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ORIGINAL ARTICLE

# The influence of local skin temperature on the sweat glands maximum ion reabsorption rate

**N. Gerrett[1] · T. Amano[2] · G. Havenith[3] · Y. Inoue[4] · Narihiko Kondo[1]**

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## Abstract

**Purpose** Changes in mean skin temperature ($T_{sk}$) have been shown to modify the maximum rate of sweat ion reabsorption. This study aims to extend this knowledge by investigating if modifications could also be caused by local $T_{sk}$.

**Methods** The influence of local $T_{sk}$ on the sweat gland maximum ion reabsorption rates was investigated in ten healthy volunteers (three female and seven male; 20.8 ± 1.2 years, 60.4 ± 7.7 kg, 169.4 ± 10.4 cm) during passive heating (water-perfused suit and lower leg water immersion). In two separate trials, in a randomized order, one forearm was always manipulated to 33 °C (Neutral), whilst the other was manipulated to either 30 °C (Cool) or 36 °C (Warm) using water-perfused patches. Oesophageal temperature ($T_{es}$), forearm $T_{sk}$, sweat rate (SR), galvanic skin conductance (GSC) and salivary aldosterone concentrations were measured. The sweat gland maximum ion reabsorption rates were identified using the ΔSR threshold for an increasing ΔGSC.

**Results** Thermal [$T_{es}$ and body temperature ($T_b$)] and non-thermal responses (aldosterone) were similar across all conditions ($p > 0.05$). A temperature-dependent response for the sweat gland maximum ion reabsorption rates was evident between 30 °C (0.18 ± 0.10 mg/cm$^2$/min) and 36 °C (0.28 ± 0.14 mg/cm$^2$/min, $d = 0.88$, $p < 0.05$), but not for 33 °C (0.22 ± 0.12 mg/cm$^2$/min), $d = 0.44$ and $d = 0.36$, $p > 0.05$.

**Conclusion** The data indicate that small variations in local $T_{sk}$ may not affect the sweat gland maximum ion reabsorption rates but when the local $T_{sk}$ increases by > 6 °C, ion reabsorption rates also increase.

**Keywords** Sweat ion regulation · Sweat glands · Skin temperature · Aldosterone

## Abbreviations

| | |
|---|---|
| ANOVA | Analysis of variance |
| CFTR | Cystic fibrosis transmembrane channels |
| $Cl^-$ | Chloride |
| CVC | Cutaneous vascular conductance (%) |
| ENaC | Epithelial sodium channel |
| GSC | Galvanic skin conductance (μS) |
| HASG | Heat-activated sweat glands |
| HR | Heart rate (bpm) |
| $K^+$ | Potassium |
| MAP | Mean arterial pressure (mmHG) |
| $Na^+$ | Sodium |
| SGO | Sweat gland output |
| SR | Sweat rate (mg/cm$^2$/min) |
| $T_b$ | Body temperature (°C) |
| $T_{es}$ | Oesophageal temperature (°C) |
| $T_{sk}$ | Skin temperature (°C) |
| $O_{2max}$ | Maximum oxygen uptake (ml/kg/min) |

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✉ Narihiko Kondo
kondo@kobe-u.ac.jp

[1] Laboratory for Applied Human Physiology, Graduate School of Human Development and Environment, Kobe University, 3-11 Tsurukabuto, Nada-Ku, Kobe 657-8501, Japan

[2] Laboratory for Exercise and Environmental Physiology, Faculty of Education, Niigata University, Niigata, Japan

[3] Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Loughborough, UK

[4] Laboratory for Human Performance Research, Osaka International University, Osaka, Japan

## Introduction

Sweating is an essential physiological function for maintaining thermal homeostasis and the content of sweated ions is important for maintaining epidermal barrier homeostasis

and antimicrobial function of the skin. Despite rapid developments in biosensor technology that aim to determine sweat rate and its ion concentration (Gao et al. 2018), our knowledge of sweat ion regulation is limited. It is well established that when eccrine sweat glands are stimulated, the secretory coil, located at the base of the sweat gland, forms an isotonic fluid and as sweat traverses the straight duct ion reabsorption occurs; resulting in a hypotonic sweat released on the skin surface (Sato 1977; Shamsuddin et al. 2005b). It has been suggested that with an increasing sweat rate (SR) the secretion rate increases proportionally faster than the reabsorption rate, resulting in a linear relationship between SR and sweat $Na^+$ concentration (Buono et al. 2008). Whilst this may be the case there are numerous studies providing evidence that the reabsorption rate can be enhanced, most notably following heat acclimation whereby a reduction in sweated ions occurs despite an increased sweat production (Buono et al. 2007; Amano et al. 2016). Furthermore, the maximum rate of ion reabsorption has been shown to differ between habitually trained and sedentary individuals and is also known to vary across the body (Amano et al. 2017). What regulates eccrine sweat gland ion reabsorption remains unknown.

A regulatory mechanism that has been previously reported to affect the maximum ion reabsorption rate is $T_{sk}$. The influence of $T_{sk}$ on sweat production is well established (Nadel et al. 1971) but its impact on sweated ions is somewhat contradictory with studies reporting an influential role (Johnson et al. 1944; Robinson et al. 1985) and others reporting little or no effect (Bulmer and Forwell 1956). These earlier studies were primarily focused on the concentration of sweated ions but more recently Shamsuddin et al. (2005a) investigated the reabsorption of these ions that ultimately affects the sweated ion concentration. By changing the ambient conditions (15 °C or 25 °C), Shamsuddin et al. (2005a) manipulated mean $T_{sk}$ by approximately 3 °C during an exercising protocol, the result of which was a significantly lower ion reabsorption rate at a lower compared to higher mean $T_{sk}$ ($0.21 \pm 0.04$ vs. $0.52 \pm 0.06$ mg/cm$^2$/min, respectively). The inhibition of the sweat gland ion reabsorption capacity was associated with the temperature dependency of epithelial sodium channel (ENaC) excitability and open probability (Chraïbi and Horisberger 2003). However, they did not report the local $T_{sk}$ where the ion reabsorption rates were measured and also only focused on the effects of low $T_{sk}$ (< 31 °C) on the sweat gland maximum ion reabsorption rates. Therefore, it is still unknown whether the maximum ion reabsorption rates are proportional to local changes in $T_{sk}$ systematically.

It is also necessary to determine the influence of local $T_{sk}$ on the sweat gland maximum ion reabsorption rates as there is cumulative evidence for regional differences in ion reabsorption rates, with the torso generally having a higher reabsorption rate than the extremities (Amano et al. 2017; Gerrett et al. 2018a). However, these regional differences were also mirrored by regional differences in local $T_{sk}$. It would be advantageous then to investigate the influence of local $T_{sk}$ on the sweat gland ion reabsorption rate within temperature ranges expected whilst sweating.

Shamsuddin et al. (2005a) speculated that higher $T_{sk}$ might enhance the responsive ability of the sweat glands to a given concentration of circulating aldosterone, a hormone considered to be a primary effector of sodium exchange at the sweat gland (Hegarty and Harvey 1998; Harvey and Higgins 2000). Aldosterone concentrations and other water-regulatory hormones such as atrial natriuretic peptide, vasopressin and renin are higher during exercise and are considered to be exercise intensity dependent (Convertino et al. 1983; Freund et al. 1991; Yoshida et al. 2006). Shamsuddin et al. (2005a) employed an exercise protocol (cycling at 60% $\dot{V}O_{2max}$) sufficient enough for the release of these hormones although their influence on sweat glands ion reabsorption is inconclusive (Yoshida et al. 2006; Hew-Butler et al. 2010, 2014). As such, it is important to investigate the role of $T_{sk}$ on the sweat gland maximum ion reabsorption rates when hormonal responses associated with exercise are isolated.

To determine the role of local $T_{sk}$ on the sweat gland ion reabsorption rates, we aimed to manipulate local forearm $T_{sk}$ to elicit a Cool (30 °C), Neutral (33 °C) and Warm (36 °C) $T_{sk}$, with the latter reflecting typical $T_{sk}$ experienced during heat stress on the sweat gland ion reabsorption. To minimize any non-thermoregulatory mechanisms affecting sweat gland ion reabsorption rates, the influence of local $T_{sk}$ on ion reabsorption during a passive heating protocol was selected. We hypothesized that eccrine sweat gland maximum ion reabsorption rates are temperature dependent, with maximum ion reabsorption occurring at a higher sweat rate (SR) with a higher local $T_{sk}$ (36 °C) compared to Neutral (33 °C) and cool $T_{sk}$ (30 °C).

## Methods

Participants were informed about the study purpose and procedures prior to providing verbal and written consent. The Human Subjects Committee of the Graduate School of Human Development and Environment at Kobe University (Japan) approved the study (report no. 259), which conforms to the standards set out by the Declaration of Helsinki (except for registration in a database).

### Participants

Ten young healthy recreationally active participants (three female and seven male; $20.8 \pm 1.2$ years, $60.4 \pm 7.7$ kg, $169.4 \pm 10.4$ cm) were recruited for this study during winter

in Japan and thus were considered unacclimated. Both males and females were recruited, as our previous research indicated no sex-related differences in ion reabsorption rates (Amano et al. 2017). Participants were asked to refrain from consuming high-sodium foods, caffeine or alcohol and to avoid any strenuous exercise 24 h preceding the trials. For the experimental trials, they were instructed to record their food and beverage intake during the preceding 24 h and asked to replicate this for each trial. To promote euhydration, participants were instructed to consume 500 ml of water 1–2 h prior to the experiments. Upon arrival to the laboratory, participants provided a urine sample and hydration status was checked by a handheld refractometer (Atago Co. Ltd, Tokyo, Japan). All participants met the criteria for adequate hydration (USG < 1.025) except two participants both on one occasion each. In these cases, the participants were required to consume a further 300 ml prior to the start of the experiments. All participants were non-smokers and were not taking any medications. Menstrual cycle phase per se was not controlled for in the female participants but each female was tested within the same stage of their cycle.

## Experimental trials

Participants visited the laboratory twice for the manipulation of local forearm $T_{sk}$. Each trial was separated by at least 48 h. All experimental trials were conducted in a climatic chamber (SR-3000; Nagano Science, Osaka, Japan) controlled at 27 °C, 50% relative humidity, with minimal air movement. All tests were completed at the same time of day (± 1 h), at least 2 h after their last meal. During all experimental trials, participants wore standardized shorts and females also wore a sports bra underneath a water-perfused suit (Allen-Vanguard, Ottawa, Canada) to help elevate the thermal load and in an attempt to maintain a similar $T_{sk}$ across the body.

Prior to each experiment, participants provided a urine sample for the analysis of aldosterone. Prior to entering the experimental chamber, participant self-inserted an oesophageal thermometer, as an index of core temperature ($T_{es}$), to the distance of one-fourth of standing height from the external nares (Mekjavic and Rempel 1990). After entering the chamber, participants donned a water-perfused suit that covered the body except face, forearms, hands and lower legs (from above the knee). Participants then rested in a semi-supine position for approximately 60 min whilst the measuring instruments were attached (detailed below) and local $T_{sk}$ of the forearm was manipulated and remained stable at the desired local $T_{sk}$ (detailed below). During the instrumentation preparation phase, water at 34 °C was passed through the suit at a flow rate of 750 ml/min to maintain a stable resting mean $T_{sk}$. Following instrumentation, baseline data were recorded for 5 min and a salivary aldosterone sample collected. Participants were then heated exogenously for 45 min separated into two phases. The first phase involved submerging the lower legs into a water bath set at 42 °C and increasing the water temperature inside the suit to 40 °C for 20 min. For the remaining 25 min, the lower leg water bath temperature was increased to 43 °C and the temperature of the water inside the suit was increased to 45 °C.

During all experiments, one forearm was controlled to elicit a Neutral $T_{sk}$ of 33 °C (Neutral), whilst the other forearm was either manipulated to elicit a cool $T_{sk}$ of 30 °C (Cool) or a warm temperature of 36 °C (Warm) in a balanced order. For clarity, in the rest of the document the phrase Neutral–Cool will be used to indicate when one forearm was manipulated to be Neutral and the other Cool, and Neutral–Warm when one forearm was manipulated to be Neutral and the other Warm. Sweat rate on bilateral forearms are comparable (Buono et al. 2011; Kenefick et al. 2012; Smith and Havenith 2012) and thus we assume asymmetry between the left and right arms and use the mean of the two Neutral conditions. To manipulate local forearm $T_{sk}$, custom-made water-perfused patches were wrapped around the left and right ventral forearm during each experiment. The water-perfused patches consisted of tubes (inside diameter 2 mm, outside diameter 4 mm) running in a circular motion with no gaps between tubes. A small hole positioned in the centre of the patch allowed for entrance and exit of the sweat capsule tubes. Both patches were of equal surface area (16 × 13 cm) and water was supplied to each patch at a flow rate of 250 ml/min (Variable-flow Chemical Transfer Pump, Fisher Scientific™). The patches were connected to two separate water baths (Taitec Therminder DX-10 and SP12, Taitec Corporation, Saitama, Japan) where the water temperature was altered to achieve the desired local $T_{sk}$. The water temperature used varied for each participant but was approximately 29.4 ± 3.2 °C for Neutral, 15.8 ± 5.8 °C for Cool and 40.2 ± 2.2 °C for Warm conditions. To control the cold-water temperature, an immersion cooler (Taitec Cool pipe 300LF, Taitec Corporation, Saitama, Japan) was used concomitantly with the water bath.

The water patches were positioned onto the forearms for a minimum of 30 min prior to the start of the test, whereby local $T_{sk}$ was altered until the desired temperatures were reached. Local $T_{sk}$ was maintained at the desired temperature for a minimum of 5 min prior to the start of the experiment. If the local $T_{sk}$ of the forearms during passive heating increased or decreased by more than 1 °C of the target local $T_{sk}$, the temperature of the water bath was altered.

During the final minute of each experiment, a salivary aldosterone sample was collected. This was then followed by the removal of the forearm skin patches and all instruments so that the number of heat-activated sweat glands (HASG) using the starch–iodine technique (Inoue 1996) could be measured. Once these samples were collected, the passive heating protocol was completed.

## Measurements

For the determination of mean skin temperature (mean $T_{sk}$), four sites (chest, forearm, thigh and calf) were measured. In addition, local $T_{sk}$ underneath the skin patch at the left and right forearm was measured at two locations adjacent to the sweat capsule and averaged. Both $T_{es}$ and $T_{sk}$ were measured using copper–constantan thermocouples (Inui Engineering, Higashi Osaka, Japan). The tip of the oesophageal thermometer was covered with silicon and the skin thermocouples were uncovered and attached to the skin using Medipore tape. Mean $T_{sk}$ and mean body temperature ($T_b$) were calculated using the following respective formula (Stolwijk and Hardy 1966; Gagge and Nishi 2011):

$$T_b = \left(0.8 \times T_{es}\right) + \left(0.2 \times \text{mean } T_{sk}\right),$$

$$\text{Mean } T_{sk} = (\text{chest} \times 0.34) + (\text{calf} \times 0.18) + (\text{thigh} \times 0.33) + (\text{forearm} \times 0.15).$$

The average of both the left and right forearm $T_{sk}$ was used in the calcualtion of mean $T_{sk}$.

SR was measured using the ventilated capsule method on the right and left mid-ventral forearm. Dry nitrogen gas was flushed (500 ml/min) through the apparatus approximately 1 h prior to each experiment to ensure stable readings. Each capsule (3.14 $cm^2$) was affixed to the skin using double-sided tape at least 30 min prior to data collection. The temperature and humidity of the air flowing out of the capsule were measured using a capacitance hygrometer (HMP50; Vaisala, Helsinki, Finland). Two Ag/AgCl electrodes (Vitrode J, Nihon Kohden, Tokyo, Japan) for measuring GSC were attached to either side of the sweat capsules, approximately 3 cm apart (MP100 and GSC100C; Biopac, Goleta CA, USA). GSC is expressed as a change from baseline (ΔGSC), recorded during the 5-min resting phase prior to heating. Cutaneous vascular conductance (CVC) was estimated by measuring skin blood flow on each forearm using laser-Doppler velocimetry (ALF21; Advanced, Tokyo, Japan). CVC was calculated as a percentage of the baseline value recorded during the resting phase prior to heating. $T_{es}$, local $T_{sk}$, SkBf, SR and GSC were recorded every second by a data logger (MX100; Yokogawa, Tokyo, Japan) and 1 min average was calculated. Heart rate and arterial blood pressure were continuously measured on the left middle finger using a Finometer (Finometer; Finapres Medical Systems, Amsterdam, The Netherlands); mean arterial pressure (MAP) was subsequently calculated and averaged over 5-min periods.

The number of HASG was determined using the starch–iodine technique (Inoue 1996). Briefly, the residual sweat on the skin was first wiped away, followed by placing a small amount of iodine onto the skin with a cotton guaze. Excess iodine was removed by blotting the area with tissue paper. Starch paper attached to a small wooden block was then held in place over the measurement area for approximately 3 s. The iodine was transferred from the HASG to the paper as indicated by a small dot. The same investigator counted the dots within a defined area (1 $cm^2$). The sweat gland output per gland (SGO) at the respective site was calculated by dividing the SR (averaged from the last 5 min of the experiment) by the number of HASG.

Salivary and urinary aldosterone were collected using Salivettes™ (Sarstedt, Newton, NC, USA) whereby a plain cotton swab was inserted into the mouth and chewed for 60 s. The cotton swab was then returned into the Salivette™ tube and spun at 4000 RPM for 10 min. Samples were then frozen at − 30 °C until analysis. After thawing, salivary aldosterone (pg/ml) levels were quantified by competitive ELISA (LDN, GmbH & Co.KG, Germany). The sensitivity of the assay for aldosterone was 14 pg/ml and the inter- and intra-assay coefficients of variation were between 3.9–7.5% and 9.4–9.7%, respectively.

## Data analysis

As described in our previous experiments (Amano et al. 2016, 2017; Gerrett et al. 2018a), the maximum reabsorption rate of the sweat glands was obtained by plotting ΔGSC against ΔSR. By plotting this relationship, it is possible to identify three distinct phases representing different stages of sweat production. In the first phase, there is an increase in ΔGSC but no change in ΔSR, which represents the isosmotic precursor sweat production in the proximal secretory coil. Such changes in ΔGSC and no changes in ΔSR are frequently utilized to identify pre-secretory sweat gland activity (Thomas and Korr 1957; Darrow 1964; Machado-Moreira et al. 2009; Gerrett et al. 2018b). In the second phase, an increased ΔSR without an increase in ΔGSC can be observed. As ΔGSC is influenced by both the amount of sweat produced as well as the electrolyte concentration, the fact that ΔSR increases but there is no change in ΔGSC represents reabsorption of sweated ions in the sweat duct. Once the rate of sweat ion secretion exceeds its reabsorption limit in the duct, the third phase occurs where there is a proportional increase in ΔGSC with increasing ΔSR. The point at which the second and third phases intersect is used to identify the maximum rate of sweat gland ion reabsorption. In the present study, the thresholds were determined using segmented regression analysis on GraphPad Prism (version 7) software.

To investigate the effect of local $T_{sk}$ on local maximum ion reabsorption, local SR, local ΔGSC and local CVC, a one-way repeated measure ANOVA with condition (Warm, Neutral and Cool) was carried out. The relation between temperature and ion reabsorption rates was analysed with correlation analysis, using normalized data to reduced individual effects. Correlation coefficients were

considered as strong (≥ 0.60), moderate (0.40–0.59), and weak (0.20–0.39) (Cohen 1977).

A two-way ANOVA was used to assess the remaining thermophysiological parameters ($T_{es}$, $T_b$ and mean and local $T_{sk}$) and cardiovascular responses (CVC, a one-way repeated measure ANOVA) to determine any differences between conditions (Neutral–Cool vs. Neutral–Warm) and over time. When any significant effects were observed, post hoc comparison using the Bonferroni test was carried out. All data were checked for sphericity and normality (Shapiro–Wilk test). As ANOVAs are fairly robust to violations of normality, if the data were approximately normal, then the data were assessed with parametric data analysis. If the data violated this assumption substantially, then a Friedman's test was performed (comparing Neutral, Cool and Warm data); this was the case for the following sets of data: local forearm, chest and thigh $T_{sk}$ and SR. All data were analysed using GraphPad Prism (version 7). Effect sizes (Cohen's *d*) were calculated for the local maximum ion reabsorption rates with the following criteria; an effect size of < 0.20 is classified as 'trivial', 0.21–0.49 as 'small', 0.50–079 as 'moderate' and > 0.80 as a 'large' effect. Values are means and standard deviations (± SD) and statistical significance was set at $p < 0.05$.

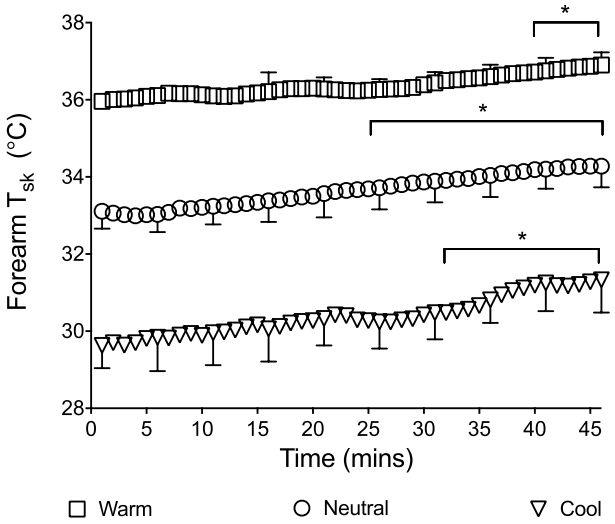


**Fig. 1** Local forearm skin temperature ($T_{sk}$) measured whilst manipulating local $T_{sk}$ to 36 °C (Warm), 33 °C (Neutral) and 30 °C (Cool) during a 45-min passive heating protocol. Forearm $T_{sk}$ was higher during Warm compared to both Neutral and Cool conditions and Neutral was also higher than the Cool condition ($p < 0.05$). Forearm $T_{sk}$ increased over time in all conditions ($p < 0.05$) and asterisk indicates when forearm $T_{sk}$ was higher than baseline from each condition. The increases were similar between conditions; hence, there was no interaction effect between condition and time ($p > 0.05$). Values are based on 1-min averages and expressed as mean ± SD for ten participants. To aid clarity, error bars are provided at 5-min intervals

## Results

### Local skin temperature

The local forearm $T_{sk}$s are illustrated in Fig. 1. Forearm $T_{sk}$ during Warm (36.4 ± 0.4 °C) was higher ($p < 0.05$) than Neutral (33.5 ± 0.7 °C) and the Cool (30.5 ± 1.0 °C) conditions ($p < 0.05$). The latter was also lower than both the Neutral conditions ($p < 0.05$). The local $T_{sk}$ on the Neutral arm was not affected by the temperature on the experimental arm (Neutral–Cool 33.6 ± 0.7 °C and Neutral–Warm 33.7 ± 0.7 °C, p > 0.05). Forearm $T_{sk}$ increased over time in all conditions ($p < 0.05$) and was significantly higher than baseline after 40, 25 and 30 min until the end of the experiment for Warm, both Neutral and Cool conditions, respectively. The increases from baseline to the end of passive heating were, however, similar between conditions (Warm + 0.9 ± 0.4 °C, Neutral + 1.2 ± 0.5 °C, Cool + 1.7 ± 0.8 °C, no interaction effect, $p > 0.05$).

### Maximum ion reabsorption

The maximum ion reabsorption thresholds, as indicated by the ΔSR threshold for an increasing ΔGSC, are illustrated in Fig. 2. There is a significant pattern for a temperature-dependent response for maximum ion reabsorption threshold

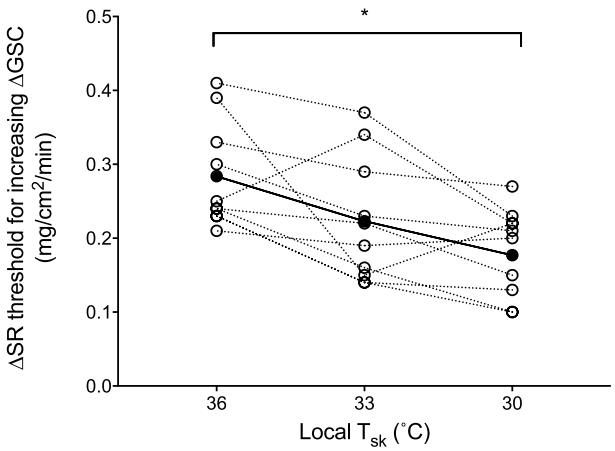


**Fig. 2** The relation between local $T_{sk}$ and the ΔSR threshold for an increasing ΔGSC. The solid line and black cycle represent the mean data ($n = 10$), whilst the dashed line and empty circles are the individual responses. Warm was significantly higher than Cool (asterisk indicates $p > 0.05$)

(Warm 0.28 ± 0.14 mg/cm²/min, Neutral 0.22 ± 0.12 mg/cm²/min, Cool 0.18 ± 0.10 mg/cm²/min, $p < 0.05$), with differences noted between Warm and Cool only ($d = 0.88$, $p = 0.024$). There were small effect sizes for the maximum ion reabsorptions between Neutral and Warm ($d = 0.44$,

$p > 0.05$) and Neutral and Cool ($d = 0.36$, $p > 0.05$). A weak, significant relation exits between local $T_{sk}$ and the ΔSR threshold for maximum ion reabsorption ($r^2 = 0.36$, $p < 0.05$).

## Thermophysiological measurements

$T_{es}$, $T_b$ and mean $T_{sk}$ are illustrated in Fig. 3a–c. $T_{es}$ was similar between conditions (Neutral–Warm 37.1 ± 0.3 °C and Neutral–Cool 37.2 ± 0.3 °C, $p > 0.05$) and both gradually increased over time ($p < 0.05$), although the increase was similar between conditions (ΔTes: Neutral–Warm 0.92 ± 0.2 °C and Neutral–Cool 0.77 ± 0.1 °C $p > 0.05$). $T_b$ were similar between conditions (Neutral–Warm 36.9 ± 0.3 °C and Neutral–Cool 36.8 ± 0.3 °C, $p > 0.05$) and both gradually increased over time ($p < 0.05$), although the increases were similar between conditions (ΔTes: Neutral–Warm 1.4 ± 0.03 °C and Neutral–Cool 1.3 ± 0.02 °C, $p > 0.05$).

Mean $T_{sk}$ was higher during the Neutral–Warm (35.7 ± 0.6 °C) compared to Neutral–Cool (34.9 ± 1.0 °C) conditions ($p < 0.05$) and did increase over time ($p < 0.05$), although the increase was similar between conditions (Δmean $T_{sk}$: Neutral–Warm 3.3 ± 0.5 °C and Neutral–Cool 3.2 ± 0.3 °C; no interaction effect, $p > 0.05$). Local $T_{sk}$s of the chest, thigh and calf were similar between conditions (Neutral–Warm 35.4 ± 5.6 °C, 33.4 ± 5.2 °C, 42.0 ± 7.0 °C and Neutral–Cool: 35.3 ± 5.5 °C, 33.2 ± 5.3 °C, 41.9 ± 7.0 °C, $p < 0.05$, respectively). They all increased over time ($p < 0.05$) although the increase was similar between conditions (no interaction effect, $p > 0.05$).

## Sweating responses

SR and ΔGSC measured at the forearms whilst local forearm $T_{sk}$s were maintained at a Warm (36 °C), Neutral (33 °C) or Cool (30 °C) temperature are illustrated in Fig. 4. SR was higher during both Warm (0.43 ± 0.26 mg/cm$^2$/min) and the Neutral conditions (Neutral–Warm 0.40 ± 0.3 mg/cm$^2$/min and Neutral–Cool 0.40 ± 0.2 mg/cm$^2$/min) than Cool (0.35 ± 0.2 mg/cm$^2$/min). SR increased over time in all conditions ($p < 0.05$) and was significantly higher than baseline from 30 min until the end of passive heating. The increases from baseline to the end of passive heating were similar between conditions (Warm + 0.62 ± 0.24 mg/cm$^2$/min, Neutral + 0.61 ± 0.23 mg/cm$^2$/min, Cool + 0.54 ± 0.15 mg/cm$^2$/min, no interaction effect, $p > 0.05$).

ΔGSC was not significantly different between Warm (10.3 ± 11.5 µS), Neutral (10.1 ± 9.8 µS), or Cool (8.6 ± 11.3 µS) conditions ($p > 0.05$). ΔGSC increased from baseline after 10 min for all conditions ($p < 0.05$). There was no interaction effect as the increases from baseline to the end of passive heating were similar between conditions (Warm

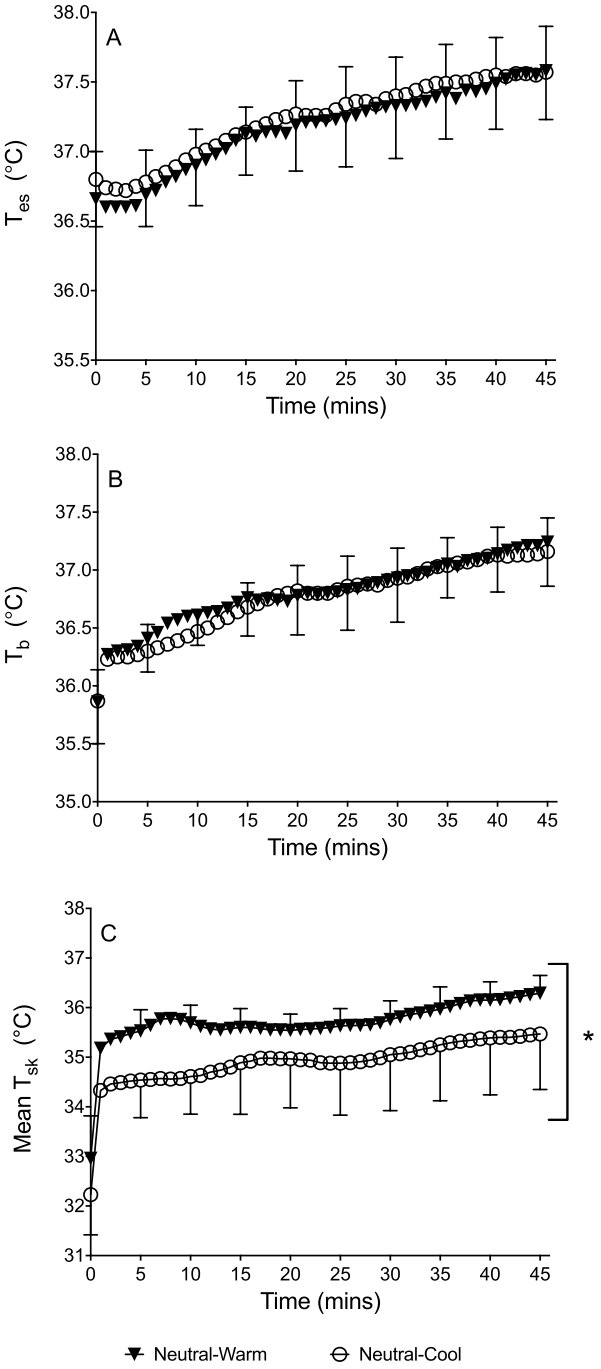


**Fig. 3** Esophageal temperature ($T_{es}$) (**a**), body temperature ($T_b$) (**b**) and mean skin temperature ($T_{sk}$) (**c**) during the 45-min passive heating protocol when local forearm skin temperature was stimulated to be Neutral and Warm or Neutral and Cool. There were no significant differences found between conditions for $T_{es}$ or $T_b$ and whilst they both increased over time, there was no interaction effect ($p > 0.05$). Mean $T_{sk}$ was higher during the Neutral–Warm compared to Neutral–Cool conditions (*$p < 0.05$) likely due to differences in local forearm $T_{sk}$ as all other skin sites were not different ($p > 0.05$). Mean $T_{sk}$ increased over time ($p < 0.05$) but this was similar between conditions ($p > 0.05$). Values based on 1-min averages are expressed as mean ± SD for ten participants. To aid clarity, error bars are provided at 5-min intervals

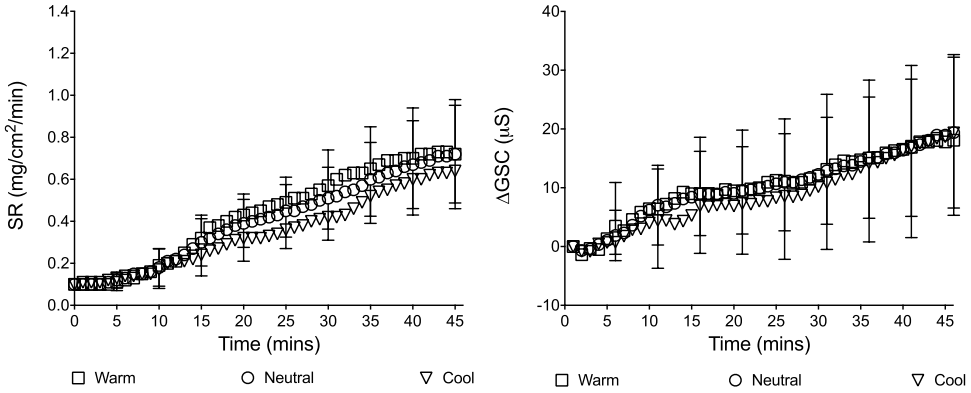


**Fig. 4** Local sweat rate (SR) (left) and ΔGSC (right) measured whilst stimulating local $T_{sk}$ at 36 °C (Warm), 33 °C (Neutral) and 30 °C (Cool) during a 45-min passive heating protocol. SR was significantly different between all conditions ($p < 0.05$) and whilst SR increases over time the increase was similar between conditions (no interaction effect, $p > 0.05$). There were no differences in ΔGSC between conditions ($p > 0.05$). Whilst ΔGSC increased over time the increase was similar between conditions (no interaction effect, $p > 0.05$). Values are based on 1-min averages and expressed as mean ± SD for ten participants. To aid clarity, error bars are provided at 5-min intervals

18.1 ± 14.6 µS, Neutral 19.4 ± 12.8 µS, Cool 19.35 ± 14.1 µS, $p > 0.05$).

The HASG was similar between conditions: Warm 107 ± 20 gland/cm$^2$, Neutral 120 ± 24 gland/cm$^2$ and Cool 115 ± 18 gland/cm$^2$ ($p > 0.05$). The SGO was similar between conditions: Warm 6.9 ± 2.7 µg/gland/min, Neutral 5.6 ± 1.7 µg/gland/min and Cool 5.3 ± 1.1 µg/gland/min, $p > 0.05$.

The $T_{es}$ threshold for SR was not significantly different between conditions (Warm 36.72 ± 0.4 °C, $p > 0.05$, Neutral 36.92 ± 0.4 °C, Cool 37.08 ± 0.3 °C). The slope was also not significantly different (Warm 0.74 ± 0.4, Neutral 1.00 ± 0.3, Cool 1.13 ± 0.5, $p > 0.05$).

### Urine and salivary aldosterone

Urine aldosterone concentrations were similar between conditions (Neutral–Warm 5.03 ± 2.6 µg/l and Neutral–Cool 5.37 ± 2.5 µg/l, $p > 0.05$). The urine specific gravity was also similar between conditions (Neutral–Warm 1.021 ± 0.01 and Neutral –Cool 1.021 ± 0.01, $p > 0.05$). Salivary aldosterone samples were similar between conditions and over time (pre vs. post); there was also no interaction effect (Neutral–Warm–pre 122.2 ± 40.5 pg/ml, Neutral–Warm–post 116.1 ± 43.0 pg/ml, and Neutral–Cool–pre 113.7 ± 28.9 pg/ml and Neutral–Cool–post 115.8 ± 41.7 pg/ml, $p > 0.05$).

### Cardiovascular measurements

HR, MAP and CVC are presented in Table 1. HRs were similar between conditions (Neutral–Warm 78.0 ± 8 bpm and Neutral–Cool 79.0 ± 9 bpm, $p > 0.05$) and both gradually increased over time ($p < 0.05$) and the increase was similar between conditions (ΔHR: Neutral–Warm 30.0 ± 2 bpm and Neutral–Cool 31.2 ± 2.bpm, $p > 0.05$). MAP was similar between conditions (Neutral–Warm 99.2 ± 2 mmHg and Neutral–Cool 99.1 ± 2 mmHg, $p > 0.05$) and did not increase over time in either condition ($p > 0.05$).

## Discussion

The aim of the present study was to investigate the influence of local $T_{sk}$ on the eccrine sweat glands maximum ion reabsorption rates during passive heating. We hypothesized that the sweat glands maximum ion reabsorption rates would occur at a higher sweat rate (SR) with a higher local $T_{sk}$ (36 °C) compared to Neutral (33 °C) and Cool $T_{sk}$ (30 °C). The data indicate that there is a temperature-dependent response, which was most prominent when local $T_{sk}$ differed by 6 °C (30 °C vs. 36 °C) whilst not when local $T_{sk}$ differed by only 3 °C (30 °C vs. 33 °C and 33 °C vs. 36 °C). In practical terms, a higher ΔSR for maximum ion reabsorption means that a more dilute sweat would be secreted onto the skin surface for a given SR, which may be advantageous when sweat rate is high to prevent the excess loss of ions. By selecting a passive heating protocol, we ensured that the values were obtained in controlled conditions to eliminate any potential effect from non-thermal control mechanisms, such as aldosterone, and other potential thermal controllers such as core and body temperature. Mean $T_{sk}$ was significantly different by only approximately 0.6 °C between conditions, which is likely due to differences in local $T_{sk}$ manipulations as all other measured local skin site temperatures were similar between conditions.

**Table 1** Cardiovascular responses measured continuously and averaged over 5 min during the passive heating protocol

| | BL | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|---|---|---|---|---|---|---|---|---|---|---|
| HR (bpm) | | | | | | | | | | |
| Neutral–Warm | 61.3 ± 8.7 | 65.5 ± 6.9 | 67.9 ± 8.4 | 72.7 ± 8.8 | 77.0 ± 7.1 | 78.2 ± 9.4 | 79.2 ± 10.8 | 82.5 ± 11.3 | 86.9 ± 10.7 | 89.9 ± 10.6 |
| Neutral–Cool | 61.9 ± 8.1 | 65.6 ± 8.7 | 67.0 ± 9.9 | 72.2 ± 7.1 | 78.4 ± 7.0 | 79.7 ± 7.7 | 81.1 ± 8.1 | 84.3 ± 8.0 | 88.6 ± 8.1 | 91.4 ± 8.9 |
| MAP (mmHg) | | | | | | | | | | |
| Neutral–Warm | 93.9 ± 6.8 | 98.9 ± 10.6 | 99.1 ± 8.8 | 99.8 ± 9.6 | 101.5 ± 9.6 | 100.4 ± 9.9 | 97.4 ± 6.8 | 99.7 ± 8.5 | 99.4 ± 6.4 | 97.3 ± 6.8 |
| Neutral–Cool | 95.1 ± 7.1 | 98.3 ± 7.6 | 99.7 ± 9.7 | 99.2 ± 8.5 | 96.8 ± 8.7 | 97.8 ± 8.7 | 98.9 ± 8.9 | 99.9 ± 8.5 | 99.5 ± 8.5 | 101.5 ± 7.4 |
| CVC (%) | | | | | | | | | | |
| Warm | 100.0 ± 0.0 | 143.0 ± 97.2 | 205.0 ± 158.2 | 351.5 ± 291.0 | 480.2 ± 310.8 | 578.0 ± 304.9 | 620.5 ± 301.7 | 643.4 ± 288.7 | 648.8 ± 298.5 | 655.0 ± 310.1 |
| Neutral | 100.0 ± 0.0 | 120.5 ± 42.7 | 159.8 ± 59.9 | 252.4 ± 129.5 | 384.7 ± 163 | 460.8 ± 173.0 | 524.7 ± 170.3 | 601.7 ± 200.7 | 645.6 ± 212.3 | 663.6 ± 232.8 |
| Cool | 100.0 ± 0.0 | 101.4 ± 19.1 | 120.4 ± 35.0 | 165.4 ± 51.9 | 224.9 ± 79.4 | 281.6 ± 74.5 | 357.1 ± 105.6 | 464.5 ± 114.0 | 590.9 ± 180.9 | 645.5 ± 215.7 |

There were no differences in heart rate (HR) or mean arterial pressure (MAP) between the Neutral–Warm and Neutral–Cool conditions ($p > 0.05$). There were no differences in CVC between both Neutral (33 °C) conditions (Neutral–Warm and Neutral–Cool), Cool (30 °C), or Warm (36 °C) conditions ($p > 0.05$). All variables increased over time but there was no interaction effect ($p > 0.05$). Values are based on 5-min averages and expressed as mean ± SD for ten participants

## Thermal mechanism

We hypothesized that the maximum sweat gland ion reabsorption rate would be affected by local $T_{sk}$ as previous studies, in vivo and in vitro, have reported a temperature dependency of $Na^+$ channel excitability and ion reabsorption regulation (Ruff 1999; Chraïbi and Horisberger 2003; Shamsuddin et al. 2005a). The reabsorption of NaCl is primarily driven by the movement of $Na^+$ down a steep concentration gradient that is generated by the $Na^+/K^+$ pump via ENaC (Bovell 2015). In vitro studies utilizing a wide temperature range (19 °C and 37 °C) have demonstrated the temperature dependency of $Na^+$ channel excitability, where 30% and 93% of the channels were excitable at these respective temperatures (Ruff 1999). However, the percentages of excitable channels became less prominent when comparing 31 °C and 37 °C (85% vs. 93%, respectively), which are closer to the physiological temperatures experienced whilst sweating. Chraïbi and Horisberger (2003) more recently showed that ENaC open probability was greater at lower (15 °C) compared to higher temperatures (24–30 °C). Indeed, other studies showing temperature dependency of ENaC, and cystic fibrosis transmembrane channels (CFTR) that are responsible for the reabsorption of $Cl^-$ and interact with ENaC (Reddy and Quinton 2003) show the effects of temperature are more prominent outside the physiological ranges examined in the present study. Our data indicate that when $T_{sk}$ is within appropriate physiological ranges of 30–33–36 °C, a $T_{sk}$ difference of ~ 3 °C is an insufficient temperature stimulus to affect the maximum rate of ion reabsorption but differences of ~ 6 °C may elicit changes of approximately 0.1 mg/cm$^2$/min. Whilst the inter- and intra-individual variabilities are high for sweating responses, the ventilated sweat capsule technique is highly reliable and accurate and thus we are confident that our method is sensitive to detect these differences. Whilst GSC is more variable, the values themselves are less meaningful but the pattern of the response in relation to SR is important for detecting the sweat gland ion reabsorption rates.

In contrast to our findings, Shamsuddin et al. (2005a) reported differences in ion reabsorption rates when mean $T_{sk}$ was clamped at ~ 31 °C and ~ 28 °C, a difference of 3 °C, during dynamic exercise. These findings alongside the in vitro studies mentioned earlier may indicate that cooler temperatures (< 30 °C) have stronger effects on ion regulation. Alternatively, smaller differences in $T_{sk}$ may affect ion reabsorption rates during dynamic exercise when hormonal mediators are likely in effect.

Core temperature ($T_c$), as indicated by $T_{es}$, in our present study and by Shamsuddin et al. (2005a) were not significantly different between the two conditions, thereby eliminating the role of $T_{es}$ as a controlling mechanism. However, that is not to say that $T_c$ per se will not influence the sweat

glands maximum ion reabsorption rates in other conditions outside the realms of the studies under discussion. Temperature stimulation has been deemed an important regulatory mechanism for sudomotor activity. We reported no significant differences between conditions in the $T_{es}$ threshold for the onset of either sweating, or the slope, or the SGO in this study. Indeed, the relative importance of $T_c$ on SR compared to mean $T_{sk}$ is well known (Nadel et al. 1971) and both $Na^+$ secretion and $Na^+$ reabsorption increase linearly with increasing SR (Buono et al. 2008). As SR increases, it has been suggested that there becomes insufficient time for sweat ion reabsorption to occur and hence a maximum reabsorption rate is reached. The SR for maximum ion reabsorption occurred between 0.18 and 0.28 mg/cm$^2$/min across the three temperature ranges, which typically occurred within 15 min of passive heating. As can be seen in left panel of Fig. 4, the SR response over time is similar between conditions, as also confirmed by a non-significant interaction effect (condition × time). It seems, therefore, that if any thermal controls exist over the sweat gland maximum ion reabsorption rates, it requires a stronger thermal input (e.g. from mean $T_{sk}$ and/or $T_c$) than from small changes ($\leq$3 °C) in local $T_{sk}$. It would be interesting to determine the minimum change in local $T_{sk}$ that would affect the sweat gland maximum ion reabsorption rate. The role of $T_c$ on SR and ion reabsorption seems likely, but certainly warrants clarification, as does the role of mean and local $T_{sk}$ under varying $T_c$ responses.

Previous studies have reported higher reabsorption rates on the torso compared to the extremities but have been unable to determine any contributing mechanism as regional differences in local $T_{sk}$ existed (Inoue et al. 1998; Amano et al. 2017). The findings of the present study provide important information to help elucidate why these regional differences occur and variations in local $T_{sk}$ can be ruled out, as regional differences were less than ~2 °C. Instead, we hypothesize that structural differences in the sweat glands across the body may account for the regional differences reported in aforementioned studies.

## Non-thermal mechanism

Regulation of ion loss is predominated in the literature by renal function despite potential large fluid and ion losses from eccrine sweat glands during exercise and/or heat exposure. Although structurally and functionally different to the kidneys, the influence of various water-regulating hormones (arginine vasopressin, aldosterone and atrial natriuretic peptide) on sweat output has been investigated (Kirby and Convertino 1986; Hew-Butler et al. 2010, 2014). The precise mechanism for the regulation of the ion reabsorption is unknown but it is hypothesized that aldosterone, an important hormone in renal sodium regulation, plays a role. Acting on mineralocorticoid receptors, aldosterone increases intracellular calcium, which regulates epithelial $Na^+$ and $K^+$ channels, reportedly by increasing either the permeability of the membrane to $Na^+$, increasing active transport of $Na^+$ out of the cell and/or increasing the energy available to the $Na^+/K^+$ pump (Hegarty and Harvey 1998; Harvey and Higgins 2000).

Using a passive heating protocol, our study aimed to reduce non-thermal mediators, such as water-regulatory hormones (e.g. aldosterone, vasopressin and plasma renin activity) that are released during exercise (Convertino et al. 1983; Freund et al. 1991; Yoshida et al. 2006). We confirmed similar aldosterone concentrations between our two conditions, both before and after passive heating. In addition, hydration statuses were similar between both conditions so as to rule out any potential effects of hydration on circulating hormones. Previous research by Shamsuddin et al. (2005a) reported a role of mean $T_{sk}$ on ion reabsorption, but this occurred during dynamic exercise (cycling at 60% $\dot{V}O_{2max}$) where aldosterone concentrations would have been elevated, as demonstrated in our previous research comparing passive heating and cycling at 60% $\dot{V}O_{2max}$ (Gerrett et al. 2018a). Shamsuddin et al. (2005a) speculated that higher $T_{sk}$ might enhance the responsiveness of the sweat glands to a given aldosterone concentration. In the present study, however, aldosterone concentrations remained unchanged but local $T_{sk}$ differed and we hypothesize that small differences ($\leq$3 °C) in $T_{sk}$ may only affect ion reabsorption rates when aldosterone (or other water-regulatory hormones) are elevated. Further support is provided from our previous research where higher maximum ion reabsorption rates were reported during moderate intensity exercise (supine cycling at 60% $\dot{V}O_{2max}$) compared to passive heating (lower leg submersion 43 °C water) despite a lower mean $T_{sk}$. We attributed those differences partially to the elevated salivary aldosterone concentrations during exercise compared to passive heating. To date, no studies have determined the effect of varying $T_{sk}$ and/or $T_c$ on aldosterone concentrations during exercise but it certainly warrants investigation.

## Perspective

Sodium chloride plays an important role in the formation of sweat within the secretory coil. Why we do not, or cannot, reabsorb all the sodium chloride ions in the reabsorptive duct is not clear; it may play a role in the evaporative potential of sweat on the skin surface, it may aid skin barrier function and protection. Yet there is an adaptive response as seen with heat acclimation (Buono et al. 2008; Amano et al. 2016). We know from cases of cystic fibrosis that preventing an excess loss of these ions is an important regulatory mechanism yet, it is poorly understood and often overlooked in favour of its thermoregulatory role. The regulation of ion

reabsorption is a fundamental research question that requires further consideration.

Furthermore, in recent years, there has been a drive to produce non-invasive techniques to inform us about the human condition, using sweat as the medium. As a result, the development of sensors to continuously measure sweat content is a rapidly growing field in biomedical engineering but our knowledge of sweat ion regulation is limited and this fundamental study adds to our knowledge. We provide further insight into the methodological considerations for future studies in this area. In particular, our research group has been accumulating consistent evidence of regional differences in ion reabsorption across the body and the current study suggests that these regional differences may not have been due to differences in $T_{sk}$ but rather structural or regulatory differences at the level of the sweat gland across the body. If $T_{sk}$ is expected to vary considerably then knowing the $T_{sk}$ is important. Consistent sensor placement in the same locations will allow for better comparisons between conditions and from different studies.

## Conclusion

Local $T_{sk}$ within physiological ranges of 30–33–36 °C only influenced the sweat gland maximum ion reabsorption rates during a passive heating protocol when local $T_{sk}$ differed by 6 °C (30 °C vs. 36 °C), whilst no differences were observed when local $T_{sk}$ differed by 3 °C (30 °C vs. 33 °C and 33 °C vs. 36 °C). These findings were observed when all other potential thermal and non-thermal controlling mechanisms were similar between conditions. Information from the literature and data from our study indicate that thermal controllers may exist but most probably from stronger thermal stimulus, such as mean $T_{sk}$ and/or $T_c$, compared to smaller changes ($\leq 3$ °C) in local $T_{sk}$. We provide important insights for previous studies that have reported regional differences in maximum ion reabsorption rates but have been unable to confirm such differences in the presence of differing local $T_{sk}$. The data provide useful information for furthering our understanding of sweat gland ion reabsorption and potential controlling mechanisms. The application of which may be useful in the fields of thermoregulation, hypo-/hypernatremia, dermatology and biosensor technology research.

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## Compliance with ethical standards

**Conflict of interest** The authors declare no conflicts of interest, financial or otherwise.

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