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Investigation of human body skin temperatures as a bio-signal to indicate overall thermal sensations

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ABSTRACT

This study investigates the possibility of the use of human body skin temperature to assess thermal sensation, by studying skin temperatures from ten body segments and analyzing the correlation between the physiological data: skin temperature and overall thermal sensation.

Since the human body regulates skin temperature to balance the heat gain and heat loss, the use of skin temperature has significant potential as an index to the thermal sensation. Therefore, this research has relied on experiments using human subjects in an environmental chamber to investigate and determine how skin temperatures change, depending on the ambient thermal conditions, and to identify which data type and body segment generate the most significant physiological information that will represent the overall thermal sensation.

For this study, the experiments were conducted with 26 volunteers in an experimental chamber for about 2 h each, while the indoor temperature was changed from 20 °C to 30 °C. Results of this study revealed that skin temperature change rates (gradients) were more consistent with the thermal comfort condition than with the actual levels of skin temperatures of participants, and that the measured skin temperatures at their wrists provided more interpretable data than that of any other body segments. Therefore, the research findings have shown the potential of skin temperature as a thermal sensation index to reliably represent an individual's thermal sensation in a thermally uniformed environment.

1. Introduction

According to ASHRAE-55, thermal comfort has been defined as the condition of mind which illustrates satisfaction with the thermal environment, and thermal sensation is related to heat balance between the human body and its ambient thermal condition. Depending on the heat transfer, via heat gain or loss, the thermoregulation system in a human brain regulates skin temperature to maintain a constant core body temperature of 36.5°C. In Wang's study, a human body reacts via shivering when conditions are cold, in order to generate internal heat, and via sweating, when it is hot, to generate an evaporative cooling effect on the skin. However, in the range of a moderately warm to a cool condition (between 18 °C and 33.5 °C), the thermoregulation system controls skin temperature through vasodilatation and vasoconstriction to maintain a thermal comfort [1].

This physiological principle illustrates that skin temperature has considerable potential for assessing thermal comfort conditions, depending on temperature values. Due to its significance, many studies have been conducted to develop a formula for estimating a mean skin temperature. Such a formula selected multiple body segments, from which to collect skin temperature data, and used various weight factors for each point to estimate the mean skin temperature. In Choi's study [2], more than 16 skin temperature models were utilized to collect data from 3 to 15 skin points. However, most models have been focused on mean skin temperature predictions for the purpose of medical diagnostics [3].

In the field of building science, efforts are also being made to develop a thermal sensation/comfort model based on reading skin temperatures from multiple body segments. Most thermal sensation models have been developed based on the aforementioned mean skin temperature formulas. Yao [4] developed a regression formula based on skin temperatures at eight body points and surveyed overall thermal sensation data. Wang [1] and Fiala [5,6] selected eight and ten body segments, respectively, including the head, trunk, arms, hands, legs, and feet. These studies included experiments with human subjects in environmental chambers that

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generated transient and uniform thermal conditions. In addition to such a “room-type” condition, several researchers have detected thermal conditions by reading skin temperatures in a vehicle environment. One industry research center developed a thermal controller based on reading skin temperatures from seven points on a driver’s face [7]. Zhang developed local and whole-body thermal sensation prediction models for transient and asymmetrical thermal conditions that considered the thermal features of a car [8]. This research adopted 22 body locations and a core body temperature. However, these models were mostly designed using a standardized formula, based on a statistical regression, without fully considering physiological characteristics such as gender, body mass index, age, etc., even though biological parameters affect an individual’s skin temperature and thermal sensations [9,10]. Therefore, such models may not work for any subjects whose physiological conditions were not considered in their data set that was used for the regression formulas. In addition, these study outcomes may not be practically applicable due to the use of multiple data acquisition points on the human body. Most appropriate thermal sensation model research requires that at least eight or more sensor points be used to collect skin temperature data, so that intrusive sensor numbers and locations may be limited in system applications.

Therefore, it is critical to identify a body segment that generates a readily interpretable skin temperature as a basis for estimating the individual thermal sensation of many human subjects, regardless of their physiological characteristics (including gender and body mass index). For that reason, this research conducted human subject experiments in an environmental chamber, where the thermal conditions changed from 20 °C to 30 °C, in order to reach the following objectives:

(1) Analyze the correlation between skin temperatures of each selected body segment and the overall thermal sensation.
(2) Investigate the patterns of skin temperatures in relation to thermal conditions.
(3) Determine which data type or variable can correctly interpret a subject’s thermal sensation with a number of subjects being characterized by gender and body mass index.
(4) Identify the most responsive body location for skin temperature to correctly indicate a subject’s thermal comfort condition.

2. Methods

2.1. Human subject experiment

2.1.1. Experimental subjects

Twenty-six subjects volunteered to participate in this study: 11 females and 15 males (gender) and 16 Asians and 10 Caucasians (ethnic origin). Their ages ranged from 18 to 45, and they were primarily undergraduate and graduate students of Carnegie Mellon University. Their physical condition was normal, without illnesses or health problems such as a fever or a cold. The clothing condition of each subject was kept constant at 0.8 Clo (i.e., pants and long sleeve t-shirts with regular underwear).

A light “office-type” work such as typing or web-surfing, was selected as a subject’s activity at 1.2 Metabolic rate (Met). Multiple activity levels might have been appropriate for validation purposes but, due to the space limitations of the environmental chamber, only one activity level that is typical of an office environment was selected.

Before the experiment, the gender and age information of each subject was recorded, and their heights and weights were also measured as a basis for estimating the body mass index (BMI). The BMI ranged considerably, from 17.66 to 30.87, which are underweight and obese according to the World Health Organization [11]. Demographic information on selected subjects is summarized in Table 1.

2.1.2. Environmental chamber

An environmental chamber in the Center for Building Performance and Diagnostics at Carnegie Mellon University was selected for this study. The chamber was equipped with an under-floor distribution system with four supply air diffusers, as shown in Fig. 1. The air speed around the workstation was maintained at less than 0.2 m/s, as recommended by ASHRAE-55 [12]. As illustrated in Figs. 1 and 2, a desk was placed at the center of the chamber and a computer was installed for data acquisition. A subject simulated office work during the experiment. All walls were “blinded” to remove or minimize any distraction in the vision field. The underfloor air diffusers were placed in front of the table at approximately 1.5 m distance from the subject’s location.

To monitor the indoor conditions of the chamber, measurements were taken of air temperatures at four different heights (1.6 m, 1.1 m, 0.6 m, and 0.1 m), CO_2 concentration, and relative humidity, surface temperatures on all the indoor wall sides, mean radiant temperature, and air velocity. To meet a thermal condition recommended by ASHRAE-55 and ASHRAE-62, the vertical air temperature between the 1.6 m height and floor level was maintained within a range of 3 °C or lower. The concentration of CO_2 was maintained between 600 and 800 ppm, while the relative humidity was controlled at around 35% $\pm$ 5%, during each experiment.

2.1.3. Instrumentation

For skin temperature measurements, a sensor device (Model: STS-BTA, Vernier, US) was selected. It has an exposed thermistor, with rapid response rates, and can measure skin temperatures on contact with the skin surface. This skin surface sensor mainly absorbs heat through conduction to measure a surface temperature. Each sensor was covered and fixed on selected body parts using a medical tape (Nexcare paper first-aid tape) in order to minimize the thermal effect of exposed ambient conditions. For body weight and body mass index, a body fat monitor (Model: Omron HBH-400) was used. The skin temperature sensors and environmental sensors were connected to data acquisition boards (Model: Sensor DAQ and DAQ-USB-6008, National Instrument, US). The collected data were automatically transferred to DAQ boards and recorded on a computer through the data acquisition interface (developed by using LabVIEW, v. 8.5, National Instrument, US), shown in Fig. 3. The air temperatures, surface temperature, CO_2 concentration, relative humidity, and air speed were also measured with the same sensory devices as those used in the authors’ previous study [13]. These selected sensory instruments are summarized in Table 2.

2.1.4. Data collection and analysis

The data on skin temperatures at ten body locations and environmental conditions were recorded with a 10-s sensing interval from the 26 volunteered human subject participants. All environmental conditions were displayed on the data acquisition interface, and monitored and controlled to ensure the appropriate thermal

Table 1
Demographic information of human subjects.

Variables	Mean	St. dev.	Min.	Max.
Age	27.15	6.52	18	45
Height (cm)	171.16	9	157.48	185.42
Weight (kg)	67.44	14.1	49.62	106.14
BMI	22.84	3.26	17.66	30.87

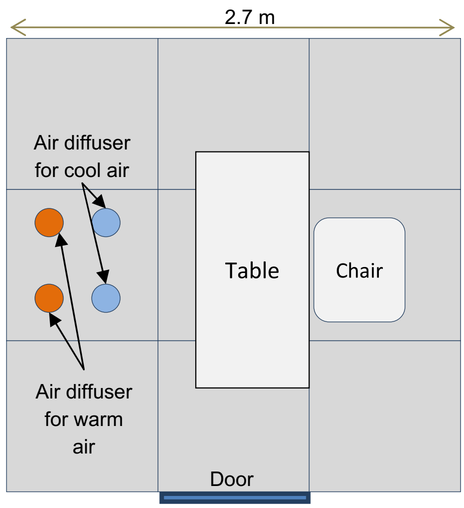


Fig. 1. Floor plan and the location of the environmental chamber.

conditions throughout the experiment. Every 10 min, during the experiment, a subject was asked to report his/her overall thermal sensation through the survey interface illustrated in Fig. 4. The survey used the ASHRAE-PMV survey designations: cold (−3), cool (−2), slightly cool (−1), neutral (0), slightly warm (+1), warm (+2), and hot (+3). Questions included local body sensations and overall thermal sensation, but only the overall thermal sensation was used for this study.

Fig. 2. Internal view of the experimental chamber with a human subject.

The survey interval selected was 10 min because a shorter interval seemed to distract the subject's awareness of his/her thermal sensation. On the basis of this timing point for the thermal sensation survey, the skin temperatures were measured every 10 s . For the data analysis, ANOVA (Analysis of Variance) was mainly used to determine any discrepancy of skin temperature between the different thermal sensations. All of the statistical analyses were performed at a level of 95% statistical significance.

2.1.5. *Variables in skin temperature*

This study considered of three variables: level of skin temperature, change rate (gradient), and mean of the square of the gradient. The collected skin temperatures were used to calculate the gradient. Since the sensing interval was 10 s, the gradient of skin temperature during each 10-s interval was too small for a gradient to be estimated. Based on an empirical study to determine the appropriate size for a time gap, 3 min were selected to estimate the gradient by using the formula below:

$$\text{Gradient of skin temperature } (t) = \text{Skin temperature } (t) - \text{Skin temperature } (t-18)$$

where t, present time point, and $t-18$: past time point by 18 units of 10 s (i.e., 180 s).

2.1.6. *Selected body locations for skin temperature measurements*

Ten body locations were selected for this experiment based on information about the existing 16 thermoregulation models [2]. Current models have adopted 3–15 body points, or segments, where skin temperatures are collected and different weighting factors are overloaded on them to estimate the mean skin temperature. As illustrated in Figs. 5 and 6, this study selected the forehead, posterior upper arm, wrist, hand, chest, belly, thigh, anterior and posterior calf, and foot from the points included in the 16 existing models, based on frequency of use and the sum of weight factors, as well as convenience in wearing sensors at a specific point.

2.1.7. *Experimental procedures*

In the authors' building indoor environmental quality study of more than 24 office buildings in the U.S., more than 98% of the investigated thermal conditions were within a range of 19.4 °C to 27.8 °C across all seasons [14]. Based on this finding, temperatures selected for this study ranged from 20 °C to 30 °C for the experiments, assuming these to be the typical minimum and maximum temperature levels in a built environment, where most subjects reported these as "cool" and "warm" in their surveys, respectively.

As summarized in Fig. 7, the experiment lasted for almost 3 h. It included wearing sensors, waiting in a standby room, staying in the environmental chamber, and answering a thermal sensation survey. The 30-min standby time was for stabilizing thermal and activity conditions affected by the earlier physical and physiological conditions that existed before the experiment. The standby area was maintained at 23 °C to 24 °C with 30% relative humidity. While the temperature changed at a rate of 1 °C/10 min in the environmental chamber, the subject was asked to report his/her overall thermal sensation every 10 min. Since this research adopts the index of PMV defined in ASHRAE-55, where thermal satisfaction rate is peak at the neutral condition, all the experiment participants were instructed how to report their warm, cool and neutral sensations considering their overall comfort. Each local body thermal sensation was also recorded so that the correlation between the local and whole body sensations could be determined. This paper, however, only used the overall thermal sensation data

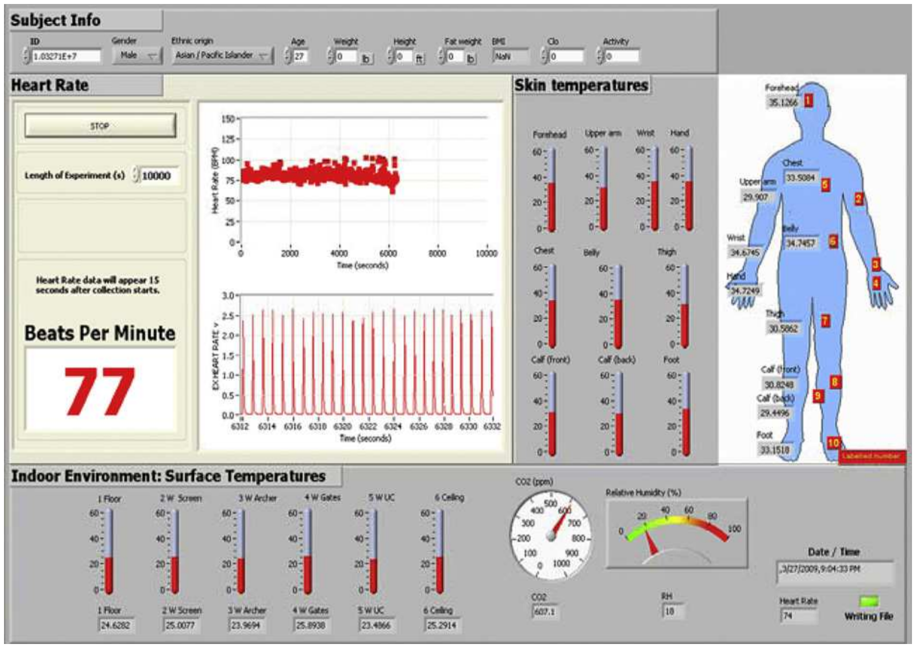


Fig. 3. Interface for the collection of human physiological and indoor environmental data (designed with LabVIEW).

to focus on skin temperature patterns per overall comfort condition in a thermally symmetric condition.

3. Results

In the human subject experiments, 26 volunteers participated and generated 260 data sets by reporting their overall thermal sensation 10 times throughout the 100 min of the experiment. The data analysis mainly focused on the differences in skin temperature and its gradient per thermal sensation.

3.1. *Skin temperature level by individuals*

Since individual subjects have different thermal preferences, their reported thermal sensation indexes were very diverse, even with the same thermal conditions. Therefore, most data analysis in this study was undertaken on the basis of thermal sensation, instead of thermal condition (i.e., air temperature). Fig. 8 illustrates the difference in skin temperatures between two human subjects at the selected body points. These differences range from 0.1 °C to 2.2 °C, depending on the body locations at the neutral sensation. Since skin temperatures are regulated under the thermoregulation principle, individual physiological characteristics, such as the body mass index, gender, and age, affect temperature levels [15]. Therefore, the absolute levels of skin temperatures may not provide appropriate information for estimating thermal sensation. Table 3 summarizes local skin temperature at ten body points on each individual subject. Data on individuals were combined based on each reported thermal sensation. In Table 3, the vertical line of each sensation level illustrates the 95% confidence intervals of the mean skin temperature on the selected body point for all the subjects. The horizontal axis indicates the overall thermal sensation. Depending on the thermal condition and an individual's thermal preferences, the duration of each thermal sensation varied.

In the upper arm, forehead, chest, and belly, the skin temperatures changed in proportion to the ambient temperature. While the air temperature changed from 20 °C to 30 °C, at a rate of 1 °C per 10 min, the body skin temperatures increased by 2 °C to 4 °C at different rates for selected body points. However, the skin temperature of the foot reacted in an opposite manner. Regardless of the increasing air temperature, the overall skin temperature of the foot essentially decreased. Even though the skin temperature increased slightly for a warm sensation, it varied, causing a wide deviation in the confidence interval range.

On the other hand, the anterior calf, posterior calf, hand, and wrist showed mostly a U-shaped curve. When the sensations were "cool" and "slightly cool", skin temperatures at these points were decreasing, and became almost stable around a neutral sensation. The two temperatures on the calf showed minimum mean values for the slightly cool and neutral sensations. The hand and wrist generated the lowest temperatures for the slightly cool and neutral sensations, respectively.

As illustrated in Table 3, the confidence intervals in different thermal sensations were mostly overlapped with those of other neighbor sensations. This finding indicates that there is no statistically significant difference in skin temperatures between two

Table 2
List of data acquisition devices.

Device	Model	Specification
Heart rate sensor	HER-BTA	Transmission frequency 5 kHz ± 10%
Temperature sensor	LM35DT	Accuracy: ±0.5 °C, resolution: 0.01 °C
Air velocity sensor	Testo 405-V2	Accuracy: ±5%, resolution: 0.01 m/s
CO_2 sensor	Telarire 6004	Accuracy: ±40 ppm
Radiant temperature sensor	OS-542	Accuracy: ±2 °C, resolution: 0.1 °C
Humidity sensor	HIH-4000-003	Accuracy: 3.5%, resolution: 0.5%
Body-fat monitor	Omron HBH-400	Resolution: 0.2 lb
Data acquisition board 1	Sensor DAQ	Resolution: 13 bit, sampling rate: 10 kS/sec
Data acquisition board 2	NI-DAQ 6008	Resolution: 12 bit, Sampling rate: 10 kS/s

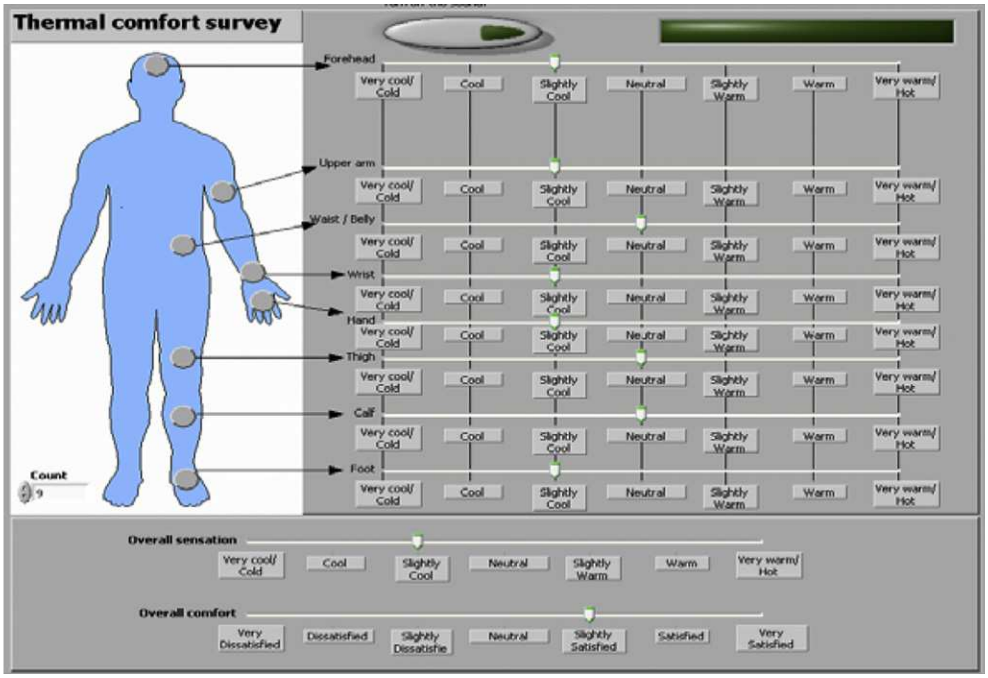


Fig. 4. Thermal perception survey interface (designed with LabVIEW).

different sensations (e.g., neutral versus slightly cool, and neutral versus slightly warm) on all of the selected body segments.

Based on these findings, we may conclude that individuals generate different levels of skin temperatures in each body location, even though their patterns are similar. The forehead and chest provide very similar patterns of skin temperatures, depending on thermal sensations. This may be due to the relatively thinner fat layers in these body locations that result in sensitive responses to variations of the air temperature [16]. The wide span of confidence intervals in the belly and posterior calf indicate that there are significantly large variations in the individual skin temperatures of the selected sensations.

According to the theory of predictive mean vote (PMV) [12], the neutral sensation is most critical for individual thermal comfort. This thermal condition represents a partial range of the slightly dissatisfied to slightly satisfied conditions that includes neutral satisfaction in order to maintain a thermal condition between the -0.5 to $+0.5$ PMV index. Therefore, detecting the neutral sensation from skin temperatures is critical and essential for any control system to determine additional heating or cooling. Accordingly, this study focused on significant differences in skin temperatures between the neutral condition and slightly warm/cool condition.

3.2. Gradient of skin temperature

For a more detailed analysis, the change rate of skin temperature (i.e., gradient) is estimated as another parameter. As discussed in the previous section, skin temperatures at the forehead, chest, and belly increased continuously in proportion to the air temperature increase. Even though there were some variations in gradients, the gradients of those body points were all positive. These positive gradients indicated there were continuous increases across the thermal sensation, from “cool” through “warm”. The gradients of the upper arm were the lowest values in the cool sensation, and the values increased until the slightly warm sensation. At the warm sensation, the value was positive; however, this indicated a wide range of confidence intervals due

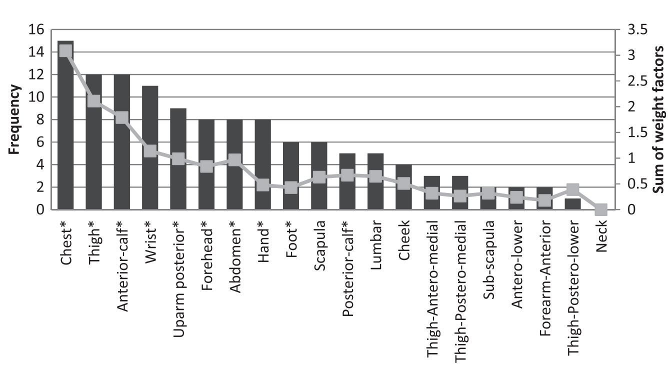


Fig. 5. Most frequently used body areas in 16 existing thermoregulation models [2].

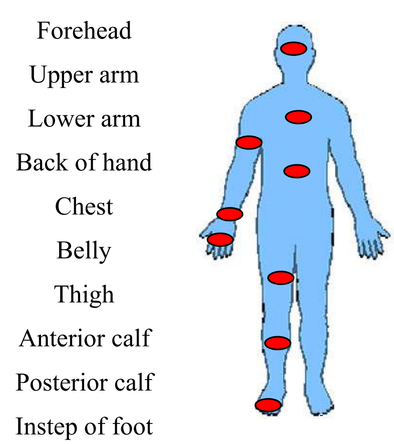


Fig. 6. Selected body locations for bio-signal data collection.

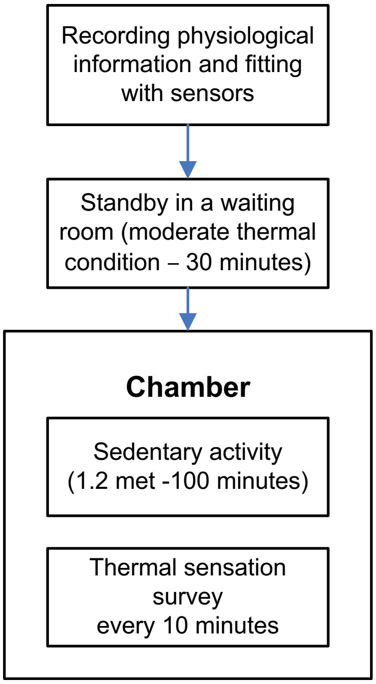


Fig. 7. The procedure of the second and third human subject experiments.

to large variations depending on the experimental subjects. The limb parts (i.e., anterior and posterior calves, hand, and wrist) showed minimum vectors in the sensations of slightly cool, neutral, or slightly warm. In the anterior and posterior calves, the neutral sensation showed that the confidence interval included the zero point, indicating no change during the sensation. However, the confidence interval had a wide range, from a negative to a positive gradient, even though it covered the zero point due to large variations in the subjects.

The hand and wrist showed a similar pattern. During the cool and cold sensations, the gradients were negative or zero, but changed to positive values when in the slightly warm / warm sensations. One of the significant findings pertaining to these two body points was that the gradient of the wrist was nearly a zero, with a very narrow confidence interval. This value indicated that this pattern was consistent for all of the subjects. (Table 4).

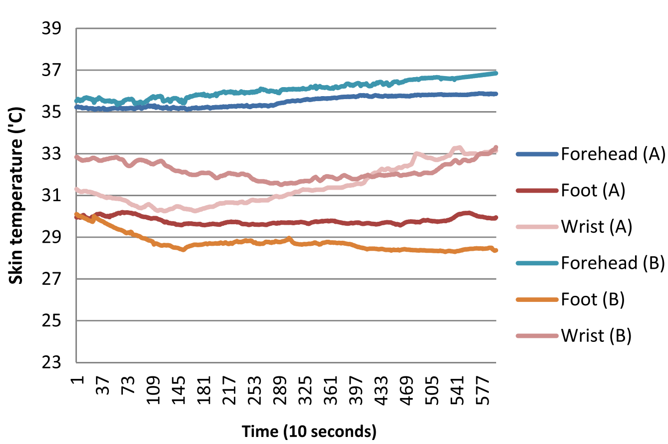


Fig. 8. Comparisons of skin temperatures between two subjects in a similar thermal environment: (A) sampled subject A; (B) sampled subject B.

3.3. Mean of square of gradient (MSG)

An analysis of the gradient may cause errors when a series of skin temperatures contains an inflection point during a neutral sensation. In that case, the average gradient could be around to zero for the period of this sensation, in spite of an inflection effect. Thus, the mean of the gradient for each thermal sensation was calculated. The gradient of skin temperature at each body location was squared to estimate the summation of the vector in the period of each thermal sensation, and the total square value was divided by the total number of the gradients calculated during the sensation. When the gradient was around zero, because of an inflection point in a selected sensation, the mean of the square of the gradient became much larger than zero. However, in the case of a constant level of skin temperature during the period with the same sensation, the MSG was around zero, with a very small value.

As shown in Table 5, most confidence intervals of each body location overlapped each other, and did not show any significant difference between the neutral and slightly warm, and between the neutral and slightly cool sensations. However, the two-sample t-test of the wrist showed a significant difference between the two sensations. Fig. 9 illustrates skin temperatures of the hand, wrist, and upper arm, and the thermal sensations reported for one sampled subject. The skin temperature line of the wrist showed an almost flat or lower slope than the line pattern of the hand and upper arm, while a neutral sensation was maintained. The hand showed an inflection at the beginning of and during the neutral sensation, while the skin temperature increased after the inflection point. On the other hand, the skin temperature of the upper arm continued to increase.

Therefore, as shown in Table 5, the wrist showed the least variation around zero at the neutral sensation, but positive values at other sensations. This data feature illustrates that the gradient was around zero for all subjects, while other selected body segments showed a wide range of variations in gradients at the neutral sensation.

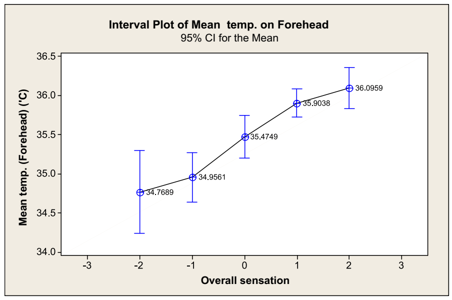
4. Discussion

As discussed in Section 3, maintaining a neutral sensation is most critical for the subjects or building occupants, particularly where the PMV is around zero. It is also important to differentiate between the slightly warm or slightly cool conditions and the neutral sensation. One of the fundamental theories for this study is that human thermal performance may vary, depending on an individual's thermal preferences that are primarily caused by differences in body mass index, gender, age, cultural background, etc. [10,17,18]. This is the main reason why this study grouped all of the skin temperatures collected from ten body points on 26 human subjects by their thermal sensations, rather than by the ambient thermal conditions. Accordingly, this study conducted two-sample t-tests comparing the two different sensations, slightly warm and neutral, and slightly cool and neutral.

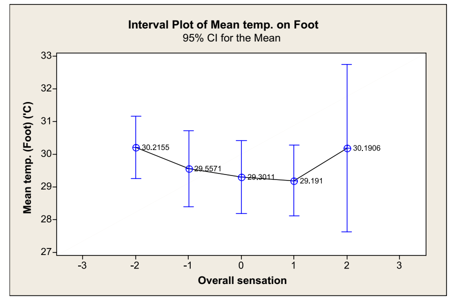
Table 6 summarizes results of the t-test comparisons of skin temperature levels at each body point for neutral and slightly cool/warm conditions. Only the forehead and chest showed a significant difference in the two comparison tests. The average temperature at the neutral sensation was 35.48 °C while it was 34.96 °C and 35.90 °C when slightly cool and slightly warm, respectively. The average differences between the two sensation sets (i.e., neutral and slightly warm sensations, and neutral and slightly cool sensations) were about 0.5 °C, and the comparisons were statistically significant with *P*-values lower than 0.05. Since the relatively thin fat layers on the forehead and chest contribute

Table 3
Absolute levels of skin temperature in each thermal sensation score.

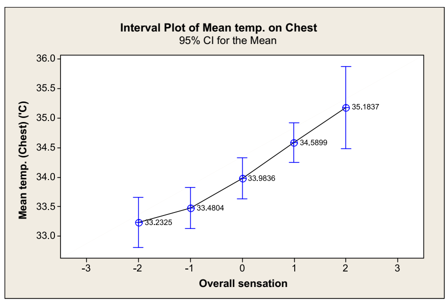
Forehead



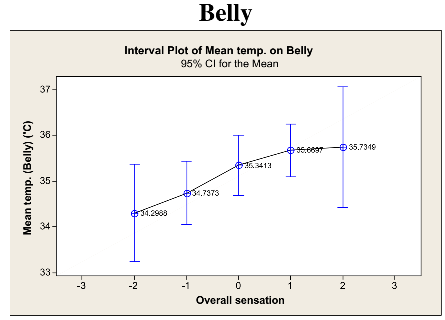
Foot



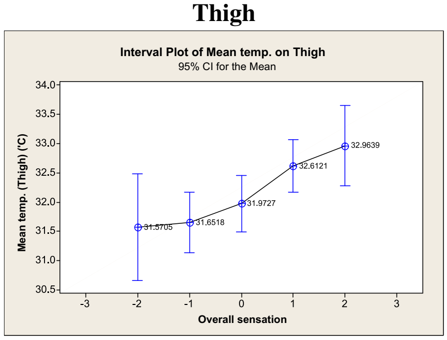
Chest



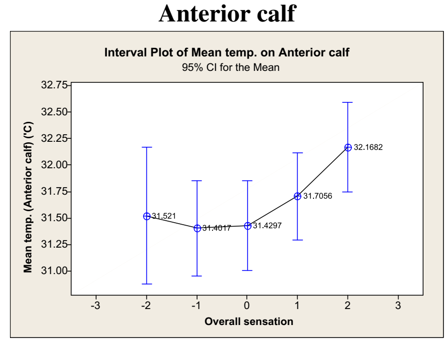
Belly



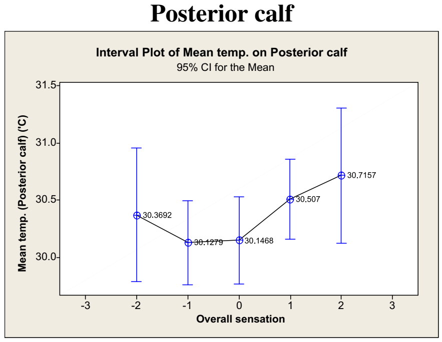
Thigh



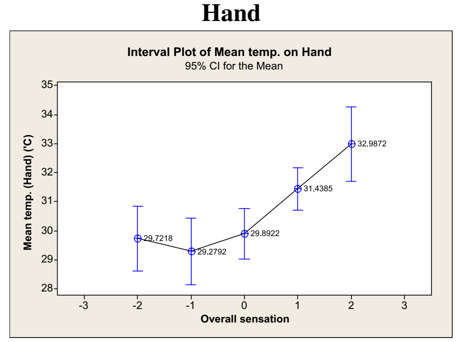
Anterior calf



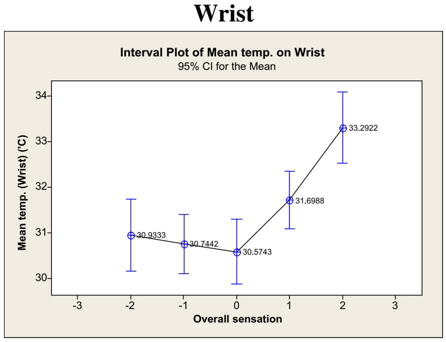
Posterior calf



Hand



Wrist



Upper arm

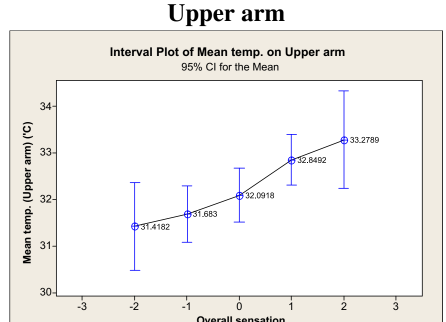
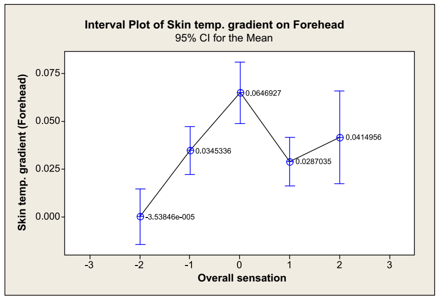
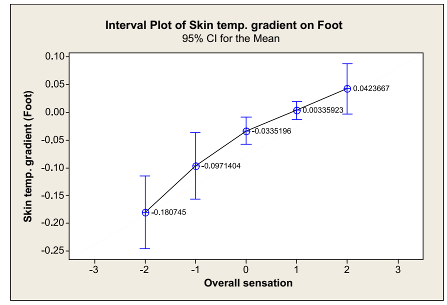


Table 4
Confidence intervals of skin temperature gradient (i.e., change rate) for all of the collected data (unit of y-axis: °C/3 min).

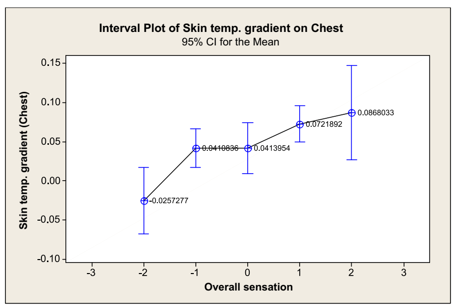
Forehead



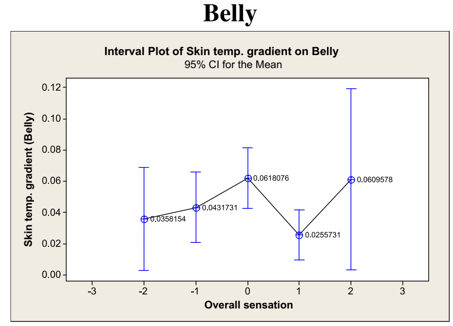
Foot



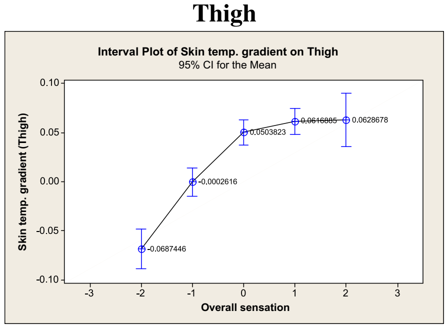
Chest



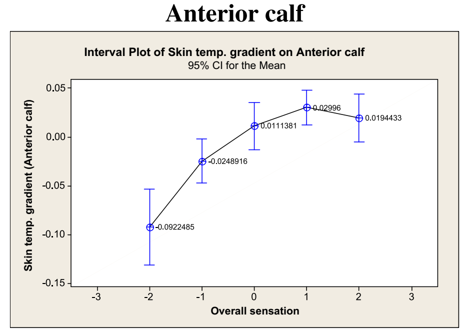
Belly



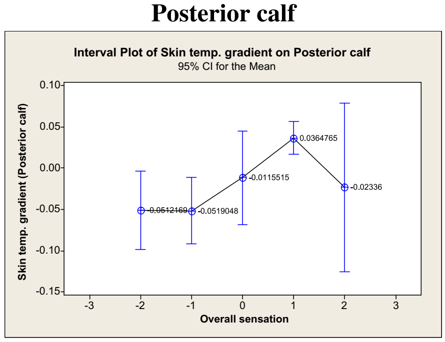
Thigh



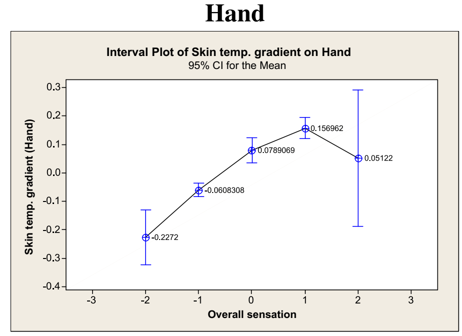
Anterior calf



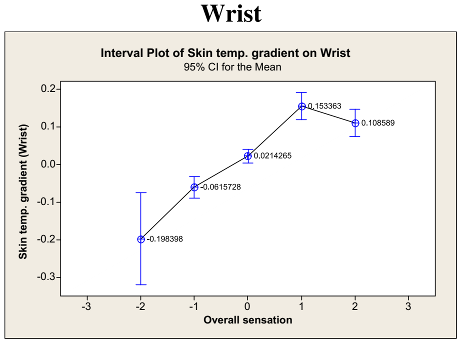
Posterior calf



Hand



Wrist



Upper arm

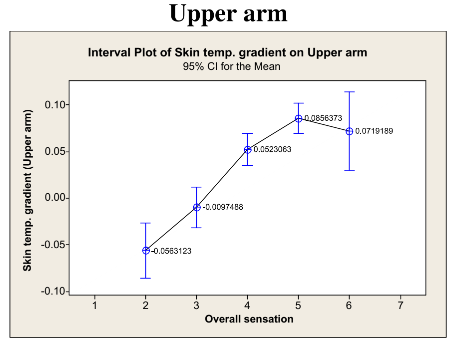
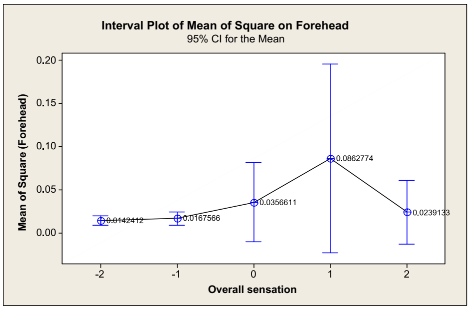
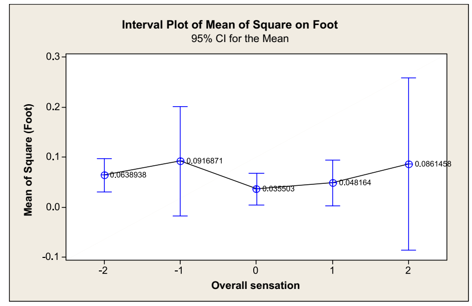


Table 5
Confidence intervals of the mean of the square of skin temperature gradient (MSG) in each body location.

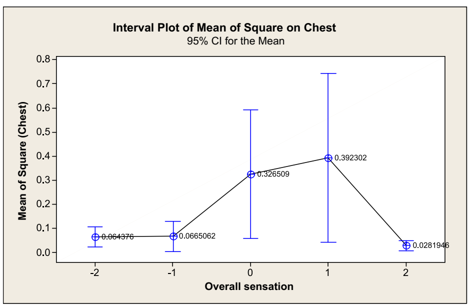
Forehead



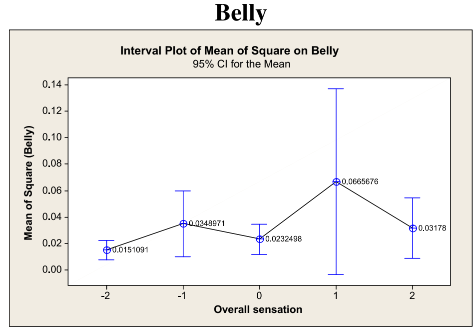
Foot



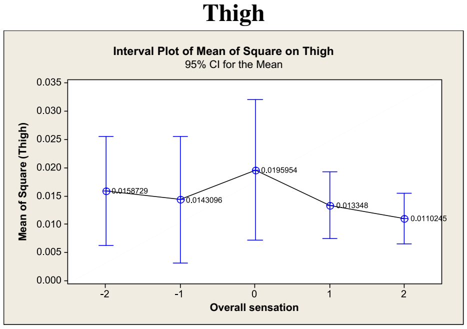
Chest



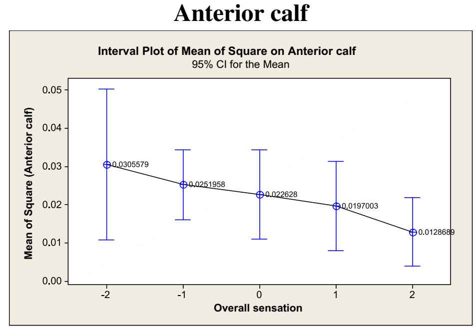
Belly



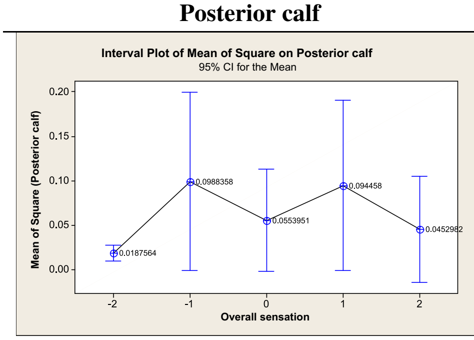
Thigh



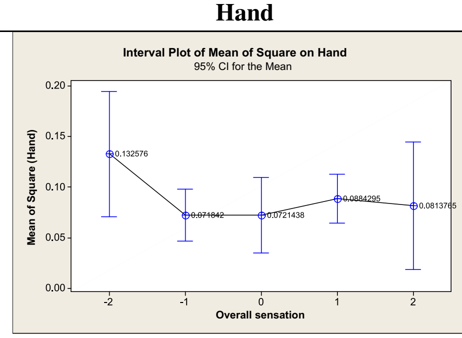
Anterior calf



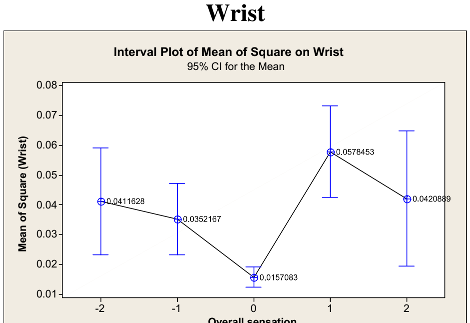
Posterior calf



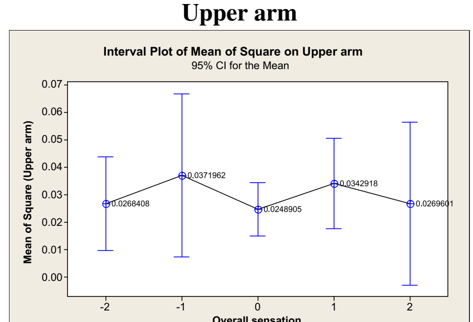
Hand



Wrist



Upper arm



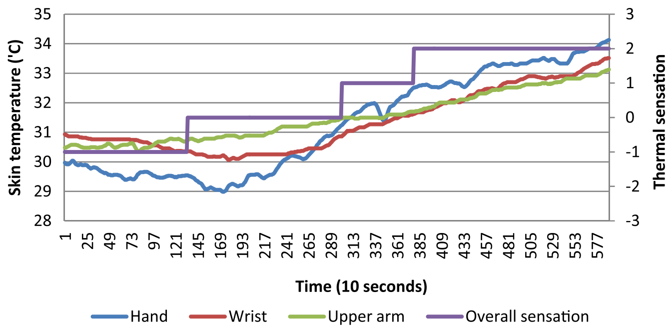


Fig. 9. Patterns of a sampled subject' skin temperatures on the hand, wrist, and upper arm, and thermal sensations (subject C).

to the constant increase in proportion to the rising ambient temperature, the comparison tests seemed to show a statistical significance.

In addition, the hand and wrist also showed a marked difference when skin temperature comparisons between the neutral and the slightly warm sensations were made, while comparisons between the neutral and the slightly cool sensations were not significant. As illustrated in Table 6, the skin temperature levels on the wrist and hand showed the lowest average at the neutral and slightly cool sensations, while the temperatures increased in relatively warmer conditions with quickly increasing rates. These sharp increases may have contributed to small *P*-values which were statistically significant. On the other hand, most levels of skin temperature and the reported overall sensations generated wide ranges of confidence intervals, especially at the slightly cool, neutral, and slightly warm sensations. This physiological feature indicated that the measured skin temperatures varied, depending on the subjects, even though their thermal sensations were at the same condition during the experiment. This limitation inferred that the absolute level of skin temperature may not be a suitable parameter for estimating a subject's thermal sensation.

The calculation of the gradient of skin temperatures provided interesting aspects of skin temperatures on the forehead, foot, hand, wrist, upper arm, thigh, and anterior calf (Table 7). The two two-sample t-test of the gradients reported variations between the neutral and slightly cool/slightly warm sensations that were statistically significant at those body points. The forehead showed significant gradients consistently while the chest did not. This was because the skin temperature on the chest increased consistently from the slightly cool sensation through the slightly warm sensation, while the forehead showed a sharp increase at the neutral sensation. The gradient of the upper arm was around zero at a slightly neutral sensation, but the values were larger when the sensation became relatively warmer. With a similar pattern, the foot, anterior calf, hand, and wrist showed significant gradient changes between the neutral and slightly warm sensations, and between the neutral and the slightly cool sensations.

The two-sample t-tests consistently supported the findings depicted in Table 8 regarding the pattern of skin temperature on the wrist. The mean of the square of the gradient was 0.0157, when the subjects were in the neutral sensation, and the value was the minimum among all of the thermal sensations. The *P*-value was 0.003 between the slightly cool and neutral sensations, and 0.000 between the slightly warm and neutral sensations. This study found the wrist to be the most responsive body location by using a filtration strategy for data analysis. This selection process was meaningful when the analyses of these three different data parameters (skin temperature, the gradient, and the mean of the square of the gradient) were sequentially estimated to be statistically significant.

Table 6
Two sample t-test of skin temperatures between neutral and slightly cool or slightly warm conditions.

	Average skin temperature (°C)			Two-sample t-test	
	Slightly cool ($n = 26$)	Neutral ($n = 26$)	Slightly warm ($n = 26$)	*P*-value (neutral vs. slightly cool)	*P*-value (neutral vs. slightly warm)
Forehead	34.96	35.48	35.90	0.013*	0.009*
Foot	29.56	29.30	29.19	0.747	0.886
Chest	33.48	33.98	34.59	0.040*	0.013*
Belly	34.74	35.34	35.67	0.198	0.442
Thigh	31.65	31.97	32.61	0.355	0.051
Anterior calf	31.40	31.43	31.71	0.926	0.343
Posterior calf	30.13	30.15	30.51	0.941	0.155
Hand	29.28	29.89	31.44	0.382	0.007*
Wrist	30.74	30.57	31.70	0.715	0.018*
Upper arm	31.68	32.09	32.85	0.320	0.056

Asterisks indicate statistical significance ($P < 0.05$).

Table 7
Two-sample t-test of skin temperature gradients between neutral and slightly cool or slightly warm conditions.

	Slightly cool ($n = 26$)	Neutral ($n = 26$)	Slightly warm ($n = 26$)	*P*-value (neutral vs. slightly cool)	*P*-value (neutral vs. slightly warm)
Forehead	0.035	0.065	0.029	0.004*	0.001*
Foot	−0.097	−0.034	0.003	0.051	0.014*
Chest	0.012	0.016	0.072	0.987	0.115
Belly	0.043	0.062	0.026	0.202	0.004
Thigh	−0.0003	0.050	0.062	0.000*	0.216
Anterior calf	−0.025	0.011	0.030	0.029*	0.205
Posterior calf	−0.052	−0.012	0.037	0.239	0.110
Hand	−0.061	0.079	0.157	0.000*	0.009*
Wrist	−0.062	0.021	0.153	0.000*	0.000*
Upper arm	−0.010	0.052	0.086	0.000*	0.005*

Asterisks indicate statistical significance ($P < 0.05$).

Table 8
Two-sample t-tests of the mean of the square of the gradient between neutral and slightly cool sensations or slightly warm sensation.

	Slightly cool ($n = 26$)	Neutral ($n = 26$)	Slightly warm ($n = 26$)	P-value (neutral vs. slightly cool)	P-value (neutral vs. slightly warm)
Forehead	0.017	0.036	0.086	0.409	0.382
Foot	0.092	0.036	0.048	0.318	0.641
Chest	0.067	0.619	0.773	0.062	0.758
Belly	0.035	0.023	0.067	0.386	0.218
Thigh	0.014	0.020	0.013	0.516	0.354
Anterior calf	0.025	0.023	0.020	0.723	0.715
Posterior calf	0.099	0.055	0.094	0.442	0.474
Hand	0.072	0.072	0.088	0.989	0.456
Wrist	0.035	0.0157	0.058	0.003*	0.000*
Upper arm	0.037	0.025	0.034	0.425	0.317

Asterisks indicate statistical significance ($P < 0.05$).

5. Conclusions

Since a human body adheres to the thermoregulation principle of maintaining a constant core body temperature, the regulation of skin temperature depends on the thermal condition of the body. As a human physiological factor, skin temperature has a lot of potential to be used for estimating a subject's thermal sensation.

This study investigated the nature of skin temperatures on ten body points, which were selected most often and significantly by the existing 16 thermoregulation models. Analysis of skin temperatures showed that the levels of temperatures vary, depending on the body points considered and the individual. It was hard to differentiate a neutral sensation from other thermal sensations (especially the slightly warm and slightly cool sensations) by only reading temperature levels. However, analysis of the gradient indicated the possibility of signal translations by reading the gradient, which was around zero at the neutral sensation while the values were positive and negative at slightly warm and cool conditions, respectively. This analysis found that the hand, wrist, and upper arm had similar skin temperature features, and showed that their average gradients were around zero at the neutral sensation. Since such a numerical feature could be caused by an inflection of the data obtained during a period of neutral sensation, the mean of the square of the gradient was required to accurately determine its significance.

The calculated MSG confirmed the numerical features of the gradient. A large MSG indicated that there was an inflection in the series of the data, and a small value around zero illustrated that the skin temperatures were very constant without any inflection or any fluctuation. As summarized in Section 4, this study found, through a series of statistical calculations, that the wrist is the most responsive body location where the skin temperature generated data during the neutral sensation that significantly differentiated it from other thermal sensations.

This finding is meaningful in that it showed the possibility of identifying the most responsive data location and to use the skin temperature data collected from that point to estimate a subject's thermal sensation. It showed the application potential of this finding for building mechanical systems as an input to generate an optimal set-point temperature so that a subject's ambient thermal sensation could be maintained at the neutral level while preventing over cooling or over heating conditions.

The study's human subject experiments had some limitations. First, the environmental chamber was almost thermally symmetric with nearly ideal conditions for thermal comfort without large temperature variations, either vertically or horizontally. Thus, the finding may only be suited for use with a symmetric condition. Secondly, only one activity level was considered in the experiment. Since a metabolic rate is one of the significant components for thermal comfort, the findings may be somewhat limited in dynamically changing activity conditions. In addition, the functional performance of sensor devices might contribute to the uncertainty of the measurement due to limited resolutions. Furthermore, as discussed in Section 3, individual responses vary even under a same thermal condition. It may be due to individual physical conditions, such as gender, body mass index, and ethnic origin. Since this study used only 26 subjects as experimental samples, additional tests with a statistically significant sample size would help examine specific patterns of individual responses by their physiological condition. Accordingly, further research is required to identify all of the features of skin temperature that may be applicable in a variety of combinations of environmental and human physiological conditions with a larger number of human subject experiments.

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References

[1] Wang XL, Peterson FK. Estimating thermal transient comfort. ASHRAE Transactions 1992;98:182–8.
[2] Choi JK, Miki K, et al. Evaluation of mean skin temperature formulas by infrared thermography. International Journal of Biometeology 1997;41:68–75.
[3] Kubota H, Kamata N, Ijichi T, Horii T, Mastsuo T. Prediction of mean skin temperature as an index of human response to the thermal environment. Available from: http://www.inive.org/members_area/medias/pdf/Inive/clima2000/1997/P317.pdf [accessed 21. 2. 2012].
[4] Yao Y, Lian Z, Liu W, Shen Q. Experimental study on skin temperature and thermal comfort of the human body in a recumbent posture under uniform thermal environments. Indoor and Built Environment 2007;16(6):505–18.
[5] Fiala D. Dynamic simulation of human heat transfer and thermal comfort. Ph.D. thesis. Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK; 1998.
[6] Fiala D, Lormas KJ, Stogrer M. A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. Journal of Applied Physiology 1999;87:1957–72.
[7] Taniguchi Y, Aoki H, Fujikake K, Tanaka H, et al. Study on car air conditioning system controlled by car occupants' skin temperature. International congress & exposition, Detroit, Michigan; Feb. 1992.
[8] Zhang H. Human thermal sensation and comfort in transient and non-uniform thermal environments. Ph.D. thesis, University of California, Berkeley, Center for the Built Environment; 2003.
[9] Taylor Nigel AS, Kim Alisopp N, Parkes David G. Preferred room temperature of young vs aged males: the influence of thermal sensation, thermal comfort, and affect. The Journals of Gernotology 1995;50A(4):216–21.
[10 Mozaffarieh M, Gasio PF, Schötzau A, Orgül S, Flammer J, Kräuchi K. Thermal discomfort with cold extremities in relation to age, gender, and body mass index in a random sample of a Swiss urban population. Population Health Metrics 2010;8:17.
[11] WHO. BMI classification. World Health Organization. Available from: http://www.apps.who.int/bmi/index.jsp%3fintroPage%BCintro_3.html, [accessed 21. 2. 2012].

[12] ASHRAE Standard 55. Thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Refrigerating, and Air-conditioning, Inc.; 2010.
[13] Choi J, Loftness V, Lee D. Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models. Building and Environment 2012;50:165–75.
[14] CBPD. National Environment Assessment Toolkit™ – GSA workplace 2020 project technical report to the U.S. General Services Administration. Pittsburgh, PA: Center for Building Performance and Diagnostics, Carnegie Mellon University; 2008.
[15] Griefahn B, Künemund C, Gehring U, Mehnert P. Drafts in cold environments – the significance of air temperature and direction. Industrial Health 2000;38:30–40.
[16] Hori S, Ihuka H. Comparison of physical characteristics, body temperature and resting metabolic rate at 30 °C between subtropical and temperate natives. International Journal of Biometerology 1983;30(2):115–22.
[17] Fountain M, Brager G, de Dear R. Expectations of indoor climate control. Energy and Buildings October 1996;24(3):179–82.
[18] Yao R, Li B, Liu J. A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV). Building and Environment 2009;44(1):2089–96.