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High-density thermal sensitivity maps of the human body

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ABSTRACT

'Personal comfort systems' and thermally active clothing are able to warm and cool individual building occupants by transferring heat directly to and from their body surfaces. Such systems would ideally target local body surfaces with high temperature sensitivities. Such sensitivities have not been quantified in detail before. Here we report local thermal sensations and sensitivities for 318 local skin spots distributed over one side of the body, measured on a large number of subjects. Skin temperature changes were induced with a thermal probe 14 mm in diameter, and subjective thermal sensations were surveyed after 10 seconds. Our neutral base temperature was 31°C and the spot stimulus was ±5°C. Cool and warm sensitivities are seen to vary widely by body part. The foot, lower leg and upper chest are much less sensitive than average; in comparison, the cheek, neck back, and seat area are 2-3 times as sensitive to both cooling and warming stimuli. Every body part exhibits stronger sensitivity to cooling (1.3–1.6 times stronger) than to warming. Inter-personal differences and regional variance within body parts were observed to be 2-3 times greater than potential sex differences. These high-density thermal sensitivity maps with appended dataset provide the most comprehensive distributions of cold and warm sensitivity across the human body.

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KEYWORDS

thermal sensitivity; thermal comfort; personal comfort system; wearable comfort devices

NOMENCLATURE

ANOVA	analysis of variance
BMI	body mass index
BSA	body surface area
C	cooling sensitivity
PCS	personal comfort systems
r	Pearson correlation coefficient
R^2	coefficient of determination
SD	standard deviation
TSV	thermal sensation vote
T_{sk}	skin temperature
ΔT_{sk}	skin temperature difference
W	warming sensitivity

1 INTRODUCTION

1.1 Background

The thermal sensations elicited by skin surface temperatures are a primary input to our sensing the surrounding environment, and our judging whether we are comfortable [1,2]. The skin's warm and cool sensitivities determine the thermal sensations experienced at different temperatures. They are important for the design of heating and cooling systems, especially those that condition local body parts via radiant beams, jets of air, or by contact with warmed or cooled conductive surfaces. Such systems include personal comfort systems (PCS) in furniture such as chairs, desks, and workstations [3,4], wearable comfort devices [5], and sport and protective clothing [6]. They serve both to mitigate thermal discomfort and to induce positive sensations of thermal pleasure through heating or cooling [7]. Designers of such systems would benefit from knowing the sensitivity of different parts of the body surface in order target the more sensitive ones.

1.2 Thermal sensitivity of the skin

Physiologies related to thermal sensitivity have been mapped in the past, such as the location of thermal sensory neurons in the skin [8], skin temperature distributions [9], and sweating patterns [10]. Researchers have also measured thermal sensitivity of the human skin for various purposes, in studies summarized in Table 1. The earliest studies detected and mapped the distribution of thermally sensitive spots in the skin. Contact stimulators (thermodes) with controlled tip temperatures and tiny diameters (around 1-2.5 mm) were applied to neighboring points within a small surface area of a body part. Melzack et al. [11] mapped the distribution of sensitivity within 5×5 cm areas on the back and forearm using a 2.5mm diameter round stimulator tip. They found skin sensitivity to cooling and warming stimuli to be distributed in relatively large sensory fields rather than in isolated spots. Subsequent researchers stimulated larger skin surface areas by applying radiant heating [12,13]. They found that both the irradiation level and the area of the stimulated surface contributed to the magnitude of the warm sensation, which they termed the 'spatial summation effect' [13]. In recent studies [14–16], larger contact stimulators have been used to test thermal perception and pain thresholds across various body parts, observing large differences in these variables among the parts. Stevens and Choo [16], in mapping cooling and warming perceptional thresholds for young, middle-aged and elderly adults, found that these thresholds vary 10- to 100-fold over the body surface, depending on age.

The most detailed sensitivity mapping are from [17–19], where the authors tested 31 locations using a 25 cm^2 stimulus probe studying sensitivity under rest and exercise on males and females. Li et al. [20] measured thermal sensitivity at high density with 23 spots on the palm. Our previous study used a heating and cooling stimulus probe of 1.54cm^2 for comparing the sensitivity of glabrous and hairy skin, and the data was used in the design of a thermally conditioned insole [4].

1.3 Objective

For the purpose of designing personal comfort systems, wearables, and clothing, existing sensitivity data is either not dense enough or is focused only on a few body parts [17]. This study aims to describe the distribution of thermal sensitivity across the entire body (assuming

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that thermal sensitivity is symmetrically distributed over the left and right body halves) at a high enough resolution to be used for locating specific areas of thermal input or extraction. It also intended to quantify the extent of sex differences, and add to knowledge about inter- and intrapersonal variation in warm and cool sensitivity. -

Table 1 A summary of human body thermal sensitivity studies

Year	Year	Stimulators	Stimulated surface area (cm²)	Test conditions	Test spots in the various body segments: Forehead	Cheek	Neck	Shoulder	Chest	Abdomen	Back	Upper arm	Forearm	Buttock	Thigh	Lower leg	Palm	Dorsum	Sole	Foot dorsum	**Total test spots**
Melzack et al. [11]	1962	Tip type stimulator	0.05	Warmth and cold							—		—								—
Nadel et al. [12]	1973	Irradiation	300~1000	Warmth	1				1	1		1	1		1	1					7
Stevens et al. [13]	1974	Irradiation	3.7~22	Warmth	1	1		1	1	1	1	1	1		1	1					10
Meh et al. [14]	1994	Contacting surface	12.5		1				1	1		1	1		1	1	1			1	9
Stevens et al. [16]	1998	Contacting surface	4.84	Warmth and cold	1	2				1	1	1	1		1	1	1	1	1	1	13
Norrsell et al. [8]	1999	Contacting surface	3.75	Warmth and cold																	
Nakamura et al. [15]	2008	Contacting surface	270	Warmth and cold	1	1			1	1					1						5
Li et al. [20]	2008	Contacting surface	2	Warmth and cold													23				23
Ouzzahra et al. [21]	2012	Contacting surface	25	Cold					4	2	6	2	2								16
Gerrett et al. [18]	2014	Contacting surface	25	Warmth	1	1	2		4	3	7	2	2		4	3	1	1			31
Gerrett et al. [19]	2015	Contacting surface	25	Cold	1	1	2		4	2	6	2	2		4	3	1	1			29
Filingeri et al. [17]	2018	Contacting surface	1.32	Warmth and cold													24	25	23	22	104
Current study		Contacting surface	1.32	Warmth and cold	35		30		12	13	14	24	28	14	28	16	24	25	23	32	318

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2 METHODS

The testing was carried out in the Center for the Built Environment (CBE), University of California, Berkeley climate chamber where temperature and humidity were maintained at 25°C and 40%, a neutral condition for the subjects and their clothing. The test protocol was reviewed by University of California Berkeley's Committee for the Protection of Human Subjects, and awarded approval number 2015-08-7882.

2.1 Participants

Because of the length of the tests, we planned the measurements in three groups of body segments, each represented by a particular group of subjects. All subjects met uniform recruitment criteria. Their profiles are given in Table 2. They were all college students or junior researchers living in the Berkeley area (California, USA) for at least 3 months prior to the test. They all had light-to-none caffeine, alcohol, smoking habits – less than 2 cups of coffee or 2 cigarettes a day, and normal exercise intensity with 2-4 times per week.

Both sex groups had similar proportion of ethnicities. Male subjects included 13 Caucasian, 13 Asian, 4 Hispanic, and 2 others, while female subjects had 15 Caucasian, 14 Asian, 4 Hispanic, and 3 others. The female subjects were evenly distributed across a typical 28-day menstrual cycle (mean day = 13.4; SD = 7.8).

We informally selected subjects to reduce the difference in body surface areas (BSA) between the sexes (using larger women, smaller men). The number of test points in a given body part (and therefore its stimulated area) is the same for the sexes. Since the sensation is be proportional to the relative area of stimulation [13,18], matching the surface area of both sexes helps ensure that similar proportions of their surfaces are directly stimulated by the area of the thermal probe (see Table 2*"proportion of BSA stimulated (%)"* column), reducing the confounding effect of body size on sex differences. Each subject's body surface area was calculated following the Du Bois method [22]. Then, a proportion was defined as the ratio between stimulus probe surface area (1.54 cm^2) and BSA. Statistical differences between groups for each characteristic were assessed by independent group t-tests. The BSA for the two sexes in each subject group were not significantly different from each other.

Table 2 Subjects' profile.

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	Tested areas	Sex	Age (year)	Mass (kg)	Height (m)	BSA (m^2)	Proportion of BSA stimulated (%)
Group 1 (142 test spots)	Face, upper arm, chest, abdomen, buttock, thigh, lower leg	Male (n = 14)	22.3 ± 3.4	68.9 ± 8.1	1.70 ± 0.07	1.79 ± 0.12	0.0074 ± 0.0003
		Female (n = 18)	23.7 ± 3.7	62.0 ± 4.9	1.67 ± 0.08	1.70 ± 0.06	0.0078 ± 0.0005
		Probability (*P*)	0.248	***0.013***	0.35	0.054	0.065
Group 2 (104 test spots)	Hand dorsum, palm, foot dorsum, sole [17]	Male (n = 8)	30.2 ± 5.8	67.8 ± 13.4	1.69 ± 0.1	1.77 ± 0.2	0.0076 ± 0.0009
		Female (n = 8)	27.7 ± 5.1	58.0 ± 5.4	1.67 ± 0.08	1.64 ± 0.1	0.0081 ± 0.0005
		Probability (*P*)	0.381	0.076	0.546	0.076	0.184
Group 3 (72 test spots)	Neck, back, forearm	Male (n = 10)	29.3 ± 6.2	66.6 ± 11.6	1.72 ± 0.07	1.75 ± 0.16	0.0076 ± 0.0007
		Female (n = 10)	21.5 ± 1.2	58.3 ± 7.3	1.62 ± 0.06	1.62 ± 0.11	0.0082 ± 0.0005
		Probability (*P*)	***0.003***	0.065	***0.004***	0.16	0.17

2.2 Test Spots

The spot heating and cooling stimuli were applied to 318 spots, over the left half of the whole body, front and back. Figure 1 shows an overall picture of the test spots from front and back views of the body, and the number of test spots for each body area. The following body areas were tested: the face, neck ventral, neck dorsal, chest, abdomen, back, upper-arm, forearm, palm, dorsum of hand, buttock, thigh, lower leg, sole, dorsum of foot. We repeated our previous testing of the foot sole and dorsum [17] at the same spot locations as before, using a stronger heating and cooling stimulus level (± 7°C vs ± 5°C). So, we tested 15 body parts in total, with two of them at additional higher stimulus levels. As shown in Figure 1, the density and anatomical location of the test spots were selected to provide uniform coverage at high density, with increased density for the small but thermally important body parts: hands, feet, neck, and face. Detailed descriptions of test spots can be found in Appendix A.

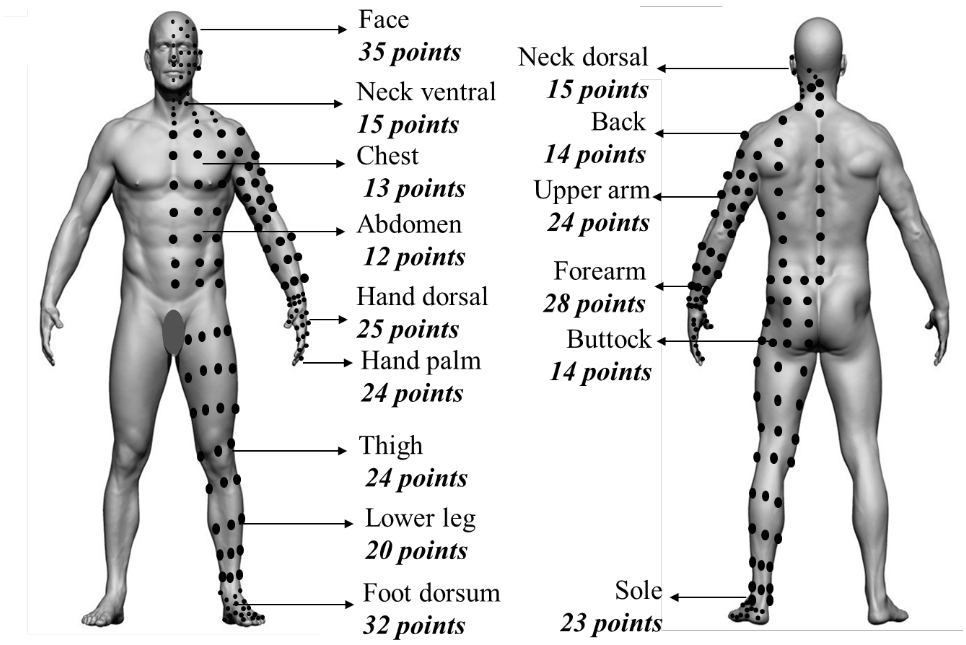

Figure 1. Distribution of test spots. All the spots were medial or on the left side of the body, assuming symmetry [14].

2.3 Experimental apparatus

The test apparatus was almost identical to that of our previous study described by Filingeri et al.[23]. We summarize it here. Figure 2 depicts the apparatus employed in the test, and Fig.2A shows the thermal probe with its 1.54 cm^2 surface area (14 mm diameter, NTE-2A, Physitemp Instruments Inc., USA). The temperature of the probe surface can be precisely controlled within a range of 15-45°C within 0.1°C accuracy, with a response rate of 2.43°C/s.

We monitored the temperature changes at the interface between the skin and thermal probe before, during, and after the application of each heating/cooling stimulus. In order to read the spot skin temperature (T_{sk}) induced by the probe, a 0.6mm diameter spherical Type T thermocouple bead was centered on the probe surface. It has a 0.7 sec time constant and was read by a BAT-12 Microprobe Thermometer (accuracy of ±0.1°C between 0-50°C; Physitemp Instruments Inc., USA). We judge that half of the sphere's surface area is in direct contact with the skin into which it is pressed, while the contact area between the spherical bead and the planar steel probe surface is very small.

We made two changes from our previous study [25]: 1) we increased the stimulation time prior to sensation measurement from 5 seconds to 10 seconds to assure that the skin temperature reached stability. We observed in the earlier tests that though the cooling stimulus reached

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a stable skin temperature value in 3 seconds, warming sensation required 4 to 7 seconds. Measurements must be taken soon after this, because over longer durations adaptation causes the thermal sensation to diminish. 2) the thermistor bead had been smaller (0.3mm) in the previous study but proved fragile. The increase in time constant for the larger bead (0.7 vs 0.5 sec) is very small compared to the length of the stimulation time prior to sensation measurement.

Fig.2C presents the programmed temperature cycling of the probe. The temperatures were selected as described in [17]. The neutral skin temperatures for different body parts are largely between 30 and 32.5°C, the average skin temperature of the human body is around 31°C [24], and the temperature range for maximal activation of cutaneous cold thermoreceptors is 27-22°C, and for warm thermoreceptors is 36-42°C [25]. We could not practically vary the baseline temperature during the course of the study because of large interpersonal and intraregional variation. Instead we adopted 31°C as the baseline temperature and pre-adapted the skin to it for 5 seconds before applying the warm or cool thermal stimulus. Subjects do not perceive a temperature change when 31°C is applied (they perceive it as neutral), and their skin temperature adapts to that temperature within the five seconds. The subsequent warming and cooling stimulus temperatures were selected to be ±5°C from 31°C, thus 26°C for the cool stimulus and 36°C for the warm stimulus. We made an exception for the foot dorsum and sole: because we had measured them before in our earlier study at ±5°C and found low sensitivity for both heating and cooling [25]; in this study we increased the stimulus temperature to ±7°C and re-measured each of the earlier test spots to see whether our previous map of the foot would change with increased stimulus temperature.

Sensation voting happened upon the investigator's verbal request at the 10th second of each stimulus's application. The subjects were instructed that they should report the magnitude of the very first local thermal sensation resulting from each stimulus application. Fig. 2D gives the 0-10 numerical thermal sensation vote scale (TSV). The anchor points 0 and 10 are labeled as "Not hot/Not cold at all" and "Very Hot/Very Cold" respectively. This scale is similar to the one used in similar studies [18,21], and its choice was based on extensive evidence supporting the applicability and reliability of numerical rating scales for somatic sensations in humans [26,27]. For each body segment, the order of heating or cooling stimulus was randomly arranged.

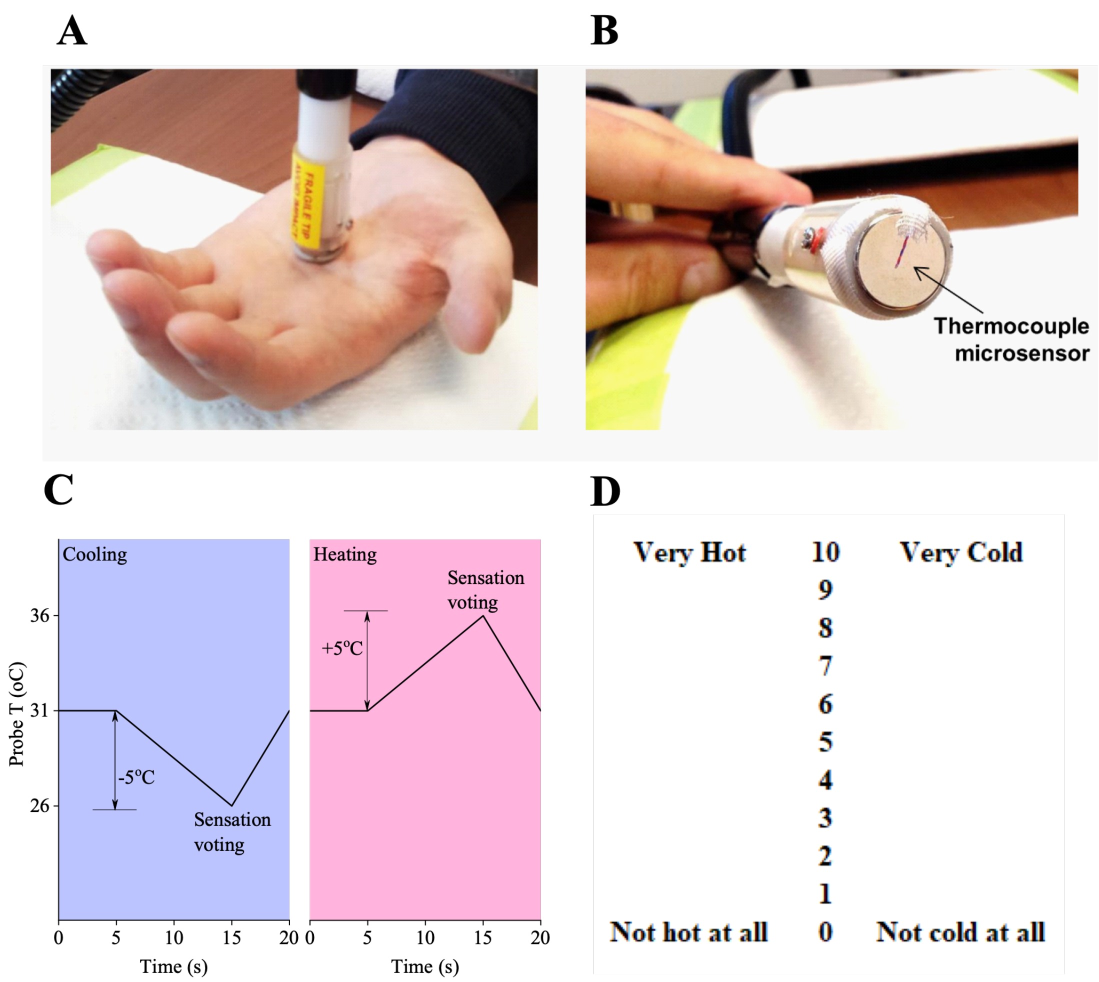

Figure 2. A) and B) Experimental apparatus, thermal probe diameter 14 mm; C) Temperature cycling of the probe; D) Thermal sensation voting scale.

2.4 Test protocol

Groups 1 and 2 were carried out in two separate 2-hour tests on different days because of the large number of points. Group 3 with less points was done in one day. The test protocol is described in [25].

Adapting, calibrating and training.

Upon arrival in the chamber, subjects changed into shorts and short-sleeve shirt, without shoes. Then five wireless skin temperature sensors (iButtons, Maxim, USA) were taped with medical paper tape (3M, USA) at five locations on the right side of their body (i.e. cheek, upper arm, abdomen, lower back and thigh) to record local T_{sk} in 10s intervals. The whole-body mean skin temperature T_{sk} was estimated from the iButton measurements according to the following equation [28]:

$$\text{Whole body mean } T_{sk} = (Cheek\ T_{sk} \times 0.07) + (Upper\ arm\ T_{sk} \times 0.19) + (Abdomen\ T_{sk} \times 0.175) + (Lower\ back\ T_{sk} \times 0.175) + (Thigh\ T_{sk} \times 0.39) \quad (1)$$

Once instrumented, subjects sat for 30-minutes to adapt to the ambient temperature. During this time the experimenter marked the targeted test spots with washable marker manually following a photographic template. These marks fixed the position of the test spots throughout the period of the test. The experimenter informed the subjects that non-painful warming and cooling stimuli would be applied. To avoid expectation bias, subjects were uninformed about the temperature of the stimulus, or whether the same stimulus would be applied to different test spots.

To ensure consistency in the use of the thermal sensation scale, subjects' responses were calibrated to anchor points by evaluating 3 separately delivered stimuli using the thermal probe to a representative skin site [17]. The first stimulus was set as 31°C to induce neither warm nor cold thermal sensation. The second and third stimuli were set as 31 ± 10°C to induce the anchor feelings of "Very Hot/Very Cold". The order of the second and third stimuli was randomized.

Test execution.

The 1.5-hour formal test was initiated after the 30-minute adaptation period. Subjects were instructed to only focus on the numerical rating scale placed in front of them and to report their local sensation upon researcher's request.

First, the investigator set the thermal probe at 31°C (the baseline temperature) and placed it gently on the skin test spot, with a pressure enough to ensure full contact with the skin. 10 seconds were allowed for the local T_{sk} to stabilize, at which time it was measured via the surface thermocouple and recorded as the T_{sk} at the 0^{th} second before delivery of the first stimulus.

The first round of stimuli would be either all warming or all cooling (31 ± 5°C chosen in random order) and the second round would be entirely at the opposite temperature. 10s after delivery of the stimulus, the subjects were verbally requested by the experimenter to report their local thermal sensation. At the same time, the local T_{sk} was recorded, to determine the ΔT_{sk} at the test spot between the 0^{th} and the 10^{th} second. Then the probe was lifted from the test spot, re-set to 31°C, and after a 5s break, the investigator placed the probe on the next randomly chosen test spot, and the same procedure was repeated until all skin spots in the body segment had been tested. Then, the second-round stimuli at the opposite temperature were delivered to the same sequence of test spots.

2.5 Data processing

Quantifying thermal sensitivity

Within the literature, 'thermal sensitivity' has had several general meanings, including for example describing thresholds. It is necessary to define 'sensitivity' more exactly here. We use local thermal sensation change divided by corresponding local skin temperature change (equation (2) [17]). Under the stimulus temperature of ±5°C the measured skin temperature change ranges between 2–4°C. Since we fix the base temperature to neutral, our thermal sensation votes (TSV) represent the thermal sensation change.

$$Thermal\,sensitivity\left(\frac{vote}{K}\right) = \left|\frac{thermal\,sensation\,vote}{\Delta\,local\,T_{sk}\,(K)}\right| \qquad (2)$$

To quantify the sensitivity variance within each body part, a coefficient (equation (3)) is calculated for each body part by dividing the body-part average by the whole-body average.

$$\text{Sensitivity coefficient} = \frac{Average\,thermal\,sensitivity\,of\,a\,body\,part}{Average\,thermal\,sensitivity\,of\,whole-body} \qquad (3)$$

Thermal sensitivity maps

In the maps, the measurement spots are represented as circles, each one enclosing the measured thermal sensitivity values for the spot. Values between the spots are extrapolated in order to present the body surface as heatmaps. Separate maps were created: for front and back views of the whole-body, for each of the individual body segments, for warming and cooling, and for male and female subjects. A custom MATLAB script (The MathWorks, Inc., USA) was used to generate the maps. Group-averaged thermal sensitivities were represented as Z values entered into a matrix of X and Y coordinates representing the test spot locations (see Appendix A). MatLab interpolation and extrapolation functions were used to create HeatMap objects, which were then superimposed over representative human body images, and morphed accordingly.

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Statistical analysis

A range of statistical tools were used for data interpretation. To evaluate changes in whole-body thermal state during the test in male and females, mean T_{sk} data were analyzed by two-way ANOVA, with sex as an independent factor, and time as repeated factor. In the event of statistically significant main effects or interactions, post-hoc analyses were conducted with Tukey's HSD tests.

To test whether thermal sensitivity varies significantly between different body parts, two-way ANOVA tests with body part and sex as main factors were used and repeated for cooling and warming stimulus. If there were significant main effects or interactions, Tukey's HSD tests were applied to identify which interaction caused the difference. The Tukey's HSD test results were considered statistically significant when $p \leq 0.05$. The interpretation code was as follows: $p \leq 0.001$ or '***' means highly significant, $0.001 < p \leq 0.01$ or '**' means significant, $0.01 < p \leq 0.05$ or '*' means weakly significant, and $p > 0.05$ means not significant.

A sensitivity coefficient for each body part was calculated by dividing the mean sensitivity of that body part by the whole-body average for cooling and warming stimulus. To investigate whether the human body is more sensitive to cooling than warming, a two-way ANOVA with body part and stimulus type as main factors was applied. If there were significant main effects or interactions, Tukey's HSD tests were applied to verify each interaction's significance.

To examine how the thermal sensitivity under the test condition was related to ΔT_{sk} and TSV, Pearson correlation coefficients r were calculated separately for cooling and warming stimuli, with thermal sensitivity as y input and ΔT_{sk} (or TSV) as x input.

To analyze whether there is a statistically significant difference in thermal sensitivity between sexes, a two-way ANOVA was conducted setting sex and body parts as main factors and repeated for cooling and warming stimulus.

The test results were prepared in Microsoft Excel 2016. Statistical calculation and significance analysis were performed in R (Version 3.5.1, RStudio Inc. Boston, MA, USA). Some figures were made in OriginPro (Version 2018, OriginLab, Northampton, MA, USA).

3 RESULTS

3.1 Whole-body thermal sensitivity mapping and comparisons of local body part thermal sensitivities

Fig.3A shows the mapping of cool and warm sensitivities across the human body from both front and back views. The values average male and female results.

There is clearly a large regional variation in thermal sensitivity for different body parts. In general, the face is highly sensitive. The back of torso and neck is more sensitive than the front (note the darker colors for back than front for both heating and cooling). The abdomen is more sensitive than the chest. The seat is more sensitive than other parts of the trunk. The dorsum of the hand is more sensitive than the palm. The lower extremities are the least sensitive. Table 3 presents the sensitivity magnitude and variation for each body part.

The thermal *sensation* votes that underlie sensitivity values are mapped in Fig.3B. Spot thermal sensation values range between 0.5 and 8.6 for cooling, and between 0.3 and 7.1 for warming, across the whole body. This indicates that our heating and cooling stimulus temperatures produce a wide range of responses without extreme sensations. The maps of thermal sensitivity and thermal sensation are very similar, showing the same pattern. In the following sections, we will focus on the sensitivity results.

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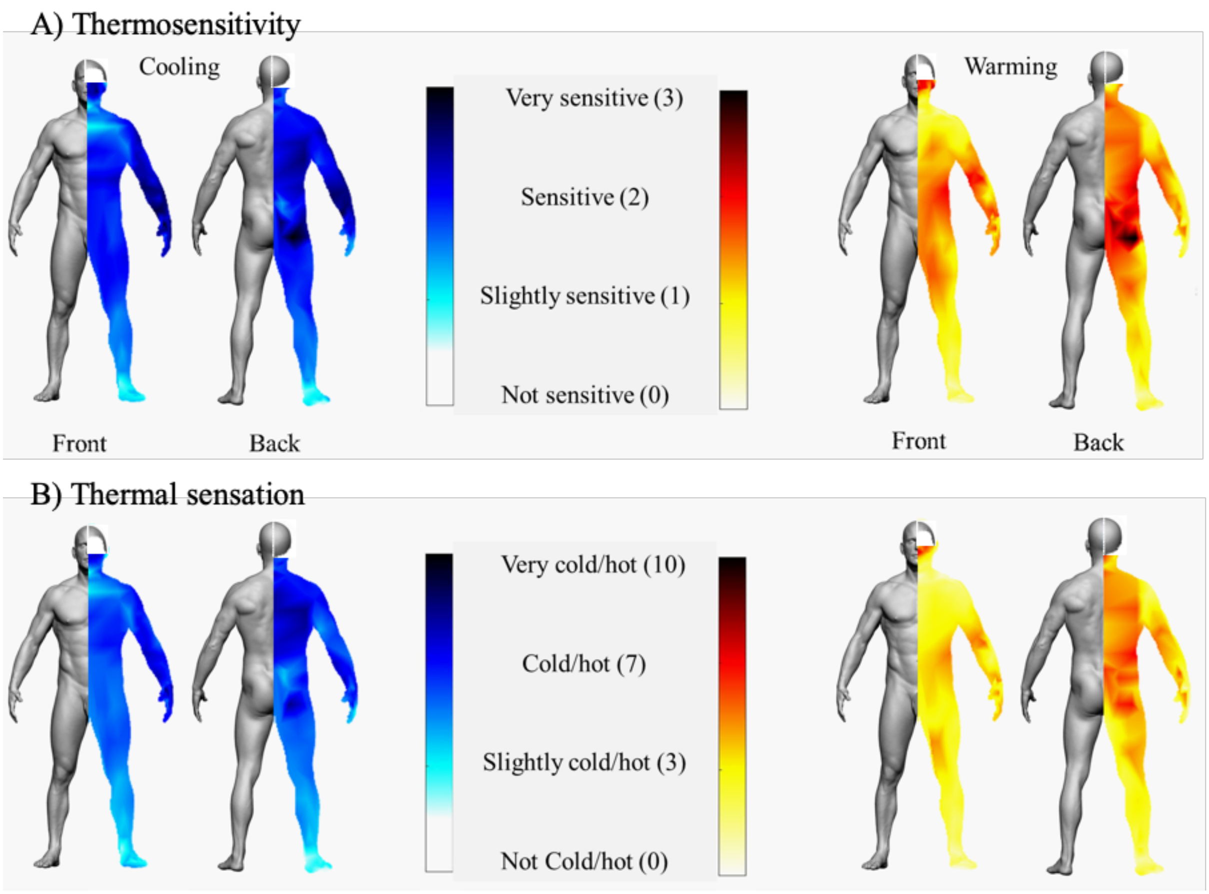

Figure 3. A) Whole-body thermal sensitivity mapping, within 4 major levels. B) Whole-body thermal sensation mapping. The hair area on the head was not measured due to hair coverage. The test spots as indicated in Figure 1 are too many to be colour-mapped in this graphic. They are shown in the more expanded views in Figure 5, 7, and Appendix A.

Table 3. Thermal sensitivity values for each body part

Body part	Cooling		Warming	
	Average	SD	Average	SD
Face	1.89	0.43	1.36	0.53
Neck dorsal	1.73	0.22	1.38	0.44
Neck ventral	1.53	0.4	0.62	0.33
Chest	1.8	0.33	1.28	0.35
Abdomen	1.98	0.16	1.51	0.26
Back	2.02	0.21	1.3	0.37
Upper arm	2.07	0.23	1.3	0.39
Forearm	1.87	0.23	1.14	0.35
Hand palm	1.84	0.32	1.11	0.25

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Hand dorsum	2.35	0.24	1.35	0.34
Buttock	2.16	0.48	2.14	0.45
Thigh	1.92	0.13	1.31	0.27
Lower leg	1.5	0.11	0.93	0.18
Sole 5	0.75	0.38	0.45	0.2
Foot dorsum 5	1.1	0.13	0.56	0.17
Sole 7	1.02	0.27	0.43	0.13
Foot dorsum 7	1.08	0.18	0.67	0.15

Examining whether thermal sensitivity varies significantly between different body parts, Table S1 in Appendix B shows that both cooling sensitivity ($F(16,8955) = 116.1$; $p < 0.001$) and warming sensitivity ($F(16,8955) = 62.0$; $p < 0.001$) exhibit significant variance. Table S3 presents the significance levels between each pair of body parts. It indicates that the extremities (like the sole, foot dorsum, and hand palm) and highly sensitive areas (like the face and buttock) are significantly different from most other body parts.

Figure 4 shows that body parts like buttock, face, dorsum of hand, and abdomen have coefficients greater than 1 while the foot, lower leg, and chest are less sensitive than the whole-body average. The neck overall is close to the whole-body average, but the back part of the neck is much more sensitive than the front part. Body parts with a high cooling sensitivity coefficient tend to be sensitive to warming as well.

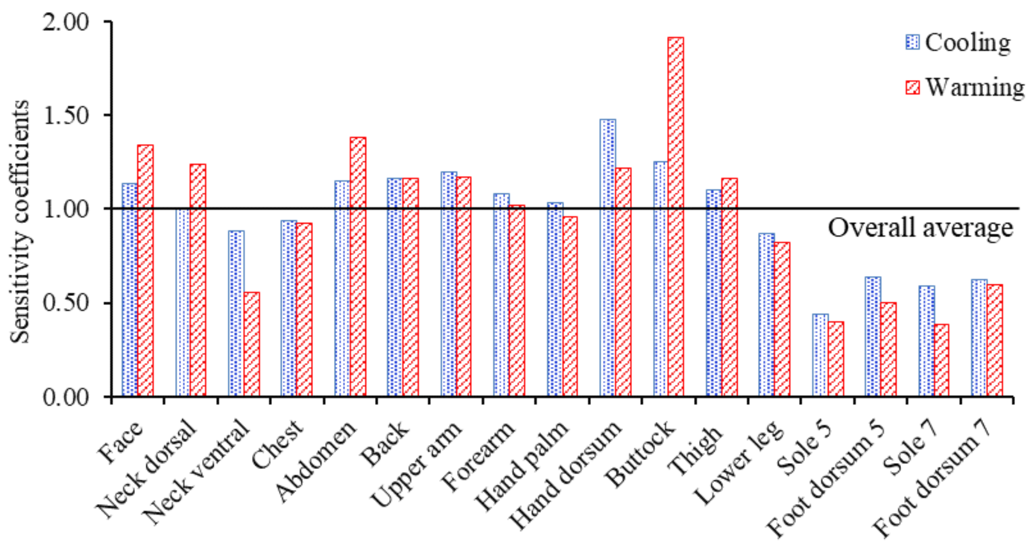

Figure 4. Sensitivity coefficients for 15 different body parts. Note that the neck is here divided into back and front parts. A coefficient greater than 1 means the body part is more sensitive than the whole-body average, otherwise it is less sensitive than the whole-body average.

3.2 Local sensitivity within example body parts

Figure 5 provides a more detailed look at sensitivity variance within a few individual body parts, with examples for face, neck, wrist, hand, foot, and the seat area. Sensitivity data for all test spots and maps of other body parts are given in Appendix A.

Fig.5A shows that the cheek (cooling average = 2.31, SD = 0.24; warming average = 1.93, SD = 0.36), ear (cooling average = 1.73, SD = 0.85; warming average = 1.72, SD = 0.96), and back of the neck (cooling average = 1.84, SD = 0.05; warming average = 1.17, SD = 0.20) are very sensitive to both heating and cooling [1]. The ventral (front of the) wrist (cooling average = 1.87, SD = 0.19; warming average = 1.40, SD = 0.27) is more sensitive than the dorsal (back of the) wrist (cooling average = 1.50, SD = 0.18; warming average = 0.84, SD = 0.23).

Fig.5B maps the thermally sensitivity for the foot as measured by both ±5^{o}C and ±7^{o}C thermal stimuli (marked as Sole 5 or Sole 7 in the figure). It shows that the dorsum of the foot (cooling average = 1.10, SD = 0.13; warming average = 0.56, SD = 0.17) is more sensitive than the sole (cooling average = 0.75, SD = 0.38; warming average = 0.45, SD = 0.20); the foot arch area (cooling average = 1.18, SD = 0.26; warming average = 0.54, SD = 0.08) is more sensitive than the toes (cooling average = 0.44, SD = 0.12; warming average = 0.29, SD = 0.07) or the heel (cooling average = 0.35, SD = 0.21; warming average = 0.33, SD = 0.12) [2]. The ±7^{o}C stimulus created slightly larger areas of cooling and warming sensitivity in both the sole and dorsum than the ±5^{o}C stimulus, but the patterns for both stimulus levels are similar.

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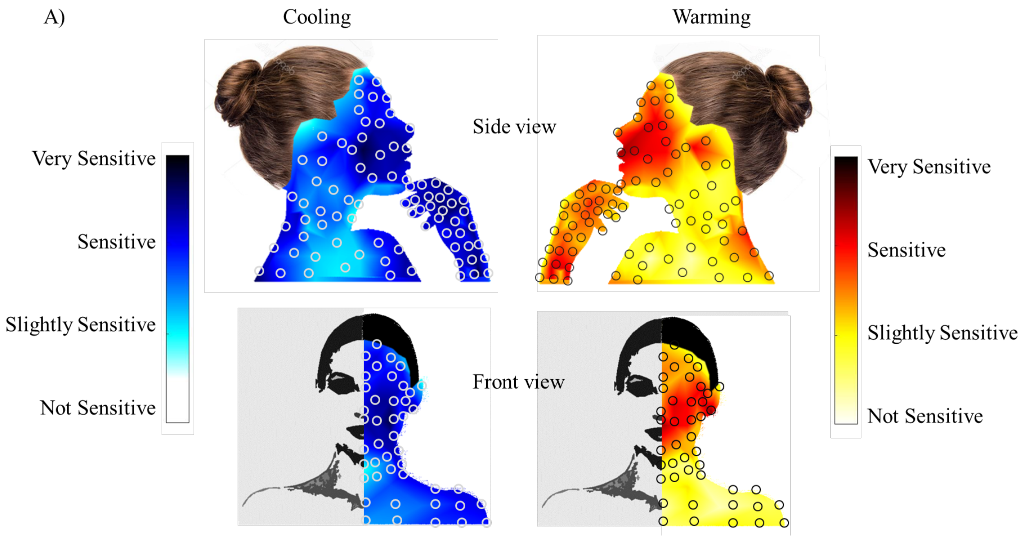
[1] The cheek data are from face test spots 9-17 (see Appendix A); the ear data from face test spots 32, 34; the ear back data from face test spots 33, 35; the back of neck data from back test spots 15-17, 24-26; the wrist data from forearm test spots 1-6, 10, 11, 15-20, 24, 25; the ventral wrist data from forearm test spots 1-6; and the dorsal wrist data from forearm test spots 15-20.

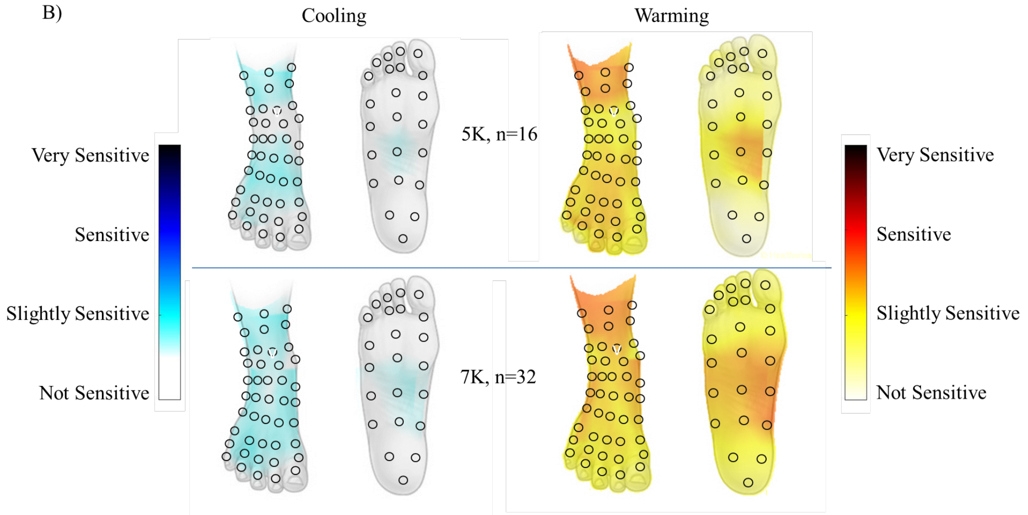
[2] The toe data are from sole test spots 23-30; the heel data from foot dorsum test spots 40-43; the foot arch data are from sole test spots 34-39.

Fig.5C presents the sensitivity variance in the seat area [3]. The lower buttocks are "extremely" sensitive to both heating and cooling (cooling average = 2.11, SD = 0.44; warming average = 2.04, SD = 0.38), more sensitive than the whole-body average (cooling average = 1.53, SD = 0.53; warming average = 1.12, SD = 0.59).

A)



B)



[3] The seat-area data are from buttock test spots 1-14, and thigh and leg test spots 3-6; the hip data are from buttock test spots 5-10.

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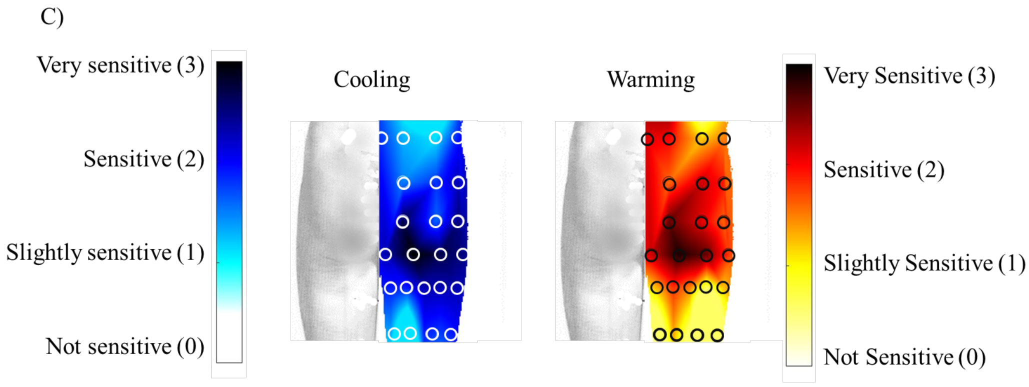

Figure 5. Thermal sensitivity of A) Face area; B) Foot area; C) Seat area. Note: the circles indicate the test spots and the colours within them represent their measured sensitivity.

3.3 Stronger cooling sensitivity than warming sensitivity

Fig. 6 shows the thermal sensitivity distributions for different body parts. Almost every body part (except the buttock area) tends to have significantly (30~60%) higher cooling sensitivities than warming ones. The average cooling sensitivity (1.9; SD = 0.37) is stronger than the average warming sensitivity (1.25; SD = 0.46).

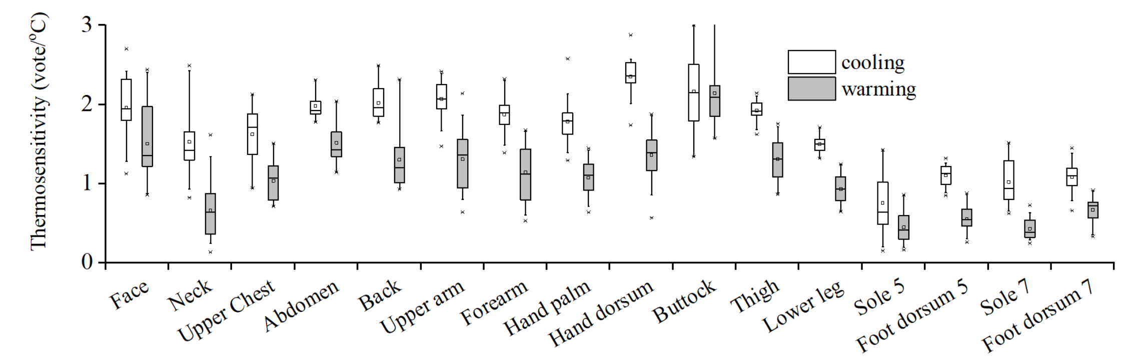

Figure 6. Cooling and warming sensitivity for individual body parts.

To verify whether cooling sensitivity is stronger than warming sensitivity, Table S2 in Appendix B shows a significant difference for both the female group ($F(1,9598) = 668.0$; $p<0.001$) and the male group ($F(1,8312) = 1178.2$; $p<0.001$). Table S4 lists the main statistics, including TSV, skin temperature change (ΔT_{sk}) and thermal sensitivity, together with significance levels of the Tukey HSD test for each body part. It strongly indicates (with most P values less than 0.001) that the human body is more sensitive to cool stimuli than warm ones. The only exception is in the buttock area where the sensitivities are equal. It should be noted that only 5 subjects participated in the buttock test for privacy reasons.

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3.4 Skin temperature changes

Although the temperature of the stimulus probe was fixed at 5 or 7^{o}C throughout the study, the skin temperatures change induced by the probe varied in different locations based on the skin's thermal conductivity, thickness, and thermal capacity. To address whether larger ΔT_{sk} causes stronger thermal sensitivity, Fig. 7 shows skin temperature and ΔT_{sk} for individual body parts. Note that during the test, the whole-body mean T_{sk} (average = 31.55°C; SD = 0.24) did not change significantly over the 1.5-hour formal test period ($F_{(10, 60)}$ = 0.3046; p = 0.537), with no difference ($F_{(1, 4)}$ = 0.1931; p = 0.418) between males (average = 31.75°C; SD = 0.12) and females (average = 31.39°C; SD = 0.20), and was maintained within a neutral range (29.6-32.7°C), close to the assumed neutral baseline temperature 31^{o}C.

Among various body parts. The average skin temperature of body parts is not identical across the human body, varying in a range of 29.6-32.7^{o}C (Fig. 7 bottom figure). Areas like face, neck, and chest have slightly higher T_{sk} than the baseline temperature 31^{o}C while the foot areas have lower T_{sk} than 31^{o}C. The regional variance in T_{sk} , as well as in physical factors such as skin thickness and capillary bloodflow, lead to different spot temperature changes (ΔT_{sk}) when the same intensity of cooling (31-5^{o}C) and warming (31+5^{o}C) stimuli are applied to these body parts.

Within a body part. For each body part, in general, the lower/higher the skin temperature is, the larger the skin temperature changes caused by the warming/cooling stimulus. This can be seen by the upper chart in Fig. 7 where warming stimuli applied to foot areas led to a larger ΔT_{sk} (average = 3.15; SD = 0.15) than that induced by cooling stimuli (average = 2.96; SD = 0.10). Other body parts like face, neck, and chest where skin temperatures were higher than 31^{o}C, had larger cooling ΔT_{sk} (average = 3.11°C; SD = 0.32) compared to warming ΔT_{sk} (average = 2.85; SD = 0.18).

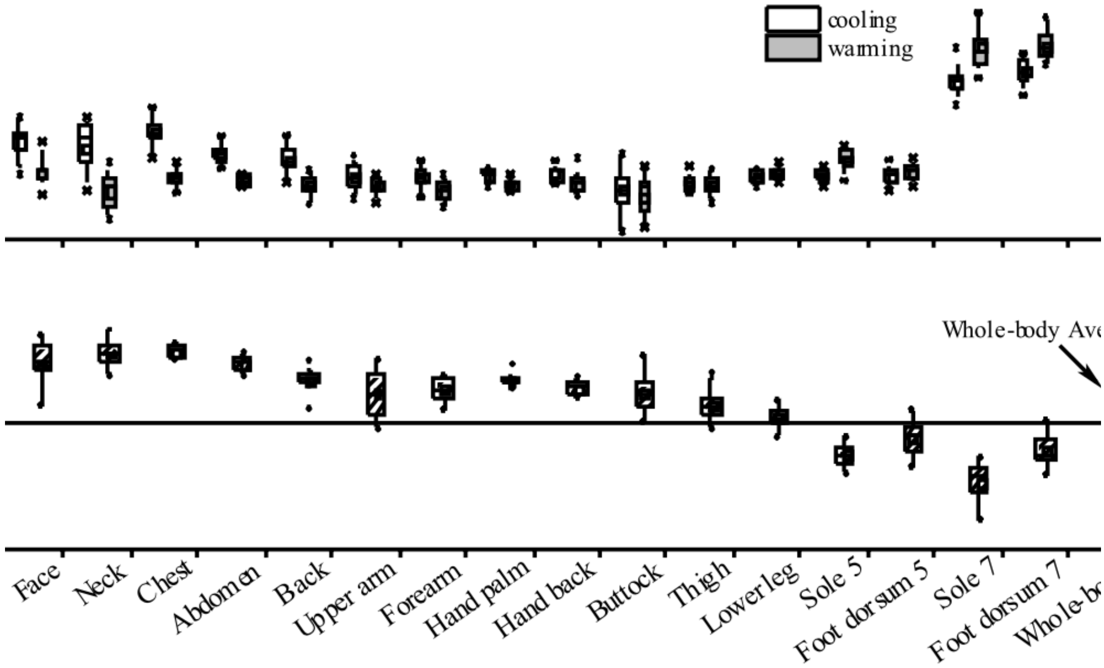

Figure 7. Skin temperature changes. T_{sk} of each local body part was measured by the thermocouple attached to the thermal probe surface. Whole-body mean T_{sk} was calculated from ibutton records using Equation 1. Sole7 and foot dorsum 7 cases had the stronger cooling (31–7°C) and warming (31+7°C) stimuli.

4 DISCUSSION

4.1 Stronger cooling than warming sensitivity

Consistent with previous findings [16], our results show that sensitivities across all body parts are stronger for cooling than for heating (Fig. 6). This is due to the features of thermoreceptors and afferent nerve fibers. The number of cold-sensory spots greatly exceeds that of warm-sensory spots [29,30], and the cold receptors are located in or immediately beneath the epidermis at an average depth of 0.1 to 0.15 mm, while the less numerous warmth receptors are deeper at an average depth of 0.3 to 0.6 mm [35, 36]. Cold receptors emit higher numbers of impulses than warm receptors for a given level of stimulation, and afferent cold fibers exhibit greatly higher conduction velocities than those of warm fibers [32,33].

4.2 Large interpersonal sensitivity differences and within-body-part variance

The sensitivity differences among people, and also the regional variances within individuals' body parts [12,34,35], are large. Fig. S2 in Appendix B interprets these two factors at 3 levels: interpersonal level difference as shown in Fig. S2a; intrapersonal body-part-level variance as in Fig. S2b; and individual test-spot level as in Fig. S2c.

The variance coefficient in Fig. S2a is defined as the sensitivity of each subject divided by the average of all subjects. The percentile distribution shows interpersonal individual differences leading to a 0.5-1.5 variance coefficient. The most-thermally-sensitive people tend to have 1.5 times the thermal sensitivity of the group average, while the least-sensitive people tend to have 50% lower sensitivities. The large individual differences can be attributed to many factors related to physiological, psychological, and context drivers. A recent review [34] shows clear contributions from body composition, metabolic rate, thermal adaptation and perceived control, while the role of other potential contributors such as age and sex remain uncertain.

The variance coefficient in Fig. S2b is defined as the sensitivity of each test spot divided by the average of all spots within a body part. With coefficients ranging from 0.8-1.2, the most thermally sensitive spots can have 20% larger sensitivity than the body-part average, while the least sensitive spot sensitivity is likely to be 20% less. The large within-part variance suggests that the thermoreceptor or innervation distribution is non-uniform.

The standard deviations in Fig. S2c shows large differences between subjects for results from same test spot. Thermal sensitivity variance at a given spot ranges from 0.6-1.5 scale units since the standard deviations are mainly distributed in that range. By comparing Fig.3a and Fig. S2c, we find that individual difference at a given spot tends to be larger in the highly sensitive areas.

It is worthy to note that, although the test spots were assembled from three subject groups (Table 2), the above three levels of variance exist even within the same subject group, and the magnitude of the variances for the subject groups does not show a significant difference. This indicates that the inter-personal and inter- and intra-body-part variances are not caused by the different test subject groups.

4.3 Small differences between BSA-matched males and females

To test whether sex entails thermal sensitivity differences, we matched our male and female groups in both the 2016 and 2018 studies for age and body surface area (see Table 2).

Fig. 9 plots both sexes' cooling and warming sensitivity distributions in individual body parts. Together with the statistical significance test, we conclude that, given comparable body size, males and females have small thermal sensitivity differences except in the chest-warming and forearm-warming cases. Fig. 10 maps the chest-cooling and warming sensitivity for both sexes. It shows that the difference exists mainly in the breast area [4], where females tend to be more cooling- and warming-sensitive than males (with independent t-test of $p < 0.001$).

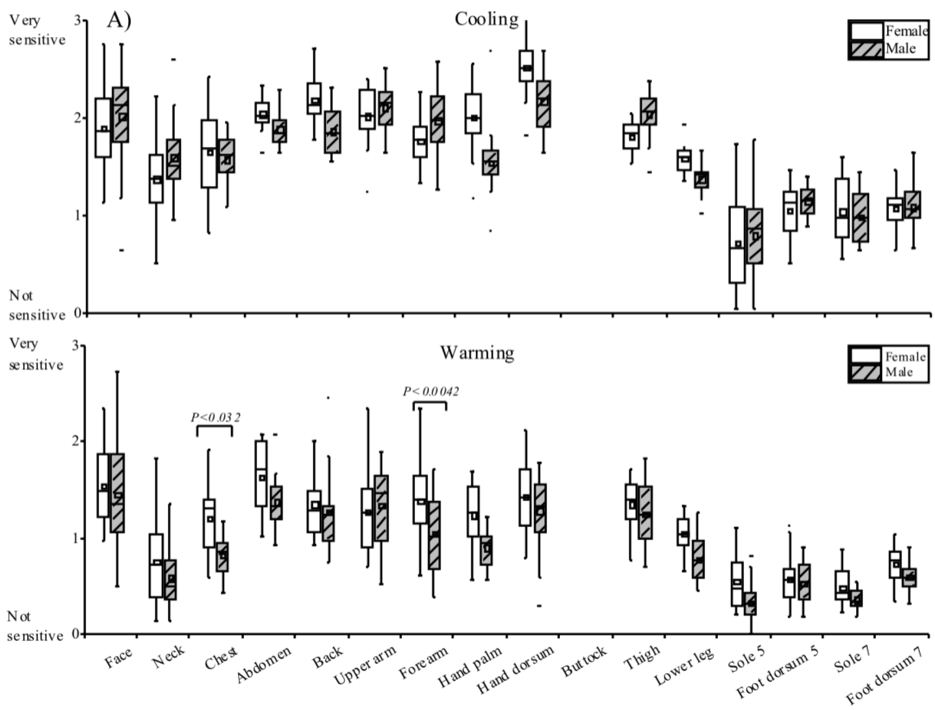

Figure 9. BSA-matched female and male thermal sensitivity comparison with Tukey HSD test P values. More detailed ANOVA test results are listed in Table S1 in Appendix B.

[4] The breast area data were from chest and abdomen test spots 4-6, 7-9, 10-12.

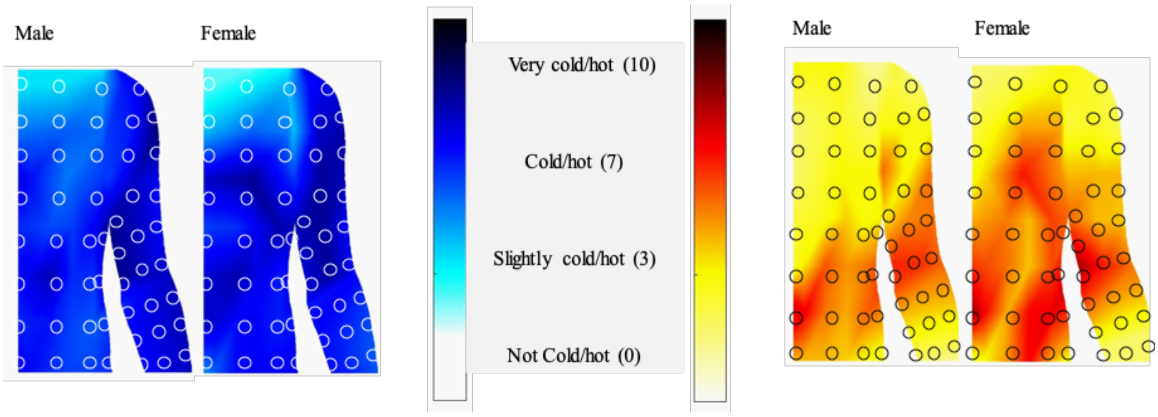

Figure 10. Chest thermal sensitivity for males and females.

Several studies have analyzed sex-differences in thermal sensation, yet no clear picture has emerged. Some have reported that females are more sensitive than males [18,19] while others found that there is no sex difference [14]. These contradictory findings might be caused by the body surface area differences among the sex groups, and some have suggested matching the surface areas for the sex groups when analyzing differences. For example, sex differences in the thermal physiological responses of hands and feet have previously been found to be reduced when male and female groups are matched by their body surface areas [36,37].

When we analyzed individual differences among people, we found that the differences are very large, exceeding the magnitude of potential sex differences. The observed thermal sensitivity sex differences are mostly in the range of 0.2-0.5 scale units (Fig. 9), while the inter-personal differences can be 0.8-1.5 scale units (Fig. S2 in Appendix B), about 3 times that of sex difference. These findings suggest that the individual difference and within-body-part variance are large enough to cover up the effects of other factors such as sex difference, and might explain the lack of significant difference observed in Fig. 9's sex comparison.

4.4 Practical applications

The high-density thermal sensitivity maps developed in the current study are the most detailed sensitivity visualization mapping to date covering all body parts. They provide a window into the peripheral mechanisms of human body thermal sensation.

Research applications: The sensitivity maps may have methodological value in locating skin temperature measurement spots that best represent body segments or parts thereof. Given the within-body-part sensitivity variance (Fig. S2b), it is inaccurate to represent an entire body segment with a few spots. The uncertainty in the traditional selection of a few spots to represent an entire segment is presented in Table 4. It varies greatly from 5%~20% for cooling and 15%~30% for warming.

Table 4. Uncertainty percentage at 99% confidence level

Body part	Cooling	Warming
Face	12.5%	19.2%
Neck	19.3%	28.7%
Chest	14.7%	26.1%
Abdomen	7.7%	17.9%
Back	9.4%	27.2%
Upper arm	7.9%	21.8%
Forearm	8.1%	20.8%
Hand palm	10.8%	15.6%
Hand dorsum	6.8%	17.1%
Buttock	20.6%	20.5%
Thigh	4.4%	14.1%
Lower leg	6.3%	18.1%
Sole 5	20.8%	27.2%
Foot dorsum 5	8.7%	22.5%
Sole 7	19.7%	22.1%
Foot dorsum 7	10.1%	12.7%

Design applications: The maps also can help to guide future development of personal comfort devices that heat or cool people locally [3]. For example, some of the more sensitive areas seen in these maps are already targets of wearable comfort devices [4,5], which must focus their limited battery power, an inherent constraint in wearable devices. Devices resembling watches, necklace, and headphones are designed to press conductive surfaces against the wrists (dorsal or ventral), back of neck, and facial areas. The arch area of the foot's sole, and the base of the toes, have also been targeted with small heated surfaces mounted in a battery-powered insole.

Desk-based comfort devices have targeted the palmar hands and wrists with heated and cooled contact surfaces on the desktop, keyboard, and computer mouse [38]. The dorsal hand and wrist has been cooled by small air jets emerging from wristpads and by desk fans. Fans are also commonly used to cool the face and neck [39]. Below the desk, foot- and leg warmers have been more difficult to make energy-efficient. Radiation applied to the dorsum of the foot, ankles shins, and top of thighs has been the most efficient [40] but there are few commercial products at present. Reviewing the power ratings of current commercial products, warming the lower extremities by heated air requires more than 4x the energy needed for focused radiation, and more also more than conductive heat transfer even if it is happening through the insulating soles of shoes. Cooling the lower body requires air movement provided by fans; in recent inventions cooled air may be efficiently provided http://mobilecomfort.us/. Finally, chair cooling and heating systems [41–43] target the highly sensitive seat and lower back area for both contact heating and convective cooling. The front of the pelvis and abdomen have been cooled by air jets emerging from the leading edge of a desk [44]. Each of these approaches could ultimately benefit from human thermal physiology and comfort modeling in which the skin sensitivity will be a component.

For all body parts, the phenomenon that cooling sensitivity is stronger than warming sensitivity tells us to pay more attention to cooling stimuli in cooling devices, because overly strong cooling may pass beyond neutral and cause cold discomfort.

4.5 Limitations

The measured skin temperature change that determines sensitivity is overestimated on both the cool and warm sides, in that the 0.6mm diameter thermocouple bead is influenced to an unknown extent by its direct conductive heat exchange with the stimulus surface. The microenvironment of the bead is complex, influenced also by radiant exchange in the cavity and by the lateral blood flow in the skin. Recognizing this, we experimented with placing a tiny rubber insulator between the probe surface and the bead, but it resulted in no measurable difference (<0.1°C) from the uninsulated bead. In addition, because it was difficult to keep in alignment, we did not use it. We reasoned that by pressing the bead into the skin, the bead's skin contact area is much greater than the area contacting the probe surface, weighting the measurement toward the skin temperature. Ultimately this issue might warrant further study.

We can also directly compare sensitivity with our measured *sensation* values, which reflect the +/-5°C stimulus only. Using the sensation metric, the relative influences of skin conductivity and neurosensor density remain unknown, whereas the sensitivity metric permits accounting for the temperature differences caused by varying skin conductance, thickness and blood flow. Our measured sensation maps do not show appreciable differences from the sensitivity maps; for those wishing to delve into this detail, sensation values are given in Appendix A.

We were limited to using a fixed baseline temperature (31°C), and a fixed level of stimulus temperature difference for both warming and cooling (except for the additional level that we tested for the foot). Either of these temperature parameters could be varied in future studies to see whether they produce any differences in sensitivity from those of the current study. Comparing our two foot-stimulus temperatures, the patterns of sensitivity varied only slightly.

Age is a limitation, since our subjects were all healthy young adults. We might expect different sensitivity levels on both the warm and cool sides for older people and infirm people, whose innervation, skin properties, blood circulation, and metabolic rate may have changed.

Our matched-surface-area subjects represent a limited data set for examining sex and individual differences in thermal sensitivity. Finally, the current study used data from 3 different groups of participants (see Table 2) to cover all the body parts. This increases error when comparing the sensitivity of body parts that were measured on different groups. Although we found the error to be minor, it would be more consistent if future studies could manage to recruit the same subject group for all the test spots.

5. CONCLUSIONS

The distribution of warm and cold sensitivities across the entire body was determined using 68 subjects divided into three groups. Measurements were taken at a high density (318 spots covering half the body), providing the most detailed thermal sensitivity mapping of the body to date. The findings are summarized below.

1) Thermal sensitivity varies largely across different body parts. Using cooling and warming coefficients (local sensitivity/average whole-body sensitivity) as the comparison parameter, foot (cooling coefficient of 0.6/warming coefficient of 0.7), lower leg (0.7/0.7) and upper chest (0.8/0.8) are much less sensitive, while cheek (1.6/1.7), back of neck (1.6/1.7), and seat area (1.6/1.7) are very sensitive to both cooling and warming.

2) The human body has (30~60%) stronger sensitivity to cooling than to warming in most of its local areas.

3) Small thermal sensitivity differences were observed between body-surface-matched males and females. But there were large inter-personal sensitivity differences and large variance between body parts and within them. These differences can be 2-3 times larger than potential sex difference, making sex differences appear relatively insignificant.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

M.H.L. and H.Z. conceived and designed research; M.H.L. and Z.W. and other authors performed experiments; M.H.L. and Z.W. analyzed data; M.H.L., Z.W. and H.Z. interpreted results of experiments; M.H.L. and Z.W. prepared figures; M.H.L. drafted manuscript; H.Z., E.A. and D.F. edited and revised manuscript; H.Z. and E.A. approved final version of manuscript.

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