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Research paper

# Cutaneous thermosensory mapping of the female breast and pelvis

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ABSTRACT

Differences in skin thermal sensitivity have been extensively mapped across areas of the human body, including the torso, limbs, and extremities. Yet, there are parts of the female body, such as the breast and the pelvis for which we have limited thermal sensitivity data. The aim of this study was to map cutaneous warm and cold sensitivity across skin areas of the breast and pelvis that are commonly covered by female underwear. Twelve young females (21.9 ± 3.2 years) reported on a 200 mm visual analogue scale the perceived magnitude of local thermal sensations arising from short-duration (10 s) static application of a cold [5 °C below local skin temperature ($T_{sk}$)] or warm (5 °C above local $T_{sk}$) thermal probe (25 $cm^2$) in seventeen locations over the breast and pelvis regions. The data revealed that thermal sensitivity to the warm probe, but not the cold probe, varied by up to 25% across the breast [mean difference between lowest and highest sensitivity location was 51 mm (95% CI:14, 89; $p < 0.001$)] and up to 23% across the pelvis [mean difference between lowest and highest sensitivity location: 46 mm (95% CI:9, 84; $p = 0.001$)]. The regional differences in baseline $T_{sk}$ did not account for variance in warm thermal sensitivity. Inter-individual variability in thermal sensitivity ranged between 24 and 101% depending on skin location. We conclude that the skin across the female breast and pelvis presents a heterogenous distribution of warm, but not cold, thermal sensitivity. These findings may inform the design of more comfortable clothing that are mapped to the thermal needs of the female body.

## 1. Introduction

The sensation of temperature is a fundamental cutaneous sensory attribute that enables the experience of our surrounding thermal environment, and of the objects that contact our skin, such as clothing [1,2]. Differences in cutaneous thermal sensitivity exist in various body locations and have been extensively mapped, particularly across skin areas of the male and female body such as the torso, limbs, and extremities [3–5]. Yet, there are parts of the body such as the breast and the pelvis for which we have limited thermal sensitivity data. This is somewhat surprising considering that inputs from cutaneous thermoreceptors innervating these body regions play an important role in resting thermal comfort at rest [6], as well as in reproductive processes [7].

To date, only a few studies have mapped cutaneous thermal sensitivity over the female breast and pelvis. Terzis et al. [8] reported an uneven distribution of thermal sensitivity across the breast, as they observed that the lateral surface of the breast presents greater thermal sensitivity than the areola [8]. Yet, more recently, Luo et al. reported conflicting findings where a more homogenous distribution of cold and warm thermal sensitivity across six areas of the female breast were observed, although it should be noted that the areas tested did not include the areola [5]. Regarding thermal sensitivity differences between the breast and pelvis, Luo et al. have also reported that the buttock portion of the female pelvis is almost twice as cold- and warm-sensitive when compared to the breast [5]. However, Luo et al.'s mapping experiments did not include the anterior portion of the female pelvis [5]. Accordingly, the distribution of thermal sensitivity across this area of the female body remains largely unknown.

There has been comparatively more research that has investigated the sensitivity to light touch of the female breast and pelvis. Regarding the breast, we know that this is significantly more sensitive in females than males, yet this difference becomes apparent only post-puberty [7].

*Abbreviations:* ANOVA, Analysis of variance; $T_{sk}$, Skin temperature; VAS, Visual analogue scale.

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Regional differences to light touch within the breast exist, yet their intensity patterns vary with the menstrual cycle, following childbirth [7] and with breast size [9]. Furthermore, breast acuity to light touch has been recently shown to be poorer compared to other regions of the body (i.e. the hand and the back) with no differences detected between the outer and the medial breast [10]. Regarding differences in light touch sensitivity between the breast and pelvis, Cordeau et al. have shown that the vaginal margin has lower detection thresholds for light touch than the areola [11]. This observation indicated that the area of the pelvis with the primary genitalia is more sensitive than the breast [11], a finding which resembles Luo et al.'s reports on the greater thermal sensitivity of the buttock when compared to the breast [5].

Thermal sensations and comfort play a key role in the regulation of thermal behaviors [12] and females present more sensitive thermal behaviors than males [13]. While providing some insights into the distribution of thermal sensitivity of the female breast and pelvis, the literature highlights the need for more empirical data. This could provide more conclusive evidence on whether and to what extent an uneven distribution of cutaneous thermal sensitivity to both warm and cold is present across the skin of the female breast and pelvis. These insights could carry fundamental value, as they could support a better understanding of female cutaneous sensory function. Furthermore, this knowledge could also directly inform the design of more comfortable female underwear (e.g. bras and briefs), which is tailored to the unique needs of the female body [6,14,15]. The aim of this study was therefore to map the distribution of cutaneous thermal sensitivity to cold and warm stimuli across locations of the female breast and pelvis that are commonly covered by underwear. We hypothesized that both the breast and pelvis will present an uneven distribution of both cold and warm sensitivity, and that the pelvis would be more thermally sensitive than the breast.

## 2. Material and methods

### 2.1. Ethical approval

The testing procedure and the conditions were explained to each participant, and they all gave written informed consent for participation. The first part of the experimental data collection ($N = 10$) was performed at Loughborough University, where the study was approved by the Ethics Sub-Committee for Human Participants (#R19-P039). The second part of the experimental data collection ($N = 2$) was performed at the University of Southampton, where the study was approved by the Research Integrity and Governance team (ERGOII 72,799). All testing procedures were in accordance with the tenets of the Declaration of Helsinki (note: the study was not registered in a database).

### 2.2. Participants

We utilized recently published perceptual data on regional differences in thermal sensitivity across the body of females to estimate a minimum sample size for the current study [16]. Using an effect size $f = 4.3$ (i.e. calculated from a 13% mean difference in cold sensitivity between the forehead and the foot), an $\alpha = 0.05$, and power = 0.95, we estimated a minimum sample of 10 participants. Accordingly, 12 non-smoking, recreationally active (i.e. >3 exercise sessions per week) young female adult participants (21.9 ± 3.2 years; 22.7 ± 1.5 BMI) with no history of cardiovascular, neurological and skin-related conditions (e.g. eczema), were recruited from the student population of the local universities. We did not control for menstrual phase based on preliminary evidence that thermal sensation in females may not be independently modified by menstruation [17]. Nevertheless, we collected participants' self-reports of the corresponding day of the menstrual cycle they were in at the time of testing. Participants were spread across a typical 28-day menstrual cycle (mean day of cycle: 15.7 ± 8.3) and only one participant presented irregular periods at the time of the study. Participants were instructed to refrain from: (i) performing strenuous exercise in the 48 h preceding testing; (ii) consuming caffeine or alcohol in the 24 h preceding testing; and (iii) consuming food in the 3 h preceding testing.

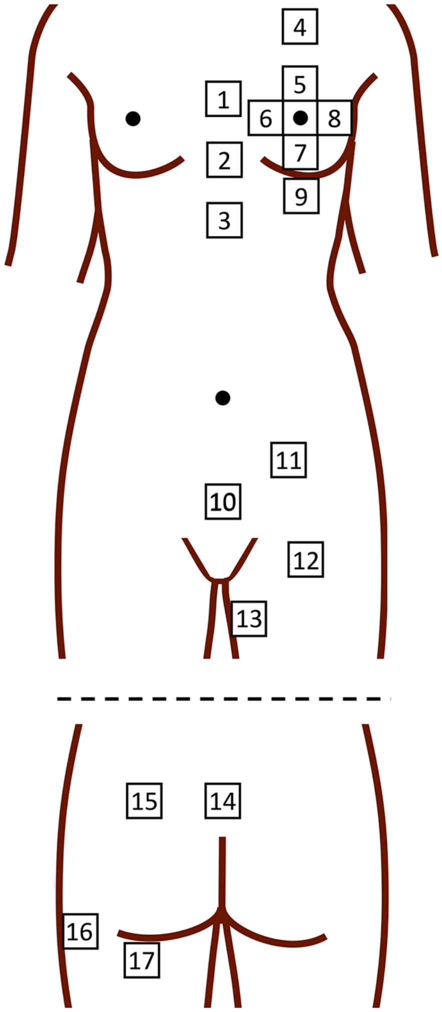
### 2.3. Experimental design

We used a single-blind psychophysical approach based on a well-established quantitative sensory test of skin temperature sensing that has been previously published [16] to map differences in regional thermal sensitivity at rest and in a thermoneutral environment (ambient temperature: 23 °C; relative humidity: 45%). All participants took part in two separate experimental sessions, during which we performed the same quantitative sensory test, using either a cold or a warm stimulus. The quantitative sensory test involved participants reporting the perceived magnitude of local thermal sensations arising from the short-duration (i.e. 10 s) of a static application of cold [(i.e. 5 °C below local skin temperature) ($T_{sk}$)] or warm (i.e. 5 °C above local $T_{sk}$) temperatures delivered through a hand-held temperature-controllable probe (surface area: 25 $cm^2$). Testing was performed on seventeen different locations over the left breast (9 locations) and left pelvis (8 locations) and each of the thirty-four combinations (i.e. stimulus/site) was presented only once to each participant. These locations were chosen to provide a detailed overview of skin regions that would be commonly covered by female bras and shorts (Fig. 1).

Participants reported the magnitude of their local perceptions on a digital Visual Analogue Scale (VAS) for thermal sensation (length 200 mm; anchor points: 0, very cold; 100, neutral; 200, very hot). We used stimuli whose temperatures were relative to the local $T_{sk}$ pre-stimulation (i.e. ± 5 °C to local $T_{sk}$) to account for the expected regional differences in local $T_{sk}$ as previously shown [16]. In this way, we ensured that the same relative thermal stimulus would be applied on each area of the body irrespective of baseline values [note: the difference between the temperature of a stimulus and that of the skin is an important determinant in the magnitude of a resulting thermal sensation (i.e. the greater the difference, the more intense the sensation) [18]. In line with previous studies, all participants were blinded to the nature and application of the stimuli to limit expectation biases, and they were only informed about the location of the stimulation [4,16,19,20]. Furthermore, participants underwent a systematic familiarization and calibration to the testing procedures and perceptual scales prior to testing [4,20]. The same investigator performed all testing.

### 2.4. Experimental protocol

Participants arrived at the laboratory on testing days and underwent preliminary measurements and preparation. We assessed their body mass on a precision scale (Model 874; Seca GmbH, Hamburg, Germany) and their height on a wall stadiometer. They were asked to be partially clothed, wearing only minimal briefs and adhesive nipple shields covering the areola. At this point, we used a washable marker to denote the skin sites to be stimulated using a reference framework based on specific anatomical landmarks (Fig. 1). Following this preparation, participants underwent 15 min of resting on a chair to adjust to the environmental conditions (ambient temperature: 23 °C; relative humidity: 45%). During this time, participants were familiarized with the experimental procedures, and calibrated to the VAS. Calibration procedures were based on those previously described by Valenza et al. and consisted of the following: Five stimuli varying in temperature were applied to the volar surface of the right forearm (i.e. midpoint between wrist and antecubital fossa) in a randomized order, and participants were instructed to associate each stimulus to a specific descriptor on the thermal scale. The stimuli and related descriptors were: (i) 10 °C above local skin temperature – scale descriptor: Very hot; (ii) 5 °C above local skin temperature – scale descriptor: midpoint between Neutral and Very hot; (iii) equal temperature as local skin temperature – scale descriptor:




| | |
|---|---|
| 1 | Centre of the sternum |
| 2 | Xyphoid process |
| 3 | 5 cm below point 2 |
| 4 | 5 cm above point 5 |
| 5 | 3 cm above the nipple |
| 6 | 3 cm to the right of the nipple |
| 7 | 3 cm below the nipple |
| 8 | 3 cm to the left of the nipple |
| 9 | 10 cm to the left of the mid-point between 2 and 3 |
| 10 | 15 cm below the umbilicus |
| 11 | 5 cm away from point 10 on the diagonal connecting 10 and the anterior superior iliac crest |
| 12 | 11 cm below the anterior superior iliac crest, over the thigh mid-line |
| 13 | 4 cm below 12, over the mid-line of the inner thigh |
| 14 | 2 cm above the intergluteal cleft |
| 15 | 15 cm to the left of 14 |
| 16 | Over greater trochanter |
| 17 | Below point 15, under the gluteal fold |

**Fig. 1.** Anatomical landamrks of the 17 locations tested.

Neutral; (iv) 5 °C below local skin temperature – scale descriptor: midpoint between Neutral and Very cold; and (v) 10 °C below local skin temperature – scale descriptor: Very cold [16]. This procedure ensured that all participants had comparable experiences of the different stimuli and related perceptual anchor points to be used during testing. Subsequently, the quantitative sensory test commenced and was executed by first recording the local $T_{sk}$ of the testing site with an infrared thermometer (Spot IR Thermometer TG54; FLIR Systems, Wilsonville, OR, USA). This was used to determine the temperature of the first stimulus (e.g. cold, 5 °C below local $T_{sk}$) and following a verbal warning, the stimulus was applied statically on the participant's skin for 10 s, during which the participant was encouraged to rate their very first thermal sensation. Application pressure was not measured but was controlled to be sufficient to ensure full contact, at the same time not resulting in pronounced skin indention. Upon acquisition of the perceptual rating, we removed the stimulus, and then repeated the same procedure for the other skin sites. The order of testing session (i.e. warm vs. cold) and site (i.e. skin region) was based on a randomized cross-over design to minimize order effects.

### 2.5. Statistical analysis

Physiological and perceptual data were tested for normality of distribution (Shapiro-Wilk test). Variations in baseline local $T_{sk}$ were analyzed for the independent effects of skin location (17 levels) and experimental session (2 levels, prior to warm vs. prior to cold stimuli application) by means of two-way repeated measures ANOVAs. Variations in thermal sensations were analyzed for the independent effects of skin location (17 levels) and thermal quality (2 levels, warm vs. cold stimulus) by means of two-way repeated measures ANOVA. To facilitate the comparison between warm and cold sensations, sensation data were transformed to fit a range of 0–100, where 0 corresponded to Neutral and 100 to Very Cold/Very Hot. In the event of statistically significant main effects or interactions, post hoc analyses were conducted with Sidak's tests.

To quantify interindividual variability in local thermal sensations within the breast and pelvic locations, coefficients of variation were calculated as the ratio between standard deviation and mean thermal sensation values ($N = 12$) and for each skin location for both warm and cold stimuli. Data were summarized into heat maps to display skin locations of the breast and pelvis with high and low interindividual variability in local thermal sensation.

We assessed the association between local Tsk and thermal sensation separately for cold and warm stimuli by means of Pearson correlation, to determine whether regional variation in thermal sensitivity would be associated with regional variations in local Tsk. Finally, a correlation analysis between warm and cold thermosensitivity across all skin site tested was performed.

Data are reported as the means, SD and 95% confidence intervals (CIs). Observed power was computed using $\alpha = 0.05$. Statistical analysis was performed using Prism, version 9.0 (GraphPad Software Inc., La Jolla, CA, USA).

## 3. Results

### 3.1. Regional variation in baseline $T_{sk}$

Baseline $T_{sk}$ values were normally distributed and varied significantly across skin locations (main effect: $F_{16,176} = 28.7$; $p < 0.001$; ~31% of total variation), with minimal differences between experimental sessions ($F_{1,11} = 4.8$; $p = 0.051$; 2% of total variation) (Fig. 2). Over the breast, location 6 presented the lowest (i.e. mean: 31.3 °C) and location 9 the highest local $T_{sk}$ (i.e. mean: 33.6 °C). Over the pelvis, site 16 presented the lowest (i.e. mean: 29.5 °C) and site 11 the highest local $T_{sk}$ (i.e. mean: 32.2 °C). Statistical significance values for multiple location comparisons are accessible as Electronic Supplementary Material at https://doi.org/10.5258/SOTON/D2515.

### 3.2. Regional variation in thermal sensations

Regarding thermal sensation, data were normally distributed, and we found an interaction between skin location and thermal quality (interaction: $F_{16,176} = 4.9$; $p < 0.001$; ~9% of total variation), which indicated that regional differences were present, yet they were dependent on thermal quality (i.e. warm vs. cold sensitivity). Specifically, we found that thermal sensitivity to warm (Fig. 3A), but not cold (Fig. 3B), varied across skin locations.

Over the breast, location 2 presented the lowest (i.e. mean: 29 mm) and location 9 the highest warm sensitivity (i.e. mean: 80 mm). The mean difference between locations 2 and 9 was 51 mm (95% CI:14, 89; $p < 0.001$) which corresponded to a ~25% difference in warm sensitivity (Fig. 3A). Over the pelvis, location 16 presented the lowest (i.e. mean: 26 mm) and location 11 the highest warm sensitivity (i.e. mean: 73 mm). The mean difference between locations 16 and 11 was 46 mm (95% CI:9, 84; $p = 0.001$) which corresponded to a 23% difference in warm sensitivity (Fig. 3A).

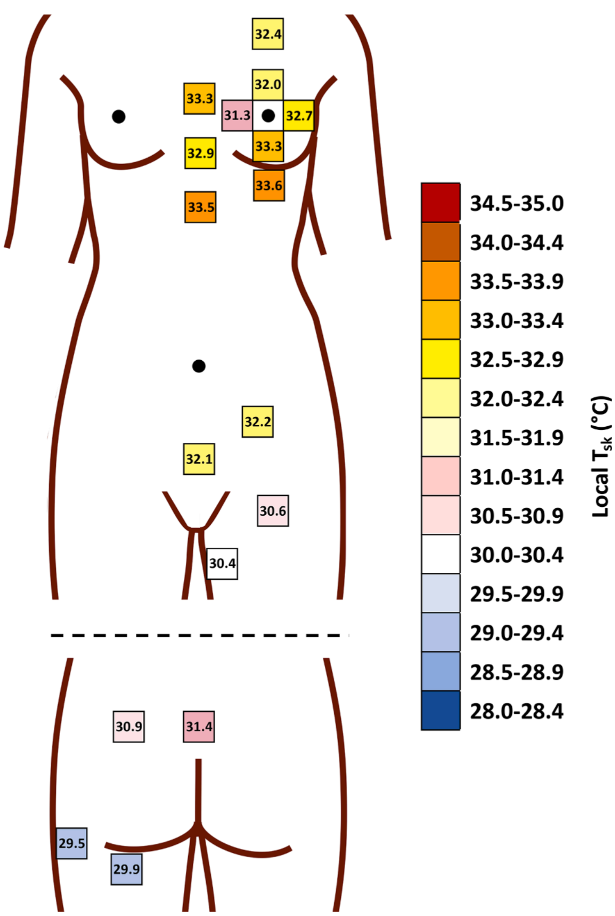



**Fig. 2.** Mean ($N = 12$) baseline $T_{sk}$ for the 17 locations tested (note: data were collapsed over experimental session). Statistical significance for multiple location comparisons are listed in Electronic Supplementary Material.

Differences in warm sensitivity followed a medio-lateral pattern of increase across the breast (compare locations 2 vs. 4, 7 & 9; Fig. 3A), and a latero-medial pattern of increase across the pelvis (compare locations 16 vs. 10, 11 & 17; Fig. 3A).

When considering warm sensitivity differences between the breast and pelvis, we found that these body areas presented similar ranges of sensitivity. Indeed, we found no differences between neither the highest sensitive locations of breast (location 9) and pelvis (location 11) (mean difference: 7 mm (95% CI: -30, 45; $p > 0.99$), nor between the lowest sensitive locations of breast (location 2) and pelvis (location 16) (mean difference: 2 mm (95% CI: -35, 40; $p > 0.99$). Statistical significance values for multiple location comparisons are accessible as Electronic Supplementary Material at https://doi.org/10.5258/SOTON/D2515.

### 3.3. Regional variation in inter-individual variability

Inter-individual differences in thermal sensitivity varied largely across skin sites (Fig. 4). Regarding the breast, inter-individual variability reached a minimum of 24% (location 9) and a maximum of 80% (location 2) for warm stimulation, and a minimum of 33% (location 5) and maximum of 101% (location 7) for cold stimulation. Regarding the pelvis, inter-individual variability reached a minimum of 35% (location 11) and a maximum of 92% (location 16) for warm stimulation, and a minimum of 41% (location 17) and a maximum of 76% (location 15) for cold stimulation.

### 3.4. Relationship between baseline $T_{sk}$ and thermal sensations

We found a statistically significant negative association between baseline $T_{sk}$ and cold sensations (Pearson $r = -0.64$; 95%CI: -0.86, -0.23; $p = 0.006$). Yet, we found no statistically significant association between baseline $T_{sk}$ and warm (Pearson $r = 0.39$; 95%CI: -0.11, 0.73; $p = 0.125$).

### 3.5. Relationship between overall cold and warm thermosensitivity

We calculated a Person correlation coefficient to evaluate the strength of the association between cold and warm thermal sensitivity. We found that correlation was low, i.e. Pearson $r = 0.22$; 95% CI: 0.09, 0.35; $p = 0.001$, indicating that skin sites of greater warm sensitivity did not always present a greater cold sensitivity.

## 4. Discussion

Our study provides detailed maps of the distribution of warm and cold thermal sensitivity across seventeen locations of the breast and pelvis of healthy young females. Overall, our findings indicated that these regions of the female body present a heterogenous distribution of warm, but not cold, thermal sensitivity. Within each region, we found highly warm sensitive skin locations (i.e. see location 9 on the breast and location 11 on the pelvis, Fig. 3A), and these locations showed inherently low inter-individual variability (see Fig. 4). The range of warm sensitivity (i.e. highest and lowest sensitive locations) was comparable between the breast and pelvis, suggesting that, overall, these regions present similar levels of warm sensitivity. Finally, we found that variations in baseline $T_{sk}$ across the breast and pelvis were not associated with variations in warm thermal sensations. This finding indicated that factors other than local $T_{sk}$ (e.g. skin morphology, thermoreceptor density) may be at play in driving the observed differences in warm sensitivity.

The first relevant finding of our study is that, while we observed an uneven distribution of sensitivity across the female breast, this was thermal-modality dependent (i.e. warm sensitivity only). This observation sits in between the observations of Luo et al. (2019) and Terzis et al.

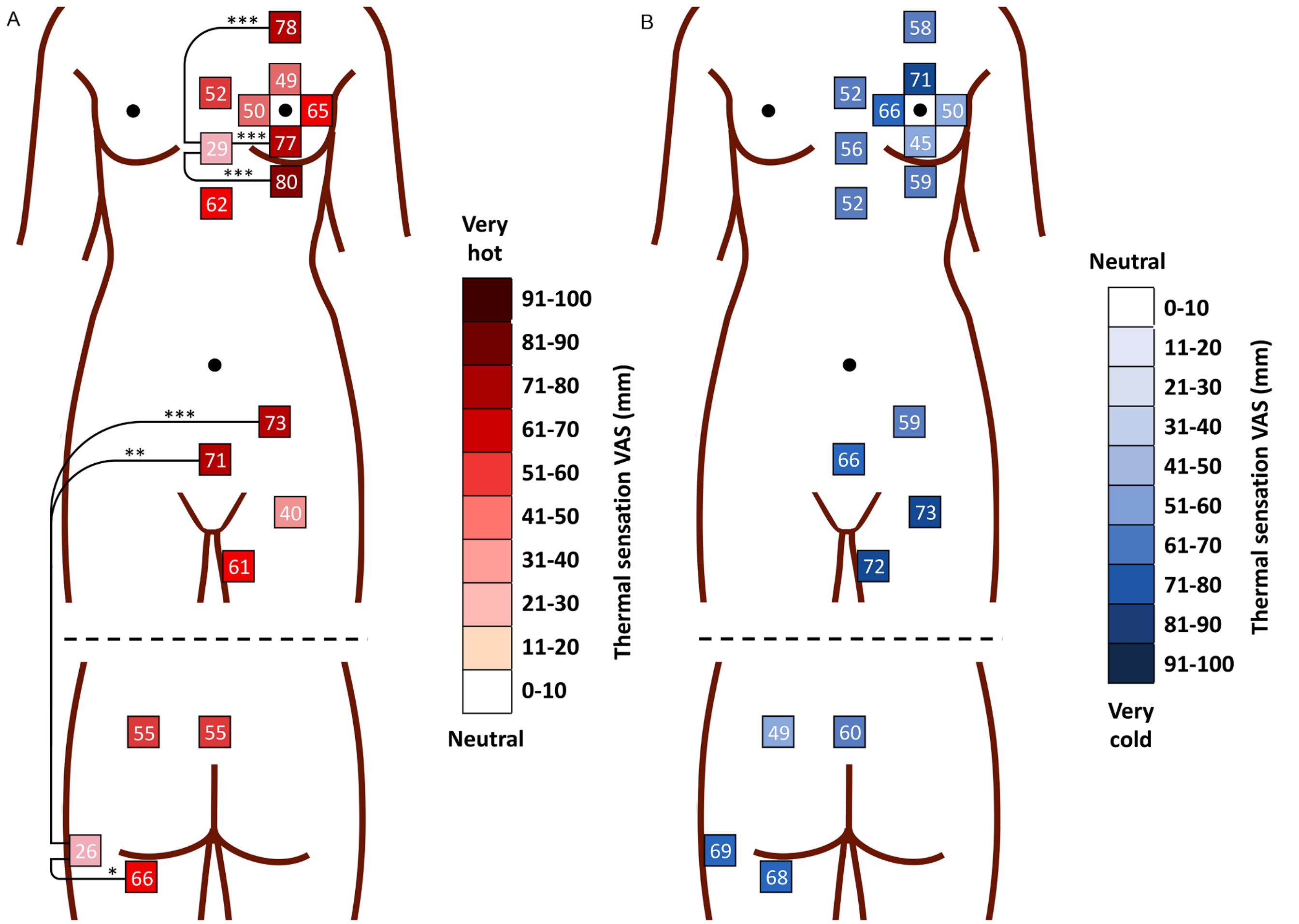



**Fig. 3.** Mean ($N = 12$) warm (A) and cold (B) sensitivity for the 17 locations tested. Statistically significant multiple comparisons are picture (*$p<0.05$; **$p<0.01$; ***$p<0.001$). Statistical significance values for multiple location comparisons are listed in Electronic Supplementary Material.

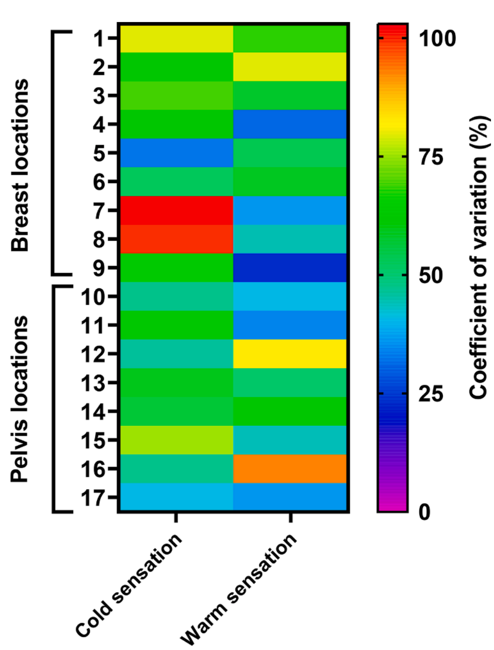



**Fig. 4.** Coefficient of variations (%) for both cold and warm sensations and for each of the 17 locations tested.

(1987), who have reported the absence and presence of differences in thermal sensitivity across the breast, respectively [5,8]. The difference between our findings and those of Luo et al. [5] could be potentially ascribed to the size of the skin locations stimulated. Indeed, our 25 $cm^2$ thermal probe covered a significantly greater proportion of skin than the round 1.32 $cm^2$ thermal probe used by Luo et al. [5] to map thermal sensitivity. Spatial summation in the thermal sense exists and it explains why, given the same thermal stimulus, stimulating a larger portion of skin induces more intense thermal sensations [21,22]. Accordingly, one could speculate that, if the distribution of warm sensitive spots and thermoreceptors is uneven across the female breast (as it is the case across other body parts) [2], stimulating very small skin areas may reduce the resolution of detecting regional differences [21]. Consider for example two locations of high and low thermoreceptor density. For these locations, thermal sensitivity differences are likely to be more pronounced if one engages a larger proportion of the thermoreceptors that innervate them. As thermoreceptor activity is spatially summed, "engaging" more receptors under a larger stimulation area will likely result in a more intense sensation [22], thereby unmasking regional differences that may otherwise go undetected if smaller stimuli are used.

When compared to the findings of Terzis et al. [8], our findings agree with the presence of thermal sensitivity differences across the breast; yet we show an inverse pattern of sensitivity, with warm sensitivity increasing as one move from medial to lateral locations across the female breast (see Fig. 3A). Direct comparisons with the study of Terzis et al. [8] should be made with caution, given that, contrary to those authors, we did not test the areola (i.e. a location Terzis et al. [8] found to have low thermal sensitivity). Yet, if one does not consider the areola, it remains to be established why such a medio-lateral pattern of warm sensitivity would be present across the female breast. Interestingly, this warm sensitivity pattern mirrors what is reported on regional sweat rates across the female breast by Smith et al. [14]. In their body maps, these authors reported the "bra triangle", a part of the female chest analogous to location 2 in the present study, to have greater local sweat rates than the lateral "upper and lower bra", i.e. locations analogous to locations 7 and 8 in the present study [14]. This inverse pattern of sudomotor vs. perceptual sensitivity is in contrast with what was reported by Cotter and Taylor [23], who showed that sudomotor and discomfort sensitivities often share similar regional patterns. However, the female breast was not considered in Cotter and Taylor's study [23]. Hence, the extent of reproducibility of the inverse relationship between sudomotor and warm sensitivity across the breast requires further investigation.

Regarding the pelvis, our findings support and expand those of Luo et al. [5]. Indeed, we found the base of the buttock to be particularly warm sensitive (see location 17, Fig. 3A). Furthermore, we found the anterior portion of the pelvis to present a similarly high warm sensitivity to the posterior pelvis, particularly when considering location 10, which also represented the closest area to the primary genitalia that we tested. Finally, we did not find the pelvis to present greater thermal sensitivity than breast, as Luo et al. had previously reported [5]. We believe the considerations we made earlier on the methodological differences in the size of our contact stimuli also applies to this apparent discrepancy in results.

It is also particularly noteworthy that we observed regional differences in warm but not cold sensitivity on both the breast and pelvis. We have long known that the skin has a greater cold than warm sensitivity [2]; as a result, regional cold sensing is often reported to be more heterogenous across the body [3,16] and to also show lower inter-individual variability than warm sensing [4]. However, our current findings indicate the opposite, that is, warm sensitivity had greater heterogeneity, and lower inter-individual variability, than cold sensing both within and between the female breast and pelvis.

It is important to consider some of our female-centered findings in the context of sex-related differences in thermosensation. For example, Luo et al. [5] recently observed that most of the differences in thermal sensitivity between body-surface-area matched males and females occurred at the chest/breast area and in response to both warm and cold stimuli only. Specifically, women appeared to be more cold and warm-sensitive than men on this body part [5]. Whilst the functional implication of this breast-specific heighted sensitivity remains unclear [24], this observation further highlights the unique thermosensory features of the female breast when compared to men.

With regard to the inter-individual variability, one potential explanation for such unexpected findings is that the observed greater inter-individual variability in cold sensing across the regions tested could have reduced our statistical power to detect consistent regional differences in cold sensitivity. We believe that this observation constitutes a finding in its own right, as this indicates that inter-individual variability in breast and pelvis sensitivity to cold is likely to be much higher than what previously reported on other body parts such as the torso, limbs, and extremities [3–5].

This functional observation is supported by anatomical evidence from cadaver dissections, which have confirmed greater between, rather than within, subject variation in cutaneous innervation of the breast [25]. It is important to note that this could also be related to differences in breast volume amongst women, as indicated by Longo et al. for touch sensitivity of nipple-areola complex [9]. However, further evidence is required to determine whether and why individual variability in breast innervation would present a thermal modality-specific pattern (i.e. greater variability for cold than warm nerve fiber innervation). It is plausible that intrinsic factors, including innervation patterns and density of thermoreceptors, could play a role in our observed patterns of sensitivity. Evidence by Peters et al. indicates that in the context of mechanosensation differences in the size of a body part (e.g. smaller vs. larger fingers) account for differences in tactile spatial acuity, likely due to size-dependent changes in receptors' density (i.e. given a fixed number of receptors innervating a body part, the larger the body part, the lower the receptors' density) [26]. It could therefore be speculated that a similar phenomenon may apply to breast thermosensation, whereby a larger breast would be inherently less sensitive, due to a lower density of receptors per square cm. This is also supported by the fact that we found no association between variations in local $T_{sk}$ and resulting warm sensations. We recognize that this study did not measure breast volume and pelvis size. As morphological variations in these areas may also influence their local sensitivity, future studies should consider evaluating the independent effects of different breast and pelvis sizes on thermal sensitivity.

Another explanation for the variability seen in thermal sensation could be partly due to the effect of the menstrual cycle. As noted in the Methods, we collected participants' self-reports of the corresponding day of the menstrual cycle they were in at the time of each test. This data was used to perform a pilot analysis of the impact of menstrual cycle phase on the inter-individual variability to cold sensitivity in our sample, using a previously described method (i.e. z-transformation) to assess sensory loss or gain in individual patients with MS [27]. This pilot analysis indicated for those tests performed when participants were in the follicular phase of their self-reported menstrual cycle (i.e. days 1–14) a greater variation in cold sensitivity (i.e. both increase and decrease in sensitivity) was present when compared to those tests that were performed when participants were in the luteal phase of their self-reported menstrual cycle (i.e. 15–28). This qualitative observation highlights the need for future research to investigate the impact of female hormones on local skin thermal sensitivity and individual variability, and the impact that this could have on thermoregulatory behaviors. Finally, we note that our assessments were conducted under resting conditions, and this provided a controlled condition to evaluate thermal sensitivity patterns. Yet, our findings may vary with individual levels of activity, as we have previously shown that thermal hypo-aesthesia can occur following on maximal running exercise [16]. Accordingly, future studies should consider investigating whether and to what extent the specific patterns of thermal sensitivity we report may be attenuated following on different exercise intensities, as this may inform the design of activewear for females.

## 5. Conclusions

We show the female breast and pelvis present a heterogenous distribution of warm, but not cold, thermal sensitivity. Fundamentally, our results indicate that mechanisms intrinsic to the thermosensory function of the skin, including cutaneous innervation density, and their within and between subject variability, may underlie some of the observed thermal sensitivity patterns. Future thermosensory mapping of the female body should therefore consider individualized analyses approaches. From an applied standpoint, we provide detailed maps of the distribution of warm and cold thermal sensitivity across female breast and pelvis areas commonly covered by bras and shorts. Accordingly, these findings may guide the design of more comfortable, sex-specific clothing that are mapped to the thermal needs of the female body.

## Authors' contributions

A.V., A.B., D.F., and P.W. conceived and designed the research. C.M., H.B., and J.W. collected the experimental data. A.V. analyzed the data and drafted the manuscript. All authors revised the manuscript for intellectual content and approved the submitted version.

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## Declaration of Competing Interest

DF has received consultancy fees from Nike Inc. and lululemon atletica.

## Data availability

We have deposited the supplementary material in our institutional repository, and a DOI has been assigned: https://doi.org/10.5258/SOTON/D2515.

## Acknowledgement



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