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# A Field Investigation to Quantify the Correlation between Local and Overall Thermal Comfort in Cool Environments

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**Abstract:** The thermal comfort of local body parts is the essential factor that affects people's health and comfort as well as a buildings' energy. This study aims to (1) investigate the characteristics of the local thermal comfort of different body parts of occupants in real buildings in winter, (2) quantify the correlation between the amount of local body parts with coolness or discomfort and the overall subjective thermal responses, and (3) validate an easy-to-use local–overall thermal comfort model. A field investigation in the office and study rooms of a university was conducted in winter. The results indicate that the top five percentages of local coolness appeared in the feet (41.02%), the hands (26.58%), the calves (25.18%), the thighs (13.99%), and the head (9.72%) and that the top five percentages of local discomfort appeared in the feet (44.99%), the palms (28.2%), the calves (24.74%), the head (19.66%), and the thighs (16.35%). Moreover, when the whole body felt cool, at least four local body parts had cool sensations; when the whole body felt thermally uncomfortable, at least three local body parts had cool sensations; and when the whole body felt that the ambient environment was thermally unacceptable, at least seven local body parts had cool sensations. Meanwhile, the correlation between local discomfort and whole-body responses was different: when the whole body felt thermal uncomfortable, at least three local body parts had discomfort; and when the whole body felt that the ambient environment was thermally unacceptable, at least four local body parts had discomfort. Further, the local–overall thermal comfort model proposed by the authors exerted high accuracy in predicting overall thermal comfort.

**Keywords:** local thermal sensation; local thermal comfort; thermal environment

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## 1. Introduction

As defined in the ASHRAE Standard 55 [1], thermal comfort is a subjective state of awareness in which the human body evaluates the ambient thermal environment; it is affected by the heat transfer of convection, radiation, and evaporation between the human body and the ambient environment, which are mainly decided by indoor air temperature, radiant temperature, air humidity, air velocity, clothing insulation, and human metabolic rate. The detailed heat transfer between the human body and the ambient environment can be calculated by the predicted mean vote (PMV) model, which is also incorporated in the ASHRAE Standard 55 [1]. Thermal comfort is the ultimate criterion for evaluating the quality of buildings' thermal environments since it significantly affects the health and work performance of the occupants of buildings [2]. To improve the thermal comfort demands of occupants and work performance in buildings, heating, ventilation, and air conditioning (HVAC) systems have been widely adopted in modern buildings and, at the same time, have resulted in massive energy consumption.

In China, the total energy consumption for heating, ventilation, and air conditioning systems accounts for up to half of the total building energy consumption [3]. One of the primary reasons for this is that a large amount of energy is consumed to create uniform thermal environments, which, however, are unable to accommodate people's comfort demands, as the local thermal states of body parts can result in individual differences [4–6]. For example, females usually feel cool discomfort in their hands and feet in the winter even when the indoor temperature is moderate and comfortable for men [7]. Numerous studies have found that local thermal comfort has a significant impact on the overall thermal comfort [8–10]. Local heating that warms one or several body parts allows a person to maintain comfort when the ambient environment is cool or cold. For example, in cold environments, warming the lower body parts (feet and legs) can make occupants feel that the environment is thermally acceptable, even if it has been lowered to 14 °C indoors [11], which helps to reduce the energy consumption needed for heating building spaces to a relatively high temperature like 20 °C. To energy efficiently improve local thermal comfort, personal comfort systems (PCSs) have been widely investigated, including seats [12,13], foot warmers [14], wrist warmers [15], radiant panels [16], garments [17], local ventilation devices [18], etc.

In recent years, to understand well how local body parts affect overall thermal responses, many researchers have conducted human experiments in climate chambers. In 2003, Zhang et al. [19] found that the local thermal sensations of different body parts had various influences on the overall thermal sensations. They proposed the UCB (University of California, Berkeley) model for predicting overall thermal sensations and further improved the model in 2009 [8]. Fang et al. [20] proposed that the local thermal sensations of body parts are sparsely distributed differently. Khiavi et al. [21] combined local thermal responses with the UCB model to form a new integrated assessment method to predict overall thermal sensations. Jian et al. [22] set up three experimental scenarios to explore how the coldest local thermal sensation affects the overall thermal sensation, and they found that the feet had the coldest sensations, with the most obvious skin temperature drops. Liu et al. [23] heated 15 body parts and found that heating the waist was better than heating the feet for overall thermal comfort. Sun et al. [24] studied wrist skin temperature during sleeping through several human experiments and found that wrist skin temperature was sufficient for predicting human thermal status. Li et al. [25] proposed that the head, the chest, the back, and the hands were easy to be warm, which led to a warm overall thermal sensation, and the arms, the hands, the legs, and the feet were easily cool, which led to a cool overall feeling during cold exposure. Du et al. [26] suggested that the occupants in their study had a preference for heating their feet and lower-body areas, with a significant increase in the thermal sensations in the feet and the whole body when local heating is provided. Cheng et al. [27] established non-contact measurements of skin temperatures and deep learning to reflect the human thermal comfort state, which can be used to control HVAC systems. Jia et al. [28] claimed that overall thermal sensation is significantly correlated with facial skin temperature.

In addition to laboratory experiments, some scholars have also explored the correlation between local and overall thermal comfort in real environments. Shahzad et al. [29] found that people's local thermal comfort in residential buildings may be improved by heated chairs, which, in turn, enhance people's overall thermal comfort. Kim et al. [30] suggested that 99% of occupants' thermal satisfaction can be obtained with PCSs that locally cool or warm human bodies. Chen et al. [31], after a questionnaire survey conducted in six areas of Harbin (with a cold climate), pointed out that the actual overall thermal sensation is decided by the thermal status of the coldest body part.

The authors have also carried out several field studies on local and overall thermal comfort in the past few years: He et al. [32], based on a field study in an office in Zhuhai, suggested that the head, the hands, the legs, and the feet affected the overall thermal sensation more than other body segments. He et al. [33] also conducted an on-site investigation in air-conditioned university dormitories. They found that, in the summer, the overall thermal comfort was determined by the two most extreme body parts, which were usually the head and the chest. Hu et al. [7] carried out a winter field survey at a university to analyze the gender differences in thermal comfort, work performance, and sick building syndromes in real-world environments, and they found that the fingers easily had very low skin temperatures in the winter. He et al. [34] proposed a new method based on infrared thermography to predict the thermal state of an occupant based on the local skin temperatures of the hands, the cheeks, and the nose.

Although the above-stated literature review indicates the importance of local thermal comfort, some critical scientific gaps remain unfilled. First, most of the above-mentioned studies are based on laboratory experiments, and the obtained results may deviate from those of realistic environments; the existing studies seldom analyze the percentages of local discomfort of different body parts in actual buildings. Second, the existing studies seldom indicate how the amount of uncomfortable local body parts affects the overall thermal comfort. For instance, when a person feels discomfort, how many local body parts are experiencing discomfort? Third, most of the existing local–overall thermal comfort models have not been validated in real buildings. An easy-to-use model with full validation in real buildings can help further the investigation of local thermal comfort in the future.

The primary purposes of this study are the following: (1) explore the local thermal comfort of occupants through an investigation in real buildings in winter, as well as determine the percentages of different local parts with cool sensations and discomfort under different indoor temperatures; (2) quantify the effects of the amount of local cool sensations and discomfort on one's overall feelings, including overall thermal sensation, comfort, and acceptability; and (3) validate an easy-to-use local–overall comfort model proposed by the authors using data collected in real office buildings.

## 2. Materials and Methods

### 2.1. Geography and Climate

The investigation was carried out between November 2019 and January 2020 (the winter period in the Hunan province includes November, December, January, and February), and all the surveys were conducted on weekdays from 8:00 a.m. to 6:00 p.m. when there were many occupants indoors. Each participant filled out the questionnaire only once, which could usually be completed within ten minutes.

The field investigation was performed at Hunan University in Changsha, which is located in central China (latitude 27°51′–28°40′ N and longitude 11°53′–114°15′ E), as shown in Figure 1, with abundant precipitation. Changsha has a warm climate in the summer (the average temperature in July is about 29 °C) and a cold climate in the winter (the average temperature in January is about 5 °C) [35]. Meanwhile, the outdoor relative humidity is often higher than 70% throughout the year.


**Figure 1.** The location of Changsha [36].

## 2.2. Investigated Buildings

The investigation was performed in the office and study rooms of three buildings of Hunan University (as shown in Figure 2), including the main hall of the College of Civil Engineering (Building A), the Research Center for Green Building Energy Efficiency and Green Buildings (Building B), and the Library of Hunan University (Building C). All three buildings had reinforced concrete structures, with a total of six floors in Building A, three floors in Building B, and nine floors in Building C. Each room had several operable single-glazed windows and split-type air conditioners, and each air conditioner had a plug-in controller panel for the occupants to freely change the indoor set-point temperature. Each window was closed, and each air conditioner was running during the investigation. In general, the air conditioning was turned on at around 8 a.m. on weekdays, when the earliest occupants entered the office, and it was turned off when the last occupant left the office, depending on when the occupants finished their work.

(**a**) (**b**) (**c**)

**Figure 2.** The investigated buildings and rooms: (**a**) Building A, (**b**) Building B, and (**c**) Building C.

## 2.3. Measurement

This study measured the same environmental and physiological parameters with the same types of instruments as those in the previous work of the researchers [6]. The main topic, scenarios, locations, and findings of this study are different from those of our previous work, which focused on the gender differences in thermal comfort, work performance, and sick building syndrome in naturally ventilated and air-conditioned classrooms [7].

The indoor temperature and humidity recorder were placed 0.6 m above the floor. An oximeter was used to measure oxygen saturation ($SpO_2$) and heart rate and was attached to a participant's left middle finger for each measurement. The instruments recorded the environmental parameters after having been placed in a room for 30 min and displayed a stable value. Portable thermocouples were adopted to record the skin temperatures of the participants' foreheads, cheeks, necks, backs of the hands, and fingertips. Since the participants generally moved and used their right hand frequently, the measurement was conducted on their left body side to reduce disturbance on the participants. Detailed information about the instruments used in this study is presented in Table 1. All the instruments were calibrated by the manufacturer before the investigation, and the measurement was conducted when the questionnaire was distributed to the participants.

**Table 1.** Experimental instruments used in this study.

| Type | Parameter | Instrument | Models | Range | Accuracy |
|---|---|---|---|---|---|
| Environmental | Air temperature | Temp. and humidity recorder | TR-72Ui | −10~60°C | ±0.3 °C |
| | Relative humidity | Temp. and humidity recorder | TR-72Ui | 10–90% | ±5% |
| Physiological | Skin temperature | Thermocouple | 905 12 | −50~350 °C | 0.1 °C |
| | Heart rate/$SpO_2$ | Oximeter | YX303 | 70–100% | ±2% |

### *2.4. Survey*

Before conducting the survey, each student who participated gave their oral consent. Second, the questionnaire was administered to subjects who had been seated in the office for more than 30 min. Third, the questionnaire was explained orally to each participant by the researchers. Figure 3 shows the main questions of the used questionnaire. The participants selected the most proper thermal sensation and comfort levels from an integer seven-point scale (from “cold” to “hot” and from “very uncomfortable” to “very comfortable”, with the corresponding values ranging from −3 to 3). In addition, the participants were asked to choose whether the indoor thermal environment was “acceptable” or “unacceptable” (the corresponding values were 1 and 0, respectively). The specific scales are shown in Table 2.

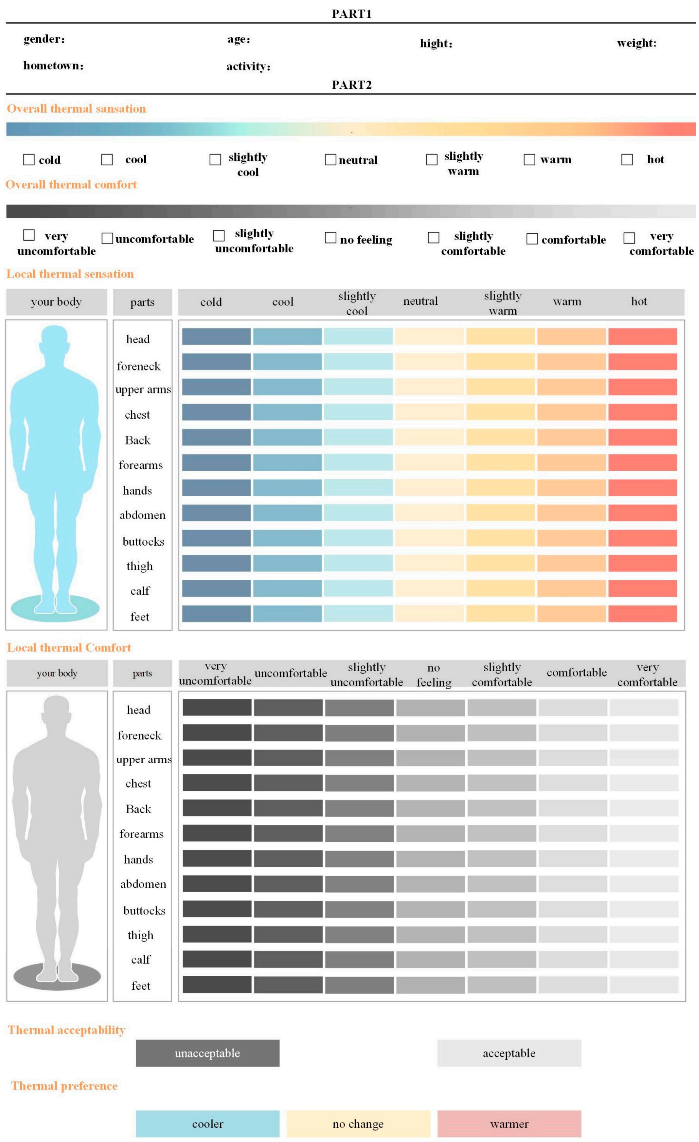


**Figure 3.** The main questions of the questionnaire used in this study.

**Table 2.** Scales of subjective responses.

| Voting Scale | Thermal Sensation | Thermal Comfort | Thermal Acceptability |
|---|---|---|---|
| 3 | Hot | Very comfortable | |
| 2 | Warm | Comfortable | |
| 1 | Slightly warm | Slightly comfortable | Acceptable |
| 0 | Neutral | Neutral | Unacceptable |
| −1 | Slightly cool | Slightly uncomfortable | |
| −2 | Cool | Uncomfortable | |
| −3 | Cold | Very uncomfortable | |

### *2.5. Participants*

All the participants were graduate or undergraduate students at Hunan University, and they were working or studying in the investigated rooms from 8:00 a.m. to 8.00 p.m. during the investigation. All the students were in good health, with no disabilities or illnesses, and they did not have alcohol or smoke before or during the survey. In addition, there were no restrictions on students' clothes in the university, and the students wore thick clothes in different rooms due to the cold weather during the investigation. To be specific, each of the students mainly wore a thick jacket, a sweater, and long trousers.

### *2.6. Data Filtration and Analysis*

In total, 1479 questionnaires were assigned, and 1356 valid questionnaires were obtained (656 men (48.4%) and 700 women (51.6%)) after eliminating the questionnaires with incomplete key data.

First, the overall percentages of cool sensations (including "slightly cool", "cool", "cold", and "very cold"), discomfort (including "slightly uncomfortable", "uncomfortable", and "very uncomfortable"), and thermal unacceptability were calculated. Then, the bin method was adopted for data analysis. Specifically, the data under different air temperatures were assigned to different integer temperature bins with an interval of 1 °C, and the integer temperature value was used as the standard temperature for each bin, based on which the key data for our analysis such as the thermal discomfort percentages were calculated at different integer temperature values. For example, the thermal comfort values under indoor air temperatures of 18.7 °C, 18.9 °C, and 19.1 °C were within the "18.5–19.5 °C" range and then were assigned to the temperature bin of 19.0 °C, which was taken as the standard temperature for the above-mentioned thermal comfort values. Afterward, the relationship between the amount of cool and uncomfortable local body parts and the overall subjective responses was analyzed using the above-mentioned percentage data.

Further, with the survey data, an easy-to-use local–overall thermal comfort model proposed in the previous experimental work of the authors [37] was validated. To be specific, the local cool sensation and discomfort data under different indoor temperatures in this study were substituted into the model to obtain the predicted overall cool sensation and overall discomfort data. The differences between the actual and predicted overall cool sensations and discomfort under different indoor temperatures were calculated as the absolute deviation (the absolute value of the difference between the actual and predicted values) to determine whether the model was applicable in real buildings. The model was expressed as follows:

(1) For thermal sensations, the association between the overall thermal sensation (*OTS*) and the local thermal sensation (*LTS*) could be represented as follows:

$$OTS = 0.5 \times (LTS_{1st,\ \ warm} + LTS_{2nd,\ \ warm} + LTS_{1st,\ \ cool} + LTS_{2nd,\ \ cool}) \quad (1)$$

where $LTS_{1st,\, warm}$ is the local thermal sensation of the warmest body segment on the warm side; $LTS_{2nd,\, warm}$ is the local thermal sensation of the second-warmest body segment on the warm side; $LTS_{1st,\, cool}$ is the local thermal sensation of the coolest body segment on the cool side; and $LTS_{2nd,\ cool}$ is the local thermal sensation of the second-coolest body segment on the cool side.

When the amount of body parts on the warm or cool side was less than two, the calculation would be based on the actual number of body parts on the warm or cool side.

(2) For thermal comfort, the association between the overall thermal comfort (*OTC*) and the local thermal comfort (*LTC*) was determined through two rules below:

(1) Rule 1: The amount of local body parts on the comfortable side (n+) was less than that on the uncomfortable side (n−). In this case, the relationship between the overall thermal comfort (*OTC*) and the local thermal comfort (*LTC*) was modeled as follows:

$$OTC = 0.5 \times \left(LTC_{1st,\quad discomf} + LTC_{2nd,\quad discomf} + LTC_{1st,\quad comf}\right) \tag{2}$$

where $LTC_{1st,\ discomfort}$ is the local thermal comfort of the most uncomfortable body segment on the uncomfortable side; $LTC_{2nd,\ discomf}$ is the local thermal comfort of the second most uncomfortable body segment on the uncomfortable side; and $LTC_{1st,\ comf}$ is the local thermal comfort of the most comfortable body segment on the comfortable side.

(2) Rule 2: The amount of local body parts on the comfortable side (n+) was greater than that of the body parts on the discomfort side (n−). In this case, the relationship between the overall thermal comfort (*OTC*) and the local thermal comfort (*LTC*) was modeled as follows:

$$OTC = 0.5 \times \left(LTC_{1st,\quad comf} + LTC_{2nd,\quad comf} + LTC_{1st,\quad discomf}\right) \tag{3}$$

where $LTS_{2nd,\ comf}$ is the local thermal comfort of the second most comfortable body segment on the comfortable side.

If no body segment had discomfort, Model (3) could be written as follows:

$$OTC = 0.5 \times \left(LTC_{1st,\quad comf} + LTC_{2nd,\quad comf}\right) \tag{4}$$

## 3. Results

### *3.1. Overview of the Subjects*

Table 3 shows the information of the participants in this study. It can be found that 92.7% of the participants were 16–24 years old; 30.0% of the female participants were in the height range of 160–170 cm, while 29.6% of the male participants were in the height range of 170–180 cm; 27.8% of the female participants weighed 50–60 kg, while 20.5% of the male participants weighed 60–70 kg. In addition, 70.1% of the participants had BMI values of 18.5–23.9 kg/m$^2$.

**Table 3.** The distributions of participants' parameters.

| Information | Range | Percentage (Overall %) | Percentage (Male %) | Percentage (Female %) |
|---|---|---|---|---|
| Age | 16–18 | 42.4 | 23.1 | 19.4 |
| | 19–21 | 41.3 | 19.9 | 21.4 |
| | 22–24 | 9.0 | 4.3 | 4.7 |
| | >24 | 7.3 | 2.8 | 4.5 |
| Hight | <160 | 16.4 | 0.1 | 16.4 |
| | 160–170 | 40.8 | 10.8 | 30.0 |
| | 170–180 | 33.1 | 29.6 | 3.5 |
| | 180–190 | 9.3 | 9.2 | 0.1 |
| | >190 | 0.3 | 0.3 | 0.0 |

**Table 3.** *Cont.*

| Information | Range | Percentage (Overall %) | Percentage (Male %) | Percentage (Female %) |
|---|---|---|---|---|
| Weight | <50 | 16.0 | 1.0 | 15.0 |
| | 50–60 | 43.0 | 15.2 | 27.8 |
| | 60–70 | 26.5 | 20.5 | 6.1 |
| | 70–80 | 11.1 | 10.3 | 0.8 |
| | >80 | 1.5 | 1.3 | 0.2 |
| BMI | <18.4 | 19.4 | 9.0 | 10.4 |
| | 18.5–23.9 | 70.1 | 32.9 | 37.2 |
| | 24.0–27.9 | 9.7 | 7.7 | 2.1 |
| | >28 | 0.8 | 0.6 | 0.2 |

### *3.2. Environmental Parameters*

During the survey period, the main outdoor temperatures in Changsha were 5.8–14.5 °C, and the outdoor humidity was mainly 60–100%. Figure 4 illustrates the indoor temperatures and indoor humidity during the survey period. The average indoor temperature and humidity were 20.4 °C and 39.7%, respectively, and most of the rooms had temperatures higher than 18 °C.

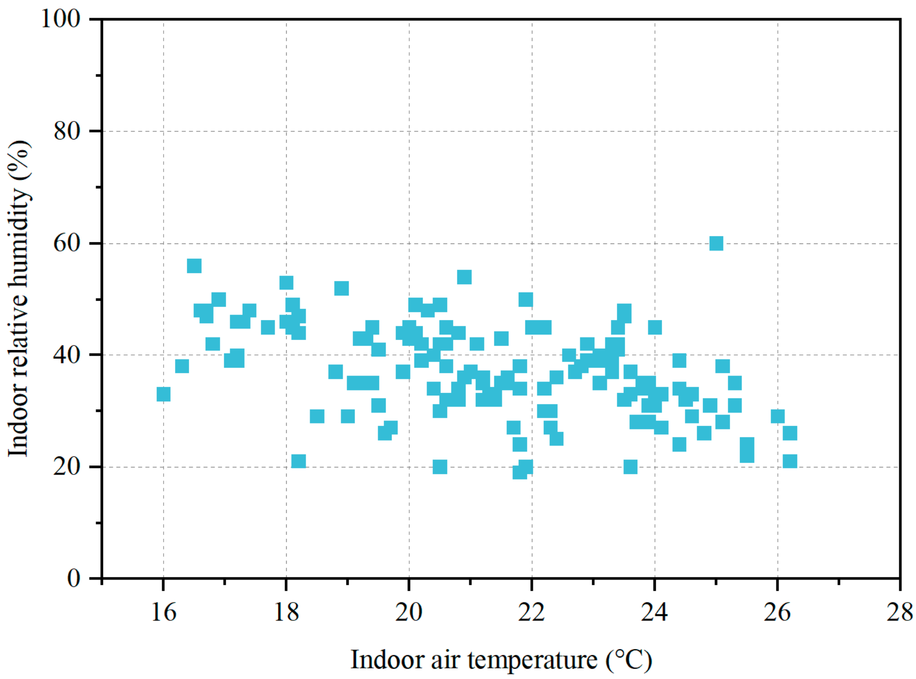


**Figure 4.** Environmental parameters: indoor temperature and relative humidity.

### *3.3. Physiological Parameters*

Figure 5 illustrates the local skin temperatures under different indoor temperatures. Noticeably, local skin temperature gradually increased as the room temperature rose. The fingertip temperatures were the lowest under different indoor temperatures, and the second-lowest one was the back of the hand.

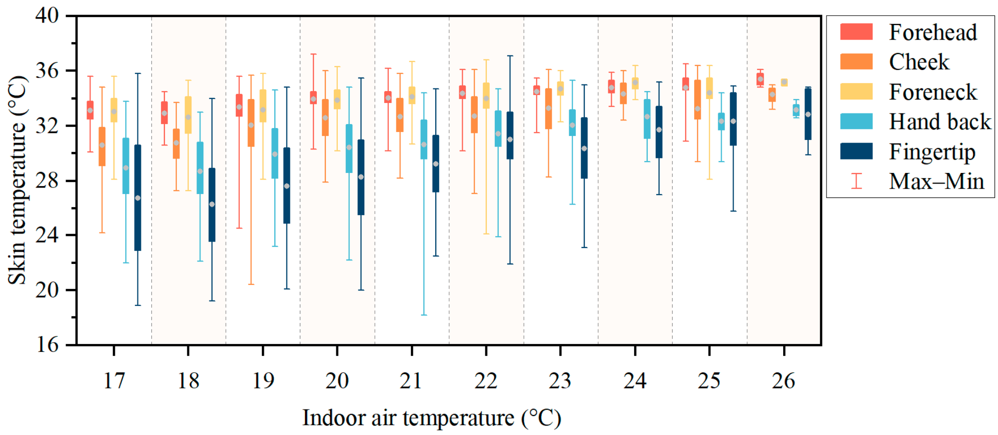


**Figure 5.** Distributions of participants' local skin temperatures.

Figure 6 shows the regression results of local skin temperatures and indoor temperatures. Local body parts had larger skin temperature differences as the indoor environment became cool. For example, when it was 17 °C indoors, the difference between the forehead and the fingertips was 6.5 °C, and, when it was 26 °C indoors, the skin temperature difference was merely 2.6 °C.

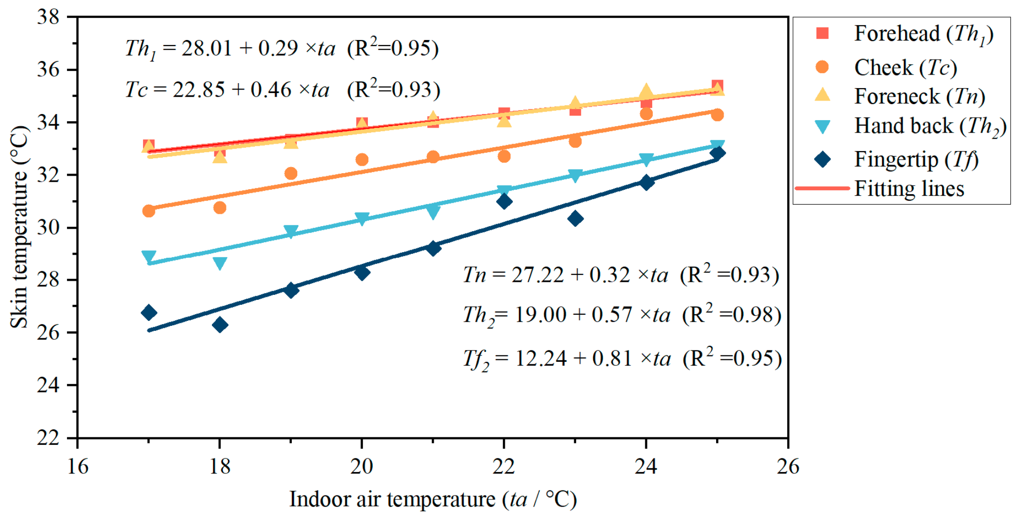


**Figure 6.** Average skin temperatures of different body parts.

In addition, at different temperatures, the $SpO_2$ values of the participants mainly varied between 97% and 98%, and the heart rate mainly varied between 60 and 80 bpm, which had no significant correlation with the indoor temperature.

### *3.4. Ranking of Local Cool Sensations*

Figure 7 represents the percentages of different local body parts with cool sensations. It shows that body extremities are prone to cool sensations. Specifically, the top five percentages of local cool sensations appeared in the feet (41.02%), the hands (26.58%), the calves (25.18%), the thighs (13.99%), and the head (9.72%). It should also be noted that the head could also have noticeable cool sensations in the winter despite the indoor temperatures being usually higher than 18 °C (see Figure 4), which could be attributed to the fact that no participants wore hats or had their heads covered when staying indoors.

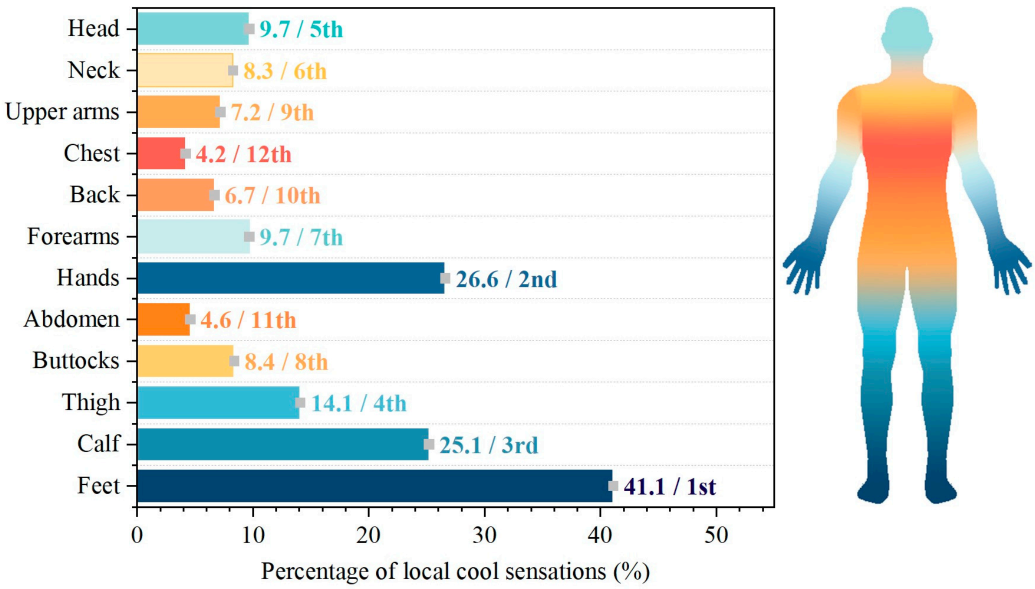


**Figure 7.** Percentages of the top five discomfort body parts under different indoor temperatures.

Figure 8 shows the change in the proportions of local coolness in the top-five-ranked body parts under different indoor temperatures. It was found that, as the room temperature decreased, the percentages of cool sensations increased rapidly for body extremities (feet, hands, calves). To be specific, when the temperature reached 19 °C, nearly half of the participants had cold sensations in their feet, and, when the temperature reached 17 °C, close to 50% of the participants had cool hands, and 40% of the participants had cool calves.

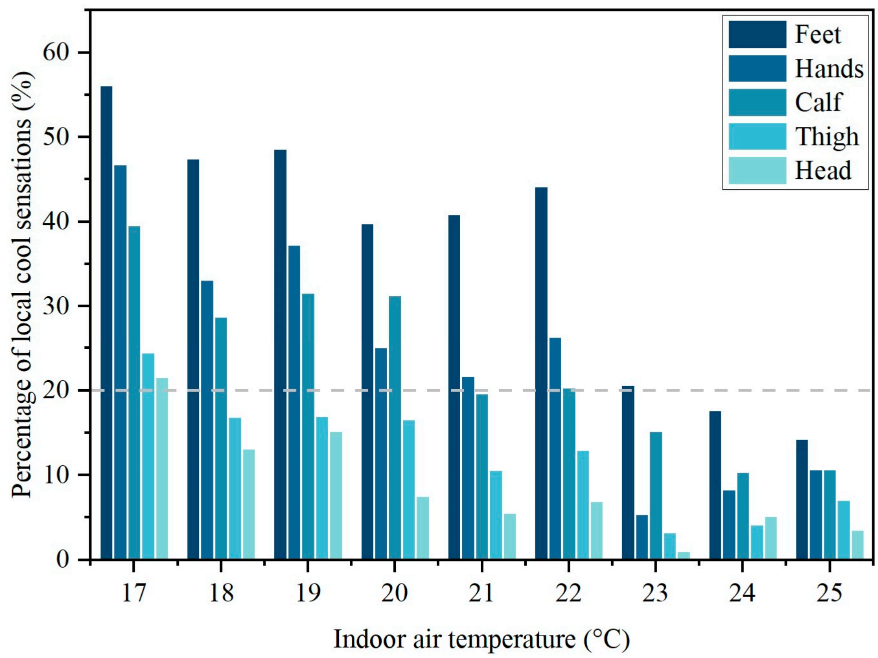


**Figure 8.** Percentages of the top five cool body parts under different indoor temperatures.

Furthermore, it was found that the top three body parts with the largest percentages of cool sensations remained unchanged under different indoor temperatures, with small differences in the order of the local body parts. Specifically, under different indoor temperatures, the top three body parts with the largest percentages of cool sensations were the feet, the hands, and the calves, and the cool sensation of the feet was much higher than that of the other two parts. In addition, it should be noted that, even when it was

20 °C or higher indoors, some body parts (feet, calves, and hands) still had noticeable cool sensations (higher than 20%), which indicates that using conventional air conditioning systems is insufficient to effectively reduce local thermal discomfort but may cause high energy costs.

### *3.5. Ranking of Local Discomfort*

Figure 9 shows the percentages of different local body parts that had discomfort. The body extremities were prone to experience discomfort. Specifically, the higher percentages of local discomfort appeared in the feet (44.99%), the palms (28.2%), the calves (24.74%), the head (19.66%), and the thighs (16.35%). It also should be noted that the head could also have notable discomfort in the winter despite the indoor temperatures being usually higher than 18 °C (see Figure 4).

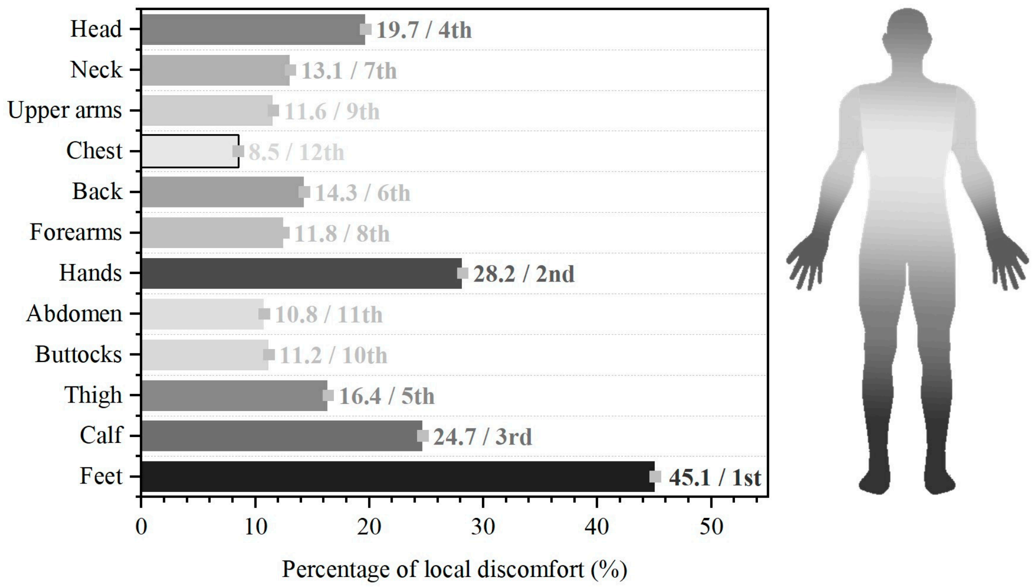


**Figure 9.** Percentages of local discomfort of different body parts.

Figure 10 illustrates the percentages of local discomfort of the top-five-ranked body parts under different indoor temperatures. It was found that, as the room temperature decreased, the percentages of local discomfort increased rapidly for body extremities (feet, hands, calves). To be specific, when the temperature reached 22 °C, more than 50% of the participants had discomfort in their feet, and, when the temperature reached 17 °C, nearly 40% of the participants had discomfort in their hands, and more than 30% of the participants had discomfort in their calves.

In addition, it could be seen that the top three local uncomfortable body parts remained unchanged under different indoor temperatures, with small differences in the order of the local parts. Specifically, under different indoor temperatures, the top three local discomforts were also felt in the feet, hands, and calves, the discomfort of the feet was much higher than the others, and the highest percentage of local discomfort was always in the feet regardless of the temperature. Moreover, it should be noted that, even when it was 22 °C or higher indoors, some body parts (feet, calves, and hands) still felt noticeable discomfort (higher than 20%), which indicates that using conventional air conditioning systems is insufficient to reduce local discomfort but may cause high energy costs.

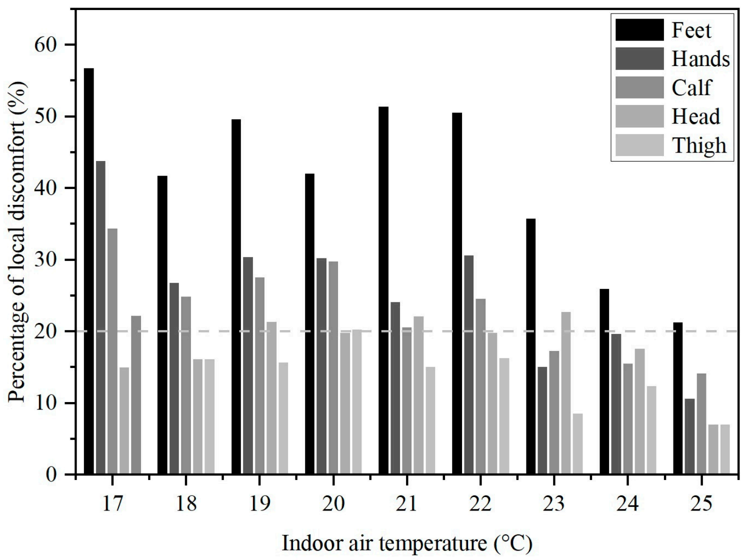


**Figure 10.** Percentages of the top five uncomfortable body parts under different indoor temperatures.

### 3.6. Correlation between the Percentages of Local and Overall Thermal Status

Figure 11 represents the percentages of participants having overall cool sensations (voting "slightly cool", "cool", or "cold"), uncomfortable feelings (voting "slightly uncomfortable", "uncomfortable", or "very uncomfortable"), and thermal unacceptability (voting "unacceptable") under the different indoor temperatures in this study. It is obvious that, under the same indoor temperature, the percentage of overall discomfort was higher than that of the overall cool sensation, and the percentage of unacceptability was usually less than 10%, regardless of what the indoor temperature was. Moreover, less than 30% of the participants was cool and uncomfortable when it was 17 °C or higher indoors. When it was 19 °C or higher indoors, less than 20% of the participants felt cool sensations, and, when it was 22.3 °C or higher indoors, less than 20% of the participants felt discomfort. The above-stated results also indicate that considering only thermal acceptability may lead to a large overestimation of occupant thermal comfort in real buildings.

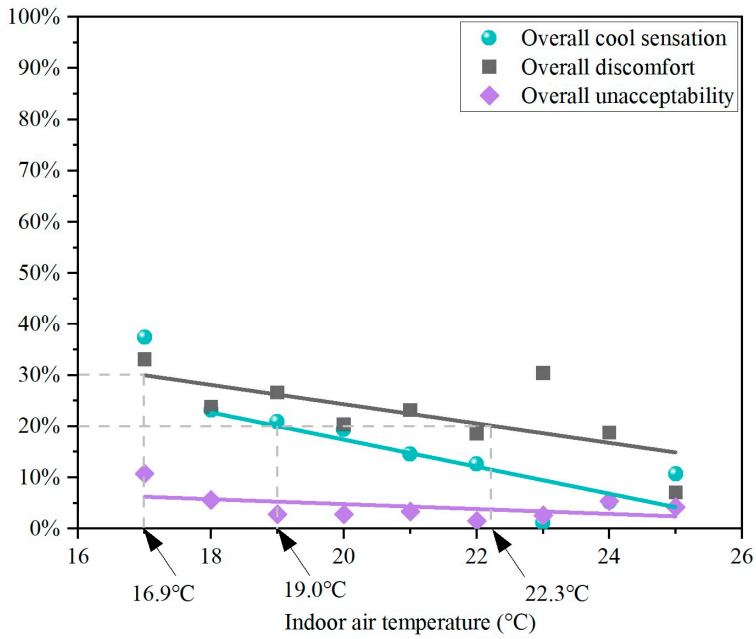


**Figure 11.** Percentages of overall cool sensation, discomfort, and unacceptability under different indoor temperatures.

### 3.6.1. Amount of Cool Body Parts and Overall Subjective Responses

Figure 12 shows the percentages of overall subjective responses and different amounts of cool body parts (local body parts had cool sensations) under different indoor temperatures. The results indicate the following: when the whole body has a cool sensation, at least four local body parts have cool sensations; when the whole body has discomfort, at least three local body parts have cool sensations; and when the whole body feels that the ambient environment is thermally unacceptable, at least seven local body parts have cool sensations.

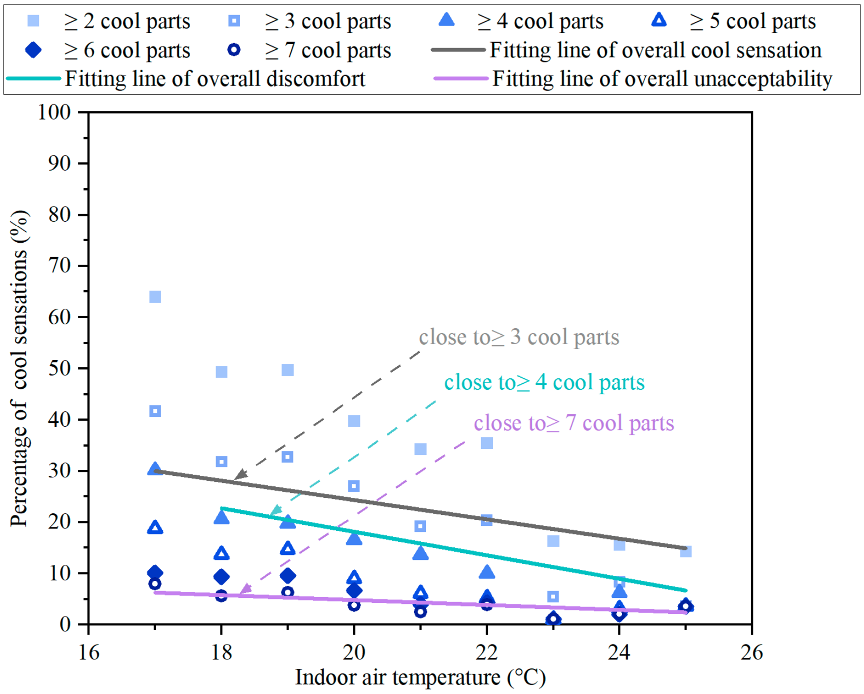


**Figure 12.** Percentages of overall subjective responses and different amounts of cool body parts.

Specifically, the percentage of at least four cool body parts was similar to that of the overall cool sensation, with an average absolute difference of 1.1%. The percentage of at least three cool body parts was similar to that of the overall discomfort, with an average absolute difference of 2.3%. At the same time, the percentage of at least seven cool body parts was similar to that of the overall unacceptability, with an average absolute difference of 0.2%.

The above-stated results also indicate that, if overall subjective responses are obtained, they can be used to estimate the amount of cool body parts.

### 3.6.2. Number of Uncomfortable Body Parts and Overall Subjective Responses

Figure 13 shows the percentages of the overall subjective responses and the different amounts of uncomfortable body parts (local body parts which had discomfort) under different indoor temperatures. The results indicate that, when the whole body feels discomfort, at least three local body parts have discomfort and that, when the whole body feels that the ambient environment is thermally unacceptable, at least four local body parts have discomfort.

Specifically, the percentage of at least three uncomfortable body parts was similar to that of the overall discomfort, with an average absolute difference of 2.9%, and the percentage of at least four uncomfortable body parts was similar to that of the overall unacceptability, with an average absolute difference of 0.09%. The above-stated results indicate that, if only overall subjective responses are obtained, they can be used to estimate the amounts of uncomfortable body parts.

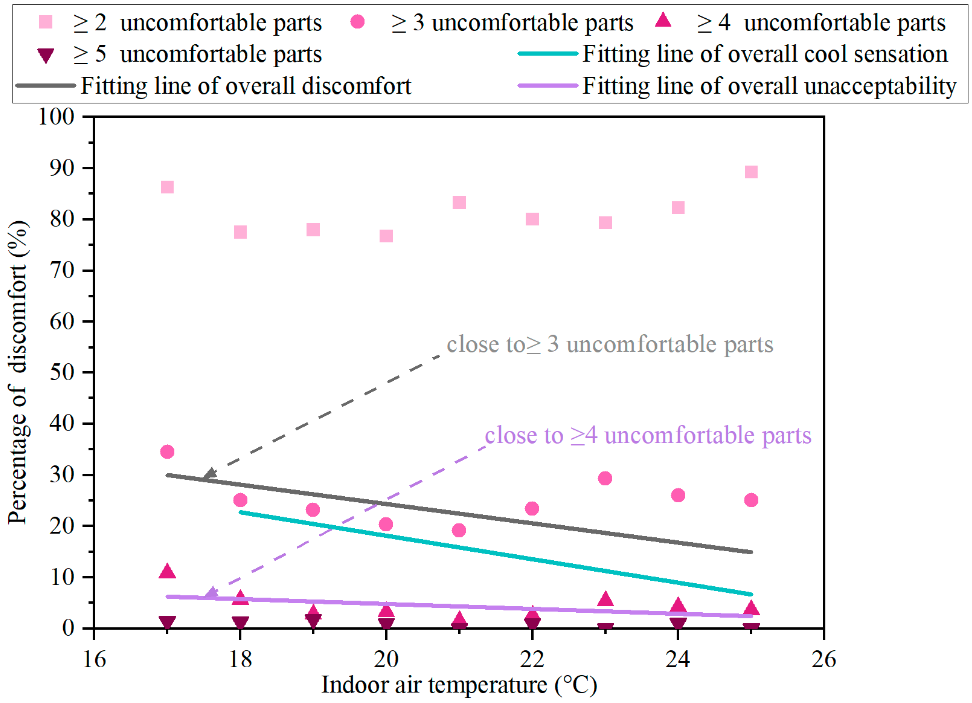


**Figure 13.** Percentages of overall subjective responses and different amounts of uncomfortable body parts.

### *3.7. Validation of Local–Overall Thermal Comfort Model*

#### 3.7.1. Local and Overall Thermal Sensations

Figure 14 shows the actual and predicted overall thermal sensation values under different indoor temperatures, which were obtained using the bin method, as described in Section 2.6, while the detailed results are represented in Table 4. It can be seen that the average deviation of the model is 0.13, and most of the deviations are lower than 0.2, which demonstrates that the local–overall thermal sensation model proposed by the authors (model (1)) has a high accuracy level.

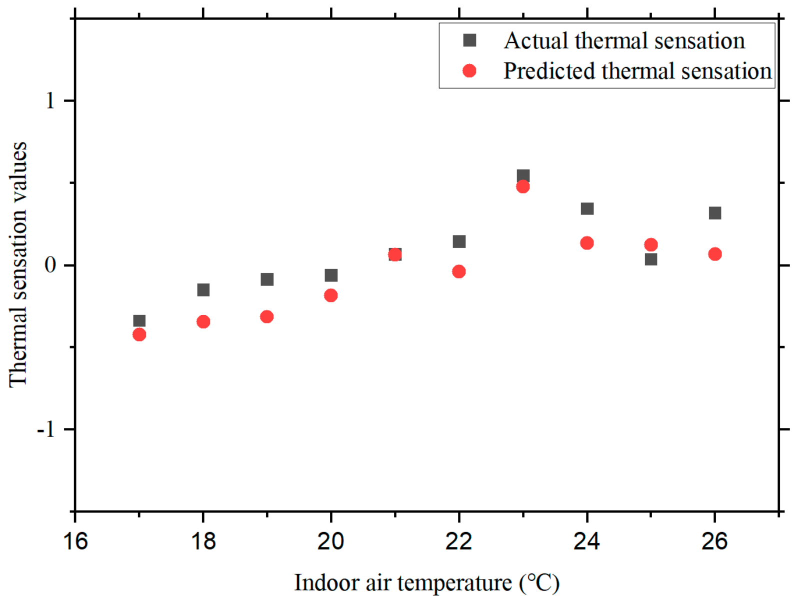


**Figure 14.** Comparison between the actual and predicted overall thermal sensations.

**Table 4.** The deviation between the actual and predicted overall thermal sensation values.

| Air Temperature (°C) | Actual Value | Predicted Value |
|---|---|---|
| 17 | −0.34 | −0.42 |
| 18 | −0.15 | −0.35 |
| 19 | −0.09 | −0.32 |
| 20 | −0.06 | −0.18 |
| 21 | 0.07 | 0.07 |
| 22 | 0.14 | −0.04 |
| 23 | 0.54 | 0.48 |
| 24 | 0.34 | 0.14 |
| 25 | 0.04 | 0.13 |
| 26 | 0.32 | 0.07 |

### 3.7.2. Local and Overall Thermal Comfort

Figure 15 represents the actual and predicted overall thermal comfort values under different indoor temperatures, and the detailed results are represented in Table 5. It can be seen that the average absolute deviation of the model is 0.07, and most of the deviations are lower than 0.3, which demonstrates that the local–overall thermal comfort model proposed by the authors (models (2), (3), and (4)) has a high accuracy level.

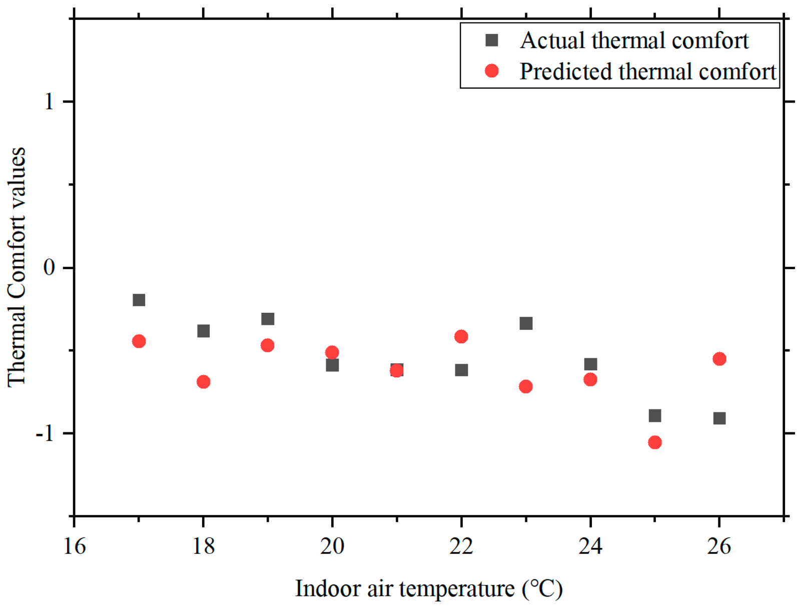


**Figure 15.** Comparison between the actual and predicted overall thermal comfort.

**Table 5.** The deviation between the actual and predicted overall thermal comfort values.

| Air Temperature (°C) | Actual Value | Predicted Value |
|---|---|---|
| 17 | −0.19 | −0.45 |
| 18 | −0.38 | −0.69 |
| 19 | −0.31 | −0.47 |
| 20 | −0.59 | −0.51 |
| 21 | −0.62 | −0.62 |
| 22 | −0.62 | −0.42 |
| 23 | −0.34 | −0.72 |
| 24 | −0.58 | −0.68 |
| 25 | −0.89 | −1.05 |
| 26 | −0.91 | −0.55 |

## 4. Discussion

Applications and Limitations of This Study

This study may contribute to current academia as follows:

(1) This study gave detailed information on the local thermal sensations and comfort of different body parts in the winter, especially under different indoor temperatures, which provided guiding suggestions for the future design and deployment of PCSs. For example, this study found that, in addition to the well-known high rates of coldness and discomfort in extremities like the hands and the feet, the head is also susceptible to coldness and discomfort. Thus, special attention should be paid to designing wearable head-heating systems like neck-warmer devices [38] and heated helmets [39]. Using the percentages of local cool sensations and discomfort rather than the average values shed some light on the future work on local–overall thermal comfort and reflected the real comfort needs of indoor occupants.

(2) This study established a quantitative correlation between the amount of local cool or uncomfortable body parts and the overall subjective thermal responses, which provided a novel method to quickly estimate how many local body parts had cool sensations or discomfort according to the overall subjective responses. Such a method can help simplify the questionnaire in the future work by reducing the metrics for evaluating the local thermal comfort of different body parts. For instance, in the existing studies, when investigating local body status, subjects are usually required to answer questions for each body part repeatedly, and then researchers can analyze the amount of cool or warm body parts [32], which is time-consuming.

(3) This study demonstrated a previous local–overall thermal comfort model proposed by the authors [37]. This model simplifies the calculations of overall thermal comfort since it only needs the most extreme local status as the input. With the understanding of local thermal comfort under different indoor temperatures, this model is convenient to use in real environments.

This study also has some limitations:

(1) In this study, it was found that the indoor temperatures were within or close to the comfortable range, and, thus, the gender difference was not as obvious as that found in our previous study [6]. However, if an indoor environment was out of the comfort range, the findings may differ significantly due to gender differences. In the future, the local thermal comfort of different groups (male and female participants) will be explored in environments deviating from the comfortable range.

(2) The participants of this study were healthy young students, who may have been more resilient to the indoor environments in our study than other groups like patients, children, and elders. The key body parts that should be heated as a priority may be different for other groups, a matter to which the development of PCSs should pay careful attention to. For example, for a patient, body parts with an injury may be sensitive to cool or warm stimuli and could easily have cool or warm sensations.

(3) The investigated buildings in this study were all air-conditioned. The applicability of the results of this study in natural-ventilated environments remains to be investigated. In naturally ventilated environments, which are usually much colder than air-conditioned environments in the winter, people can wear more clothes to cover their bodies, such as hats and gloves, which may reduce the cool sensations of the head and hands.

## 5. Conclusions

A field investigation was conducted to study the correlation between local and overall thermal comfort in the winter, including the measurements of indoor environmental parameters (e.g., air temperature and relative humidity) and participants' physiological parameters (e.g., skin temperature), in addition to 1356 questionnaires from the participants (656 men (48.4%) and 700 women (51.6%)). The main conclusions are listed below.

(1) In terms of local cool sensations, body extremities were the main areas prone to have cool sensations, and the top-five-ranked local cool sensation percentages were those of

the feet (41.02%), the hands (26.58%), the calves (25.18%), the thighs (13.99%), and the head (9.72%). The highest percentage of local cool sensation was always in the feet, regardless of the indoor temperature. Moreover, the percentage of local coolness in the feet, hands, and lower legs increased rapidly as the room temperature decreased. When the indoor temperature decreased by 1 °C, the percentages of local cool sensations of the feet, hands, and lower legs increased by 3–14%. Moreover, there was a significant cool sensation in the head when the temperature was higher than 18 °C indoors.

(2) In terms of local discomfort, body extremities were also more likely to feel uncomfortable, and the top-five-ranked local discomfort percentages laid in the feet (44.99%), the palms (28.2%), the calves (24.74%), the head (19.66%), and the thighs (16.35%), and the highest percentage of local discomfort was always in the feet, regardless of the indoor temperature. At the same time, with the decrease in the indoor temperature, the percentages of local discomfort of the feet, hands, and calves increased rapidly. It is worth noting that the head also had notable discomfort when the temperature was higher than 18 °C indoors.

(3) Moreover, it was found that the percentage of overall thermal discomfort was higher than the percentage of overall cool sensation at the same indoor temperature, while the percentage of thermal unacceptability was usually less than 10%, regardless of the indoor temperature. And, when the whole body felt cool, at least four local body parts had local cool sensations; when the whole body felt uncomfortable, at least three local body parts had local cool sensations; and when the whole body felt that the ambient environment was thermally unacceptable, at least seven local body parts had local cool sensations. In addition, at least three local body parts felt uncomfortable when the whole body felt uncomfortable, and at least four local body parts felt uncomfortable when the whole body felt that the ambient environment was thermally unacceptable.

(4) Further, the mean absolute difference between the actual and predicted overall thermal sensation values was 0.13, indicating that the local–overall thermal sensation model (Equation (1)) proposed by the authors has a high accuracy level. The mean absolute difference between the actual and predicted overall comfort values was 0.07, indicating that the local–overall thermal comfort model (Equations (2)–(4)) proposed by the authors also has a high accuracy level.

This study serves as a reference for prioritizing which local body parts should be warmed in actual cool environments, which may help develop energy-efficient personal comfort systems. For example, Figure 8 shows the percentages of different body parts experiencing cool sensations. The results show that body extremities are prone to coolness and that the head also has noticeable cool sensations in the winter even when the indoor temperatures is above 18 °C. When designing PCSs, the results of this paper can help determine which local part needs to be prioritized for heating, while the consumed energy can be lowered by reducing the heating energy spent on the body parts which are resilient to coolness when the indoor temperature is low. Also, this study contributes to quickly predicting the amount of local body parts with cool discomfort by merely investigating the overall subjective responses, which helps with the simplification of thermal comfort questionnaires for future studies.

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