LOCAL THERMAL DISCOMFORT IN LOW TEMPERATURE ENVIRONMENTS

by

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Human local parts have different thermal responses to low temperature environment. The objective of this paper is to find out the most sensitive parts which are extremely discomforting in low temperature environments. Based on previous experimental data, the relationship among skin temperature, air temperature, and clothing insulation was fitted, and the neutral skin temperatures were obtained. The local skin temperatures at different parts of the human body were compared with neutral skin temperatures in different air temperatures and clothes. The results showed that the local parts of foot, hand, upper arm, and calf deviated far from the neutral condition and were selected as the principal parts to be warmed. The findings are significant to improve human local thermal discomfort.

Key words: *skin temperature, environmental temperature, clothing insulation, steady environment, local heating*

Introduction

In non-heating regions, the air conditioning is usually used for heating in winter, but much electric energy is cost. Besides, occupants may feel discomfort due to draught sensation caused by the dry air-flow. In fact, it is not necessary to heat the whole room because occupants can feel thermal comfort by warming local parts. Besides, local heating can save more energy than the air conditioning. The problem is which parts of the human body need to be warmed.

Skin temperature is a major physiological parameter in thermal comfort research. It has been widely proved that there was a close relationship between thermal comfort and skin temperature in stable conditions [1], cold environment [2], and in cars [3]. Frank *et al.* [4] pointed out in their studies that the skin temperature was an important factor in determining the subjective thermal sensation, and when it changed in the neutral temperature range, the thermal sensation of the human body would not change. These studies illustrate that skin temperature is a useful index and can reflect the level of thermal comfort.

The skin temperature, environmental temperature, and thermal comfort were extensively measured by quite a few researchers, but the model among skin temperature, air temperature, and clothing insulation has not been constructed. Therefore, one objective of this paper is to build the unified formulas among them. Based on the literature review, the data on skin temperature and neutral skin temperature in stable condition were selected. The neutral local skin temperature is defined as the temperature when the human thermal sensation is neu-

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tral. It is a standard of thermal comfort and used to compare with other local skin temperatures to get the principal parts that should be warmed.

Air temperature, air velocity, relative humidity, mean radiation temperature, human metabolic rate and clothing insulation are six main factors that connect with thermal comfort [5]. This study chose air temperature and clothing insulation as the major factors because air velocity is usually less than 0.2 m/s in the building environment in winter, the relative humidity in winter is low and changes a little, the mean radiation temperature is very close to air temperature in a stable environment, and office workers or residents always keep a sitting posture or do slight movement with a metabolic rate about 1~1.2 met. On the other hand, ambient air temperature and clothing insulation are the important and adjustable factors in the building environment. Therefore, the two parameters were used as variables in formulas.

Methodology

The data were selected on the conditions of experimental value, indoor environment, light activity, stable condition, and healthy subject. The characteristics of subjects and instruments, and the methods to get neutral local skin temperature and mean skin temperature (MST) are as follows.

Subject

A total of 68 subjects (45 male and 23 female) were recruited by researchers [6-10], and they were university students. Each subject gave informed consent prior to the experiments. All subjects were healthy and non-smokers who were not taking prescription medication and had no history of cardiovascular disease. Subjects were asked to avoid caffeine, alcohol and intense physical activity in last 12 hours prior to experiments.

Instrumentation

Ambient temperature, black-bulb temperature, relative humidity and air velocity were measured, with the precisions of ±0.1~0.3 °C, ±0.5~2%, and ±0.05~0.1 m/s, respectively. Subjects' local skin temperatures were measured with thermocouples attaching on the test sites, fig. 1, in most experiments. Before the measurement, all the thermocouples were calibrated. The test points included head, neck, chest, belly, back, hand, forearm, upper arm, foot, calf, and thigh, see fig. 1.

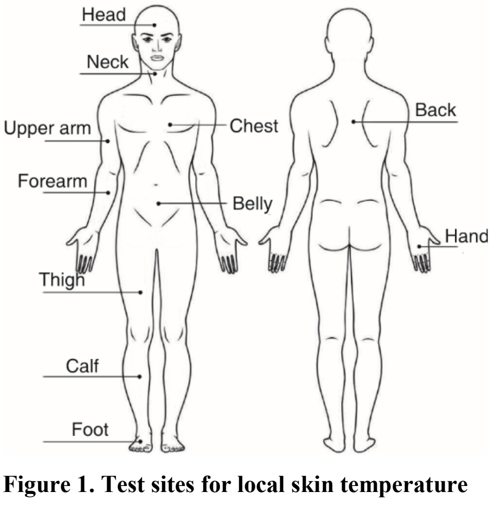

Figure 1. Test sites for local skin temperature

Skin temperature

Three groups of neutral local skin temperature measured by different researchers [11-13] were collected. The F test was used to check if there was a significant difference between them. If not, their mean values would be calculated as the standard neutral local skin temperature.

Mean skin temperature is important because of its energetics [5] and thermophysiology [14]. It is usually calculated by local skin temperatures and weighting factors, such as the 4-site method [9], 7-site method [15, 16] and the 10-site method [17]. The 4-site method was adopted to calculate the mean skin temperature because most experiments included the four sites. It is:

$$T_{\rm MST} = 0.3T_{\rm chest} + 0.3T_{\rm upper\ arm} + 0.2T_{\rm thigh} + 0.2T_{\rm calf} \tag{1}$$

The formulas for local skin temperature with the independence of ambient temperature and clothing insulation were fitted by ORIGIN 8.0. According to the formulas, the local skin temperature could be predicted when the air temperature and clothing insulation were given. By comparing the local skin temperature with the standard neutral local skin temperature, the segments deviating a long distance were considered as the discomfort parts which need to be warmed.

Results

Local skin temperature

The equations among skin temperature, ambient temperature, and clothing insulation for each segment are shown in tab. 1. The formulas showed that the clothing insulation coefficients of head and foot (0.170 and 0.194, respectively) were lower than that of other parts. It illustrated that the clothing insulation had less effect on the two parts than other parts. On the contrary, the clothing insulation coefficients of belly and back (4.364 and 3.711, respectively) were greater than that of other parts, which meant that the thermal sensation of the two parts could be improved by clothing adjustment.

Table 1. Fitted equations among local skin temperature, ambient temperature, and clothing insulation, where *C* [clo], is the clothing insulation and *T* [°C], is the air temperature

Segment	Formula	R^2
Head	$T_{\rm head} = 0.170C + 0.213T + 29.047$	0.902
Neck	$T_{\rm neck} = 3.301C + 0.236T + 27.117$	0.965
Chest	$T_{\rm chest} = 2.813C + 0.169T + 28.946$	0.850
Belly	$T_{\rm belly} = 4.364C + 0.287T + 25.040$	0.510
Back	$T_{\rm back} = 3.711C + 0.198T + 27.730$	0.785
Hand	$T_{\rm hand} = 3.017C + 0.622T + 15.041$	0.943
Forearm	$T_{\rm forearm} = 2.952C + 0.267T + 24.944$	0.624
Upper arm	$T_{\rm upper\ arm} = 2.185C + 0.403T + 21.229$	0.980
Foot	$T_{\rm feet} = 0.194C + 0.678T + 13.148$	0.677
Calf	$T_{\rm calf} = 2.341C + 0.310T + 22.635$	0.818
Thigh	$T_{\rm thigh} = 2.762C + 0.276T + 24.656$	0.959

The environmental temperature coefficients of the chest, back and head were 0.169, 0.198, and 0.213, respectively, while the values of the hand and foot were 0.622 and 0.646, respectively. It was implied that the environmental temperature had little influence on the core segments (*e. g.* chest, back, and head), but had much influence on the terminal segments (*e. g.* hand and foot).

The MST was calculated by eq. (1) based on local skin temperatures. The equation among mean skin temperature, ambient temperature, and clothing insulation is fitted as:

$$T_{\mathrm{MST}} = 2.52C + 0.289T + 24.511 \tag{2}$$

The neutral local skin temperatures were measured under the condition that human thermal sensation was neutral, and they are summarized in tab. 2. The neutral local skin temperatures of the core part (*i. e.* head, neck, chest, belly, and back) were higher than those of other parts (*i. e.* hand, forearm, upper arm, foot, calf, and thigh). The F test showed that $p > 0.05$, which meant there was no significant difference between groups. Therefore, the average value of the three groups was calculated as the standard neutral local skin temperature.

Table 2. Standard neutral local skin temperatures

Group	1 [°C]	2 [°C]	3 [°C]	Average [°C]
Head	35.8	34.2	34.8	34.9
Neck	35.6	–	34.7	35.1
Chest	35.1	34.5	35.3	35.0
Belly	35.3	34.9	35.3	35.2
Back	35.3	34.4	34.2	34.6
Hand	34.4	33.5	34.0	34.0
Forearm	34.6	32.7	32.0	33.1
Upper arm	34.2	33.5	32.4	33.4
Foot	33.3	32.2	32.7	32.7
Calf	32.9	32.2	32.2	32.4
Thigh	34.3	33.7	33.8	33.9
MST	34.2	33.6	33.5	33.8
Author	[12]	[11]	[13]	Present paper

Principal segment

There are not central heating systems in the hot-summer and cold-winter areas in China, but it is extremely cold in winter for some days. A few researchers measured the indoor temperature of this region to solve the problem of cold discomfort [7]. According to their research, the air temperature of 8 °C, 10 °C, or 12 °C was clod for occupants. In the three temperatures for examples, if the clothing insulation was 1 clo (*i. e.* underwear, long sleeved shirt, trousers, jacket or long-sleeve sweater, thick socks, and shoes), the local skin temperatures could be calculated by the formulas in tab. 1. The results are shown in fig 2(a). It shows that the local parts of human body deviating greatly from the neutral skin temperature were foot, hand, upper arm, and calf. In the air temperature of 8 °C, their deviations were 13.95, 10.92, 6.73, and 4.98 °C, respectively. In other air temperature (10 or 12 °C), the deviation had a similar trend.

Clothes are usually adjustable in the building environment. If the clothing insulation variates from 1, 1.2 to 1.4 clo, and the air temperature was constant at 8 °C, the calculated local skin temperatures (by the formulas in tab. 1) are shown in fig. 2(b). The skin temperatures of the head and foot were hardly changed by adding clothes, which meant that the clothing insulation had little effect on the two parts. While for other segments, such as belly and back, the impact of clothing insulation could not be neglected. Although adjusting clothes, the great deviation from neutral condition still happened on the foot, hand, upper arm, and calf, and they were 13.87, 9.72, 5.85, and 4.04 °C in 1.4 clo, respectively.

According to fig. 2, the discomfort of terminal parts (*e. g.* foot and hand), could be improved by rising air temperature, while the discomfort of core parts (*e. g.* belly, back, and chest) could be improved by adding clothes. However, there still was a distance between calculated local skin temperature and neutral local skin temperature. The practical method was local heating, and the key segments that should be warmed were foot, hand, upper arm, and calf.

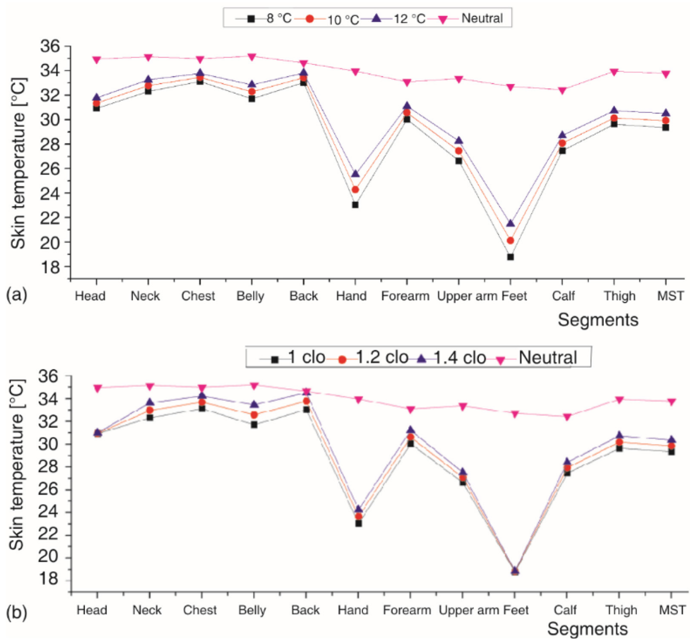

Figure 2. The deviation of local skin temperature from neutral skin temperature; (a) local skin temperatures in air temperatures of 8, 10, and 12 °C and clothes of 1 clo, (b) local skin temperatures in air temperature of 8 °C and clothes of 1, 1.2, and 1.4 clo

Discussion

Liu *et al.* [18] fitted the equations between skin temperature and ambient temperature for female and male subjects, see tab. 3. Their coefficients of environmental temperature were a little higher than present values because they did not consider the clothing insulation. The present research proved that clothing adjustment could relieve cold discomfort for some local parts (*i. e.* back, belly, and chest). Besides, clothing adjustment is the most important method in all the thermal comfort adjustments available to occupants in the building environment, and it is commonly used. Therefore, the formulas presented in this paper were much practical and flexible because both clothes and air temperature were available to be adjusted according to individual adaption. Arens and Zhang [19] reported the skin comfort temperature range of local parts, as shown in tab. 3. The neutral local skin temperatures in this paper, see tab. 2, were in accordance with these results.

Table 3. Other local skin temperature equations and thermal comfort temperature ranges, where Y is the local skin temperature [°C], X is the ambient temperature [°C]

Segment	Formula [18]		Range [°C], [19]	
	Male	Female	Low	High
Head	$Y = 0.28X + 25.84$	$Y = 0.241X + 27.05$	33.8	35.8
Neck	–	–	36.0	36.6
Chest	$Y = 0.26X + 26.76$	$Y = 0.20X + 28.334$	33.8	35.4
Belly	–	–	32.6	34.8
Back	$Y = 0.35X + 23.646$	$Y = 0.257X + 26.52$	33.8	35.8
Hand	$Y = 0.41X + 21.42$	$Y = 0.36X + 22.84$	30.0	36.0
Forearm	$Y = 0.33X + 23.76$	$Y = 0.31X + 23.99$	31.0	36.5
Upper arm	$Y = 0.25X + 26.43$	$Y = 0.31X + 23.99$	31.0	34.6
Foot	–	–	30.8	35.0
Calf	$Y = 0.371X + 20.91$	$Y = 0.375X + 20.45$	31.8	35.1
Thigh	$Y = 0.31X + 24.18$	$Y = 0.24X + 25.8$	31.6	34.8
MST	$Y = 0.458X + 19.651$	$Y = 0.23X + 25.774$	–	–

Neutral skin temperatures were the rulers to judge discomfort. Their values must be accurate. Nilsson [20] obtained the equivalent ambient temperature for local parts when the thermal sensations of the segments of human body were neutral. In his research, the equivalent ambient temperatures for head, chest, back, hand, forearm, upper arm, foot, calf, and thigh were 21.4, 17.2, 15.4, 21.6, 15.4, 15.4, 24, 20.4, and 20.4, respectively, when clothing insulation was 1 clo, and were 21.0, 25.7, 24.8, 24.1, 24.8, 28.0, 28.0, 28.0, and 28.0, respectively, when clothing insulation was 1.9 clo. If taking all those data into the corresponding formulas in tab. 1, the calculated local skin temperatures should be neutral since human thermal sensations were neutral in those conditions. The two groups of calculated neutral skin temperatures were compared with present neutral skin temperature, see fig. 3. The skin temperatures in 1 clo were close to present results, while the values in 1.9 clo were a little far

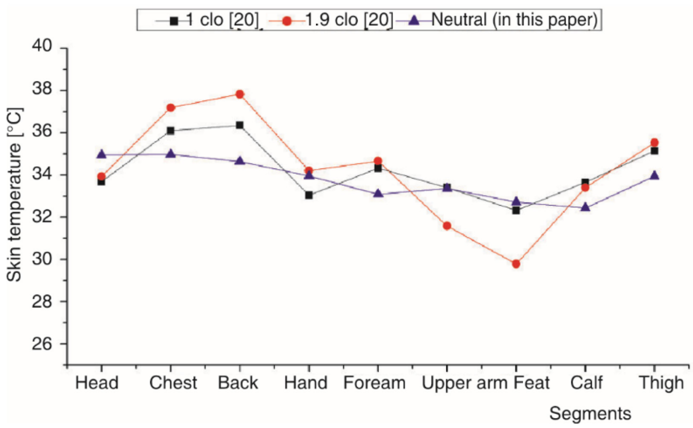

Figure 3. Comparison of local neutral skin temperatures

from present values, especially for back and foot. Limited by experimental conditions, the equations in tab. 1 only applied to 0.3-1.4 clo.

This research found that the discomfort parts were foot, hand, upper arm, and calf, and they were the key segments for heating. This conclusion was consistent with the experimental results of Liu [21] and the results measured by Hu [6]. However, Zeng [22] reported that the weighting of different segments on the overall thermal sensation was different while exposed in cold conditions. If the weighting of each part was considered, further research was needed to obtain the principal segments.

Conclusions

A few new findings were discovered by reprocessing experimental data. It was found that both the ambient temperature and the clothing insulation affected local skin temperature. The terminal parts (*e. g.* foot and head) were more affected by air temperature than by clothing insulation, while the core parts (*e. g.* belly, back, and chest) were more affected by clothing insulation than by air temperature.

The linear regression equations of the local skin temperature, clothing insulation, and air temperature were fitted. Limited by experimental conditions, the equations were suitable for 0.3-1.4 clo (clothing insulation) and 7~35 °C (air temperature). The mean skin temperature was calculated by a 4-site method which had high reliability and low sensitivity. It was suitable for the steady-state environment.

By comparing local skin temperature and neutral skin temperature in cold environments, it was inferred that the foot, hand, upper arm, and calf deviated far away from the neutral state. These parts were the principal segments for heating. That conclusion did not consider the weighting of different segments on the overall thermal sensation.

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