used. Where significance was obtained, post hoc pairwise comparisons with a Bonferroni correction were conducted. Main effects and interactions were accepted as statistically significant when $p \leq 0.05$. A main effect of time corresponded to a step increase in RH. Confidence intervals (95% CI) for differences are presented, alongside effect sizes (ES) to supplement significant findings. Effect sizes were calculated as the ratio of the mean difference to the pooled standard deviation of the difference. The magnitude of the ES was classed as trivial (<0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large (≥2.0) based on previous guidelines (4).

RESULTS

Participant characteristics. Individuals with PP were older than both AB and TP ($p < 0.01$). Compared to AB, sum of skinfolds and percentage body fat were greater in PP and TP ($p \leq 0.04$), whilst fat mass was greater ($p < 0.001$) and fat free mass smaller ($p = 0.04$) in PP.

Thermoregulatory responses. No significant differences in T_{gi} between groups were observed at the start ($p = 0.18$, AB: 37.22 (0.29)°C, PP: 36.91 (0.40)°C and TP: 37.23 (0.45)°C) or during the 20 min stabilisation period ($p = 0.08$). The change in T_{gi} during the last 5 minutes of the stabilisation period was not significantly different between groups ($p = 0.26$, AB: 0.03 (0.03)°C, PP: 0.06 (0.06)°C and TP: 0.05 (0.03)°C). Absolute T_{gi} at 65% RH was significantly cooler in AB (37.43 (0.25)°C, $p < 0.001$, ES = 2.6) and PP (37.53 (0.45)°C, $p = 0.01$, ES = 1.5) than in TP (38.16 (0.37)°C). The change in T_{gi} was smaller in AB than for TP ($p = 0.01$, 95% CI = 0.07 to 0.47, ES = 1.5, Figure 2) from 30% to 65% RH. The critical RH determined graphically for thegroups are shown in Table 2.

Insert Table 2 and Figure 2 here

No signficiant differences in T_{sk} between groups were observed at the start ($p = 0.91$, AB: 34.34 (0.65)°C, PP: 34.27 (0.90)°C and TP: 34.14 (1.05)°C) or during the stabilisation period ($p = 0.07$). Mean skin temperature at 65% RH was significantly cooler in AB (36.25 (0.36)°C) than in PP (36.91 (0.56)°C, $p = 0.05$, ES = 1.3) and TP (37.45 (0.58)°C, $p < 0.001$, ES = 2.5). The change in T_{sk} was significantly smaller in AB compared to PP ($p = 0.01$, 95% CI = 0.14 to 0.98, ES = 1.5) and TP ($p = 0.01$, 95% CI = 0.29 to 1.03, ES = 2.0) across all RH stages (Figure 2).

There was a main effect of time at all individual skin temperature sites (all $p < 0.001$), with responses shown in Figure 3. There were no differences between groups for the change in chest, hand and foot skin temperature (all $\geq p = 0.07$, $\leq$ ES = 0.4) across all RH stages. The change in forearm, upper back and abdomen skin temperature were smaller in AB and PP than TP (all $p \leq 0.02$, $\geq$ ES = 1.2) across all RH stages. The change in upper arm skin temperature was smaller in AB than TP across all RH stages ($p = 0.01$, ES = 1.5). The change in forehead skin temperature was smaller in AB than TP from 45% to 65% RH ($p = 0.04$, ES = 0.2). The change in thigh and calf skin temperatures were smaller in AB than both PP ($p < 0.01$, ES = 1.6) and TP ($p < 0.01$, ES = 1.6 -1.7) across all RH stages.

Insert Figure 3 here

No significant difference in HR was observed between groups at the start ($p = 0.18$; AB: 62 (7) $b \cdot min^{-1}$, PP: 74 (19) $b \cdot min^{-1}$ and TP: 71 (4) $b \cdot min^{-1}$), during the 20 min stabilisation period ($p = 0.16$) or during the protocol ($p = 0.43$). The change in HR during the last 5 minutes of the stabilisation period was not significantly different between groups ($p = 0.33$, AB: -5 (3) $b \cdot min^{-1}$, PP: 0 (4) $b \cdot min^{-1}$ and TP: -5 (10) $b \cdot min^{-1}$). Heart rate at 65% RH was not significantly different between groups, though, compared to AB (68 (10) $b \cdot min^{-1}$), ES were moderate for PP (86 (26) $b \cdot min^{-1}$, $p = 0.16$, ES = 0.9) and very large for TP (89 (8) $b \cdot min^{-1}$, $p = 0.09$, ES = 2.3). T_{gi}, T_{sk}, skin temperatures and HR all significantly increased over time ($p < 0.001$).

*Perceptual responses***.** No significant differences were observed between groups for thermal sensation or thermal comfort ($p > 0.05$). Participants became hotter and developed greater thermal discomfort throughout ($p < 0.001$). Wetness sensation was significantly higher in AB at 30-35% and 50-65% RH ($p < 0.001$) than TP and significantly increased over time ($p < 0.001$).

Fluid balance. Urine specific gravity was not significantly different between groups at the start ($p = 0.67$) but was significantly greater in AB compared to PP ($p = 0.02$) and TP ($p = 0.04$) at the end of the protocol. PP and TP gained body mass compared to AB ($p = 0.10$) and AB and PP tended to consume more fluid than TP ($p = 0.31$), but neither were significant. Total mass loss and sweat rate were significantly greater in AB than PP ($p < 0.001$, ES = 1.4 - 1.7) and TP ($p < 0.001$, ES = 1.7 - 2.0, Table 3).

Insert Table 3 here

Heat balance parameters. Metabolic heat production was not significantly different over time ($p = 0.46$) or between groups ($p = 0.22$, AB: 123 (21) W, PP: 111 (15) W and TP: 103 (29)) (Table 4). Dry heat exchange (R + C) was significantly different between AB and TP ($p = 0.01$). C_{res}, E_{res} ($p = 0.17$) and E_{req} ($p = 0.79$) were not significantly different between groups (Table 4). Evaporative cooling potential, based on observed sweat rates was significantly lower for PP and TP compared to AB ($p < 0.01$), and fell short of E_{req} for both PP and TP.

Insert Table 4 here

Complete and incomplete lesion responses. Figure 4 shows mean and individual responses for the change in T_{gi} and $T_{sk,}$ respectively. Statistical analysis was not conducted on this data due to the small sample size.

Insert Figure 4 here

DISCUSSION

The hypothesis of this study was that critical relative humidity limits would differ between groups, with AB having the highest critical limit, TP the lowest and PP in between, linked to their respective areas of sensate skin. While the decision on the climate settings was based on pilot work with a TP participant, both PP and TP participants in the actual experiment struggled to attain heat balance from the start of the experiment. Thus, it is evident that the response of the participant used in the pilot study was not representative of the groups studied; an unfortunate reflection of the large variability in physiological responses in individuals with an SCI. Nevertheless, the order of the groups in terms of their T_{gi} response was as expected. While 7 out of 8 AB showed stable T_{gi} at the start and a defined threshold where T_{gi} stability was lost, only 3 out of 8 PP and none of TP achieved this. This result was directly linked to a shortfall in evaporative cooling potential (Table 3) in PP and TP, compared to required evaporative cooling (E_{req}).

Metabolic heat production is the primary determinant of E_{req}, hence the similar metabolic heat production (and metabolic energy expenditure) between the three groups in the present study infers similar values for E_{req}. Yet neither PP nor TP attained a steady T_{gi} response (Figure 2), and hence heat balance during the protocol. For instance, at 65% RH, the change in T_{gi} for PP and TP was 0.29°C and 0.51°C greater than AB, respectively. For AB T_{gi} was stable, up until a mean critical RH of 79% RH. The results therefore indicate that, evaporative capacity was insufficient from the start for TP and at the limit for PP in the studied conditions where evaporation was the primary pathway for heat dissipation.

The attenuation in evaporative heat loss in individuals with an SCI is further depicted by the greater change in T_{sk} and smaller total mass loss in PP and TP compared to AB. Both the change in thigh and calf skin temperature, i.e. skin sites below the lesion level, were significantly greater in PP and TP than AB throughout the protocol (Figure 3), contributing to the greater T_{sk} response. These results further support the notion that latent heat loss is greatly reduced and insufficient to attain heat balance at rest for TP and most PP in the absence of convective heat loss.

Body composition. Historically body fatness was considered an important parameter for thermoregulatory response. Though it was later shown that fat percentage is only a relevant predictor of individual T_{core} and sweating responses to exercise when cool climates are considered, and skin blood flow is low (16–18). This has been confirmed more recently (7) showing that heat production and E_{req} are the main driving factors in explaining most of the variance in T_{core} and whole body sweat loss in the heat. Whether body fatness explains a similar amount of variance in T_{gi} in individuals with an SCI is unclear. It could be argued that the reduced skin blood flow to the body regions below the lesion level would make heat transfer from core to skin more sensitive to the thickness of the fat layer insulation, similar to what happens in AB in the cold. In the present study, given the close to isothermal conditions, this would however not have affected outcomes. Individuals with an SCI, due to skeletal muscle denervation and inactivity of their lower limbs, have adverse changes to their overall body composition. These include a greater fat mass of their legs and trunk not only compared to their upper limbs but also in comparison to AB (20, 39, 40). Hence a large proportion of fat mass in individuals with an SCI is below the lesion level, which for these individuals are body regions not considered to be an effective body surface area (area of skin that can partake in heat dissipation). In relation to methodology, the Durnin and Wormsley four site method has been shown to under-predict body fat percentage compared to dual energy x-ray absorptiometry in wheelchair athletes by 4.2% (44). Thus, actual differences in body fat percentage between AB and both PP and TP are likely to be greater than reported. Nevertheless, in the current study the greater percentage of body fat of PP and TP compared to AB should have had minimal influence on the amount of evaporative heat loss, while due to the chosen minimal temperature difference between air and skin, a negligible effect on convective heat loss is expected.

Although PP were significantly older than both AB and TP, this is likely to have had a minimal effect on the findings. Previous research has shown that the capacity to dissipate heat reduces with age, with a decrease in evaporative heat loss of 4-11% in humid conditions (35°C, 65% RH) and 4-6% in dry conditions (35°C, 25% RH) in 40-50 year olds compared to 20-30 year olds (26). These findings are related to exercise in the stated conditions and are therefore likely to be even less in resting conditions. In addition, an individual's $\dot{V}O_{2max}/\dot{V}O_{2peak}$ is likely to play a larger role regarding an individual's T_{core} and sweat response to a warm humid environment than the individual's age (16, 17). Thus, in the current study despite PP being significantly older than AB and TP, the actual difference in age between the groups is unlikely to have a major influence on heat dissipation. The presence, level and completeness of an SCI and the individual's cardiovascular fitness, which will correspond to the individual's lesion level, i.e. lowest cardiovascular fitness for TP, is likely to have a much larger influence.

*Lower body skin temperatures***.** In individuals with an SCI, T_{sk} is likely to mask regional skin temperature differences, in particular skin temperatures above and below the lesion level (32). The change in thigh and calf skin temperatures were greater in both PP and TP than AB, due to the disrupted blood flow, vascular atrophy, lack of sweating response and skeletal muscle denervation below the level of the lesion (19). In individuals with an SCI, thigh and calf skin temperatures (28-31 ºC) have been shown to be cooler at rest than the upper body (32-34ºC) and compared to AB (32, 38). Hence, the lower body may be a potential site for heat storage in hot conditions (32), due to the combination of a reduced capacity to dissipate heat and cooler initial skin temperatures, leading to a greater thermal gradient between the skin and environment.

Upper body skin temperatures. For upper body skin temperatures of the upper back and forearm in PP and TP, the magnitude of the change in skin temperature reflected the preservation of the sweating capacity of these regions. Yet, large standard deviation in chest skin temperature within SCI groups (Figure 2), potentially due to differences in lesion completeness, could have masked a statistically significant finding. The chest skin temperature site is below the lesion level for TP so one would expect a greater increase in chest skin temperature compared to AB and PP. Compared to other regions of the torso, the chest has a lower regional sweat rate (37), thus the sweat response of AB and PP may have had a lower evaporative cooling effect, leading to a similar skin temperature for all three groups.

At the forehead, though the magnitude of the effect was small (ES = 0.2), the change in skin temperature was significantly greater in TP than AB (Figure 3). Individuals with TP have a small surface area of sensate skin and exhibit little to no sweat response above the lesion level. Incomplete injuries and thus intact neural pathways may however lead to some individuals still exhibiting a small sweat response. Nevertheless, given the resulting small surface area of sensate skin this sweat response would not be large enough to provide effective evaporative heat loss, in conditions where heat loss is solely dependent on the evaporation of sweat, clearly demonstrated by this study.

Perceptual responses. In the able-bodied, thermal sensation is largely dictated by skin temperature, independent of T_{core} (36). In the present study, despite a higher T_{sk} in PP and TP, thermal sensation was not significantly different between the groups suggesting that PP and TP may not be able to perceive the magnitude of thermal strain compared to AB. These results imply that the role of skin temperature for reporting thermal sensation may be limited for individuals with an SCI, in particular TP, as a result of the small body surface area of sensate skin (2). For thermal comfort, T_{core} and T_{sk} have been reported to contribute equally in AB (11). Despite similar thermal comfort scores, TP had a greater change in T_{gi} and T_{sk} suggesting they should have been in greater thermal discomfort than AB. Alternatively, this finding may suggest that their tolerance to thermal discomfort is in fact greater, though this cannot be confirmed by the results of this study. Wetness sensation was lower in TP compared to AB and PP, due to the small body surface area of sensate skin and minimal sweating capacity. The upper body has a greater proportion of high sweat rate regions than the lower body (37). Thus, despite a lower total mass loss and sweat rate in PP, perceived wetness of the sensate areas of PP led to a similar wetness sensation score to AB.

Complete and incomplete lesion responses. As noted earlier, the large variance in thermoregulatory responses in SCI is further complicated by the completeness of the lesion. Individuals with incomplete lesions potentially having a greater amount of sensory information and a greater body surface area available for sweating (43). The T_{gi} data grouped by lesion completeness supports this notion (Figure A), yet individually there was disparity between the T_{gi} of PP with incomplete lesions (all of which had a lesion below T8). Lesion completeness did also not dictate which individuals with PP obtained a stable T_{gi}, i.e. prescriptive zone, and a clear critical environmental limit. If complete lesions lead to a lower sweating capacity, one would expect a complete lesion to have a greater T_{sk} response than incomplete lesions. Yet this was not the case in the present study, suggesting how completeness of the lesion influences thermoregulatory responses is still not fully understood.

Limitations

Gastrointestinal temperature has been previously reported to demonstrate a temporal lag when used by able-bodied individuals (25, 41). Thus in the present study a lag in T_{gi} could suggest the critical humidity limits reported could be higher than if oesophageal temperature had been used. Yet if the lag was consistent between the three groups the differences in evaporative heat loss between the groups would still be correct. A recent study by Au et al. (3) investigated the comparison between oesophageal and T_{gi} during exercise in AB and individuals with an SCI. Their results demonstrated that both methods provided similar elevations in T_{core} in both AB and PP. Unfortunately there was no increase in T_{core} in TP in their study, but this was most likely attributed to their lower heat production in TP of the exercise undertaken. Therefore the study suggests that the lag is similar between AB and PP, yet it is difficult to conclude whether a similar pattern is apparent for TP. However, a recent study by Forsyth et al. (10) reported that the use of telemetric pills was appropriate for both high and low level PP and TP during both exercise and recovery with a close relationship between T_{gi} and oesophageal temperature reported. In addition, practically due to the limited ability to grip, TP (especially high level lesions) would also likely struggle to self-insert the oesophageal probe.

Unfortunately, we did not measure the coverage of each wheelchair (seat and back rest) on each participant, which is likely to differ depending on the level of support required. However, it is important to note that for TP any sensate skin above the lesion is mostly nude skin, so would not be affected by the coverage of the wheelchair or clothing. In PP, the sensate skin areas of participants with the lowest lesion levels would be covered by the t – shirt and back rest, whereas for participants with high level PP only half of their torso would be active in convective and evaporative heat loss. In AB both the t-shirt, shorts, seat and back rest will cover skin surface areas active in convective and evaporative heat loss. Thus the coverage of clothing and the wheelchair is likely to have the greatest effect on AB and presents the best case scenario for this group in the current study. As a result of these differences in clothing and wheelchair coverage between and within groups, in our heat balance calculations we have not taken into account the amount of skin surface covered by the clothing and wheelchair.

As is evident from the results obtained, the chosen starting environmental conditions for TP were too high to ensure the environment was compensable for all participants. In part this was due to the pilot test results not matching the main experiment outcomes. A second factor is the speed of the air flow in the chamber during the actual testing. The air flow of the climatic chamber is usually 0.3 m/s given the settings used, however for this study it was recorded at $0.12 \pm 0.07\ m\cdot s^{-1}$. Using the usual climatic chamber air flow and a maximum skin wettedness value of 0.25 for TP, the starting environment would have been just compensable for these individuals. Therefore upon reflection of the results a lower ambient temperature in the range of 33 to 35°C for all trials would have ensured the starting environmental conditions were compensable for all three groups, while still minimising convective heat losses.

Conclusion. The current study demonstrates that despite producing similar low levels of metabolic heat and thus requiring the same low rate of evaporative cooling for heat balance, TP had a heightened T_{gi} and T_{sk} response throughout the protocol compared to AB. Thus, even at rest, in the absence of convective heat loss, evaporative heat loss in TP is not large enough to balance the heat load at 37ºC in an environment without solar radiation. Despite possessing a greater sweating capacity and a smaller increase in T_{gi} than TP, the continual increase in both T_{gi} and T_{sk} for a number of the PP participants and the too low evaporative cooling potential observed, signifies evaporative heat loss capacity is also insufficient in PP, compared to AB. Lastly, in the studied conditions, both PP and TP were unable to subjectively determine the magnitude of their thermal strain and hence perceptual responses should not be relied upon for this population group.

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DISCLOSURES

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

K.E.G., G.H., M.J.P and V.L.G.T conceived and designed the research. K.E.G performed experiments, analysed the data and prepared figures. K.E.G., G.H., M.J.P and V.L.G.T interpreted the results of the experiments and drafted, edited, revised and approved the final manuscript.

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Table.1 Participant characteristics for able-bodied individuals (n = 8), individuals with paraplegia (n = 8) and individuals with tetraplegia (n = 7).

	Age (years)	**Height (m)**	**Body mass (kg)**	**Sum of four skinfolds (mm)**[a]	**Body fat (%)**[b]	**Fat mass (kg)**	**Fat free mass (kg)**	**Body surface area (m^2)**[c]	**Lesion level (range)**	**Completeness of lesion**[d] **(number of participants)**	**Motor or sensory incompleteness (number of participants)**
Able-bodied	28 (5)	1.88 (0.07)	75.99 (2.86)	31.5 (9.4)	14.4 (3.3)	11.0 (2.9)	65.0 (2.0)	1.96 (0.05)	n/a	n/a	
Paraplegia	45 (7) [§#]	1.77 (0.06)	77.41 (7.26)	61.8 (28.20)[§]	25.5 (7.3)[§]	17.5 (9.8)[§]	57.1 (4.6)[§]	1.94 (0.11)	T3-T12	Complete (5), Incomplete (3)	Sensory (1), Motor and sensory (2)
Tetraplegia	32 (3)	1.80 (0.09)	73.78 (12.24)	58.3 (13.7)[*]	21.5 (2.1)[*]	16.0 (3.8)	57.8 (8.6)	1.92 (0.20)	C5/6-C6/C7	Complete (2), Incomplete (5)	Sensory (3), Motor and sensory (2)

Data are mean values with SD in parentheses. All participants were male. [§] = significant difference between individuals with paraplegia and able-bodied individuals, [#] = significant difference between individuals with tetraplegia and individuals with paraplegia, [*]= significant difference between individuals with tetraplegia and able-bodied individuals. [a] Sum of skinfolds from biceps, triceps, subscapular and suprailliac sites. [b] Body fat percentage, was calculated using the Durin and Wormsley four site method (9). [c] Body surface area was calculated using the Dubois formula (8). [d] An individual with a complete injury has no motor and/or sensory function preserved in the lowest sacral segments of the spinal cord (S4-S5), whilst a motor or sensory incomplete injury refers to the preservation of motor and/or sensory function in the lowest sacral segments (S4-S5, (24))

Table 2 Mean critical relative humidity for able-bodied individuals and individuals with paraplegia. The number of participants a critical relative humidity could be determined for and the level and completeness of lesion for those individuals with a spinal cord injury is also shown.

Group (n)	Mean critical relative humidity (%)	Number of participants showing a critical relative humidity limit	Lesion level/ Completeness of spinal cord injury
Able-bodied (8)	77 (6)	7	-
Paraplegia (8)	53 (14)	3	T4/5 complete, T8 incomplete sensory, T12 incomplete motor and sensory

Data are mean values with SD in parentheses. All participants were male.

Table 3 Fluid balance and evaporative cooling potential during the stepwise protocol for able-bodied individuals, individuals with paraplegia and individuals with tetraplegia.

	Able-bodied	Paraplegia	Tetraplegia
Urine specific gravity (pre)	1.018 (0.009)	1.016 (0.006)	1.019 (0.006)
Urine specific gravity (post)	1.025 (0.008)	1.015 (0.006)§	1.016 (0.003)*
Body mass loss (%)	0.06 (0.44)	-0.37 (0.39)	-0.19 (0.28)
Amount of fluid consumed (L)	0.41 (0.36)	0.46 (0.27)	0.24 (0.21)
Total mass loss (kg)	0.45 (0.05)	0.18 (0.11)§	0.11 (0.12)*
Sweat rate ($L \cdot h^{-1}$)	0.22 (0.03)	0.09 (0.06)§	0.06 (0.07)*
Potential cooling power (W)	147 (21)	63 (41) §	43 (46)*

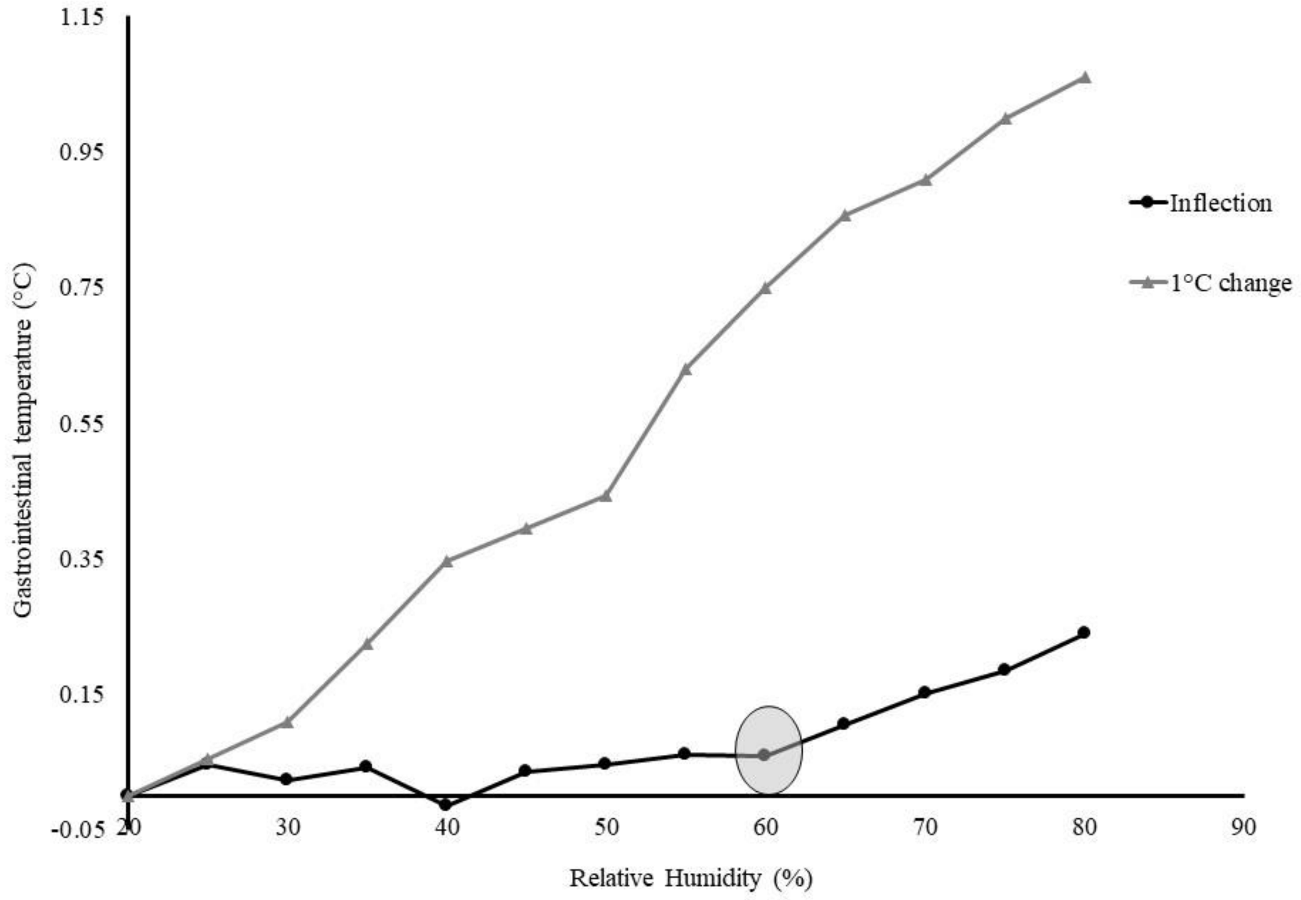
Data are mean values with SD in parentheses. All participants were male., § = significant difference between individuals with paraplegia and able-bodied individuals, *= significant difference between individuals with tetraplegia and able-bodied individuals. Sweat rate was adjusted for respiratory mass losses (M_{res}). Percentage of body mass loss was calculated using the following formula (($Mass_{pre}$ - $Mass_{post}$) / $Mass_{pre}$ · 100). Total mass loss was calculated using the following formula: (($Mass_{pre}$ - $Mass_{post}$) + fluid consumed).

Table 4 Heat balance parameters during the stepwise protocol for able-bodied individuals, individuals with paraplegia and individuals with tetraplegia.

	Able-bodied	Paraplegia	Tetraplegia
M (W)	123 (21)	111 (15)	103 (29)
Dry (W)	-2 (1)	-1 (2)	0 (2)*
C_{res} + E_{res} (W)	6 (2)	5 (2)	5 (2)
E_{req} (W)	113 (20)	107 (17)	106 (29)

Data are mean values with SD in parentheses. All participants were male. M = metabolic energy expenditure/heat production, Dry = radiative (R) and convective heat exchange (C), E_{res} = evaporative respiratory heat exchange, C_{res} = convective respiratory heat exchange, E_{req} = required rate of evaporative cooling. *= significant difference between individuals with tetraplegia and able-bodied individuals.

Figure 1 Two methods for removing participants from the climatic chamber. Participants were withdrawn from the climatic chamber after a clear inflection point in T_{gi} had been observed (critical RH limit, (26)), or T_{gi} increased by 1°C from the initial value upon entering the chamber. Note: To ensure a clear inflection in T_{gi} participants may not have been immediately removed from the climatic chamber following an initial rise in T_{gi}.



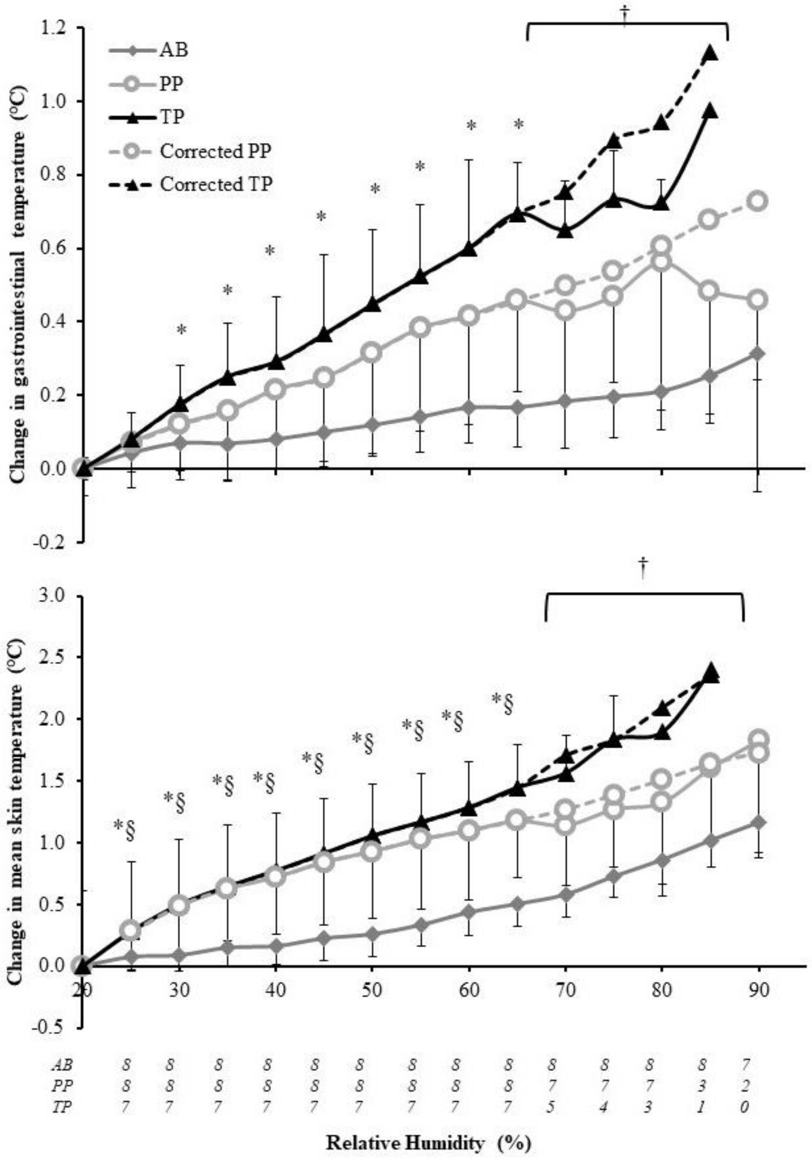


Figure 2 Change in gastrointestinal and mean skin temperature at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PP) and tetraplegia (TP). *= significant difference between individuals with tetraplegia and able-bodied individuals, § = significant difference between individuals with paraplegia and able-bodied individuals, † = statistical analysis was not conducted on these data, due to a reduced number of participants. The number of participants in each group for each time point are listed underneath the x axis. To calculate the predicted data, the difference between each time point (up till 65% RH) for each individual was calculated. The average differences for each time point were then added to the previous time point to estimate data points for 70-90% RH.

Figure 3 Change in upper arm, upper back, forehead, chest, calf and, thigh skin temperature at rest in constant environmental temperature (37°C) and increasing humidity for able-bodied individuals (AB), and those with paraplegia (PP) and tetraplegia (TP) upto 65% relative humidity. § = significant difference between individuals with paraplegia and able-bodied individuals, # = significant difference between individuals with tetraplegia and individuals with paraplegia, *= significant difference between individuals with tetraplegia and able-bodied individuals.

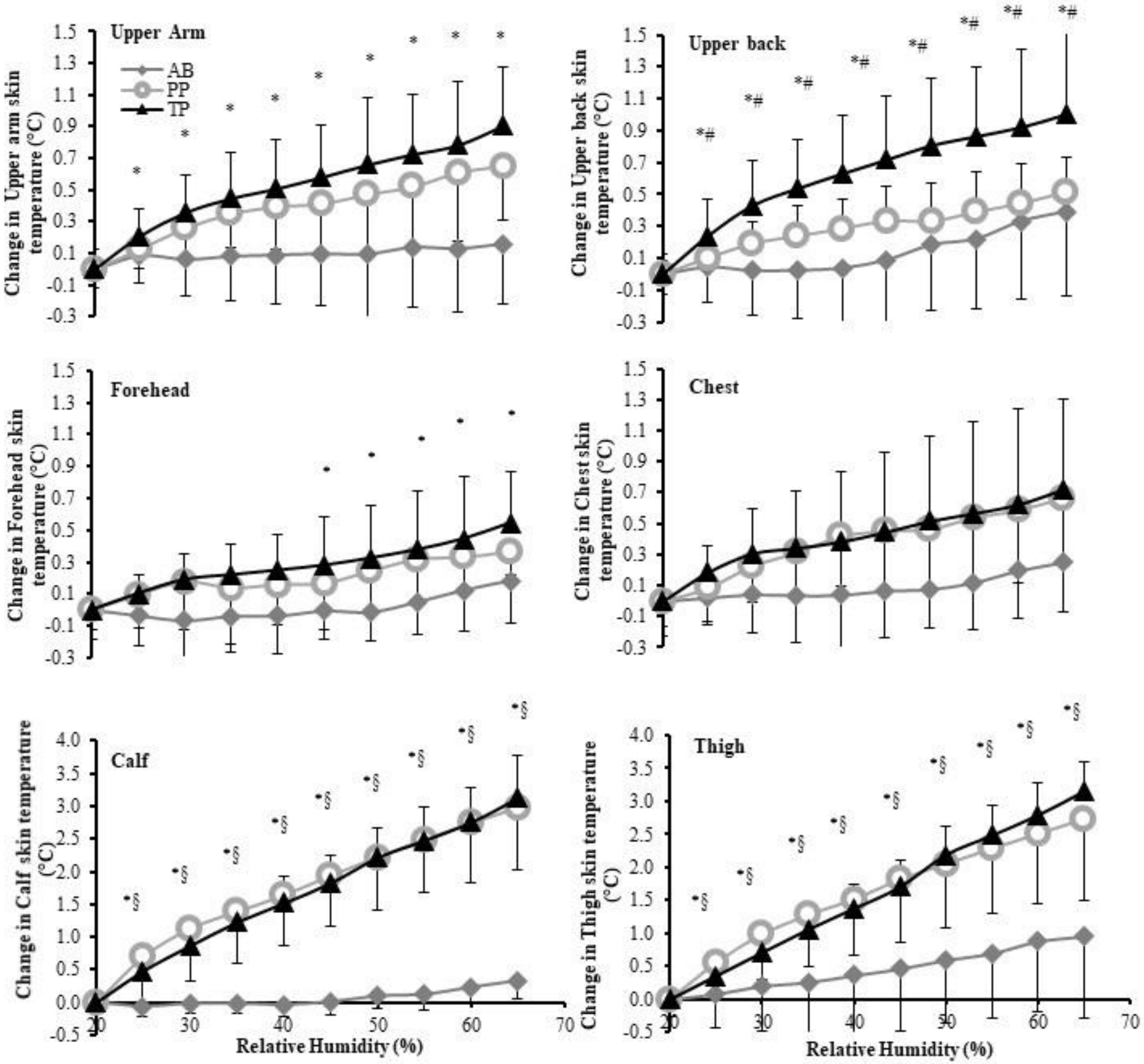


Figure 4 (A) The change in gastrointestinal and mean skin temperature for individuals with paraplegia (PP) and individuals with tetraplegia (TP) with complete and incomplete lesions compared to able-bodied individuals (AB). (B) Individual responses for the change in gastrointestinal and mean skin temperature for complete and incomplete lesions for PP and TP. Note: five individuals with paraplegia had complete lesions and three with incomplete lesions. Two individuals with tetraplegia had complete lesions and two with incomplete lesions