The key local segments of human body for personalized heating and cooling

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ABSTRACT

Thermal characteristics of local body parts of a human subject are markedly different in cold or hot environments. Some body segments are known to be much more susceptible to heat loss than the others, thus strongly influencing the overall thermal sensation of a subject. If these body parts can be effectively cooled in a hot environment or warmed in a cold environment using personal environmental control systems, thermal comfort of human occupants can be achieved at the minimum cost of energy without heavily relying on centralized heating, ventilation, and air conditioning systems. With an objective to understand the influence of local thermal sensation on the subjects' overall thermal comfort perception, experiments in the two sets of climate chambers were carried out simulating summer and winter conditions, respectively. A total of 24 subjects (12 females and 12 males) were recruited for this study, and their local skin temperature, conductive heat flux, and thermal sensations were recorded during the experiments. The local thermal characteristics of the subjects were compared between the 'neutral' and 'hot' conditions to identify predominant body segments in the summer scenario. Moreover, the comparison was also made between the 'neutral' and 'cold' conditions to derive predominant body segments in the winter scenario. The analysis of the results indicated that leg, thigh, and back are the key segments desirable for local cooling; whilst leg, thigh, back, and upper arm are the crucial segments for local heating. The findings can have important implications for the design of low-energy cost-effective personal heating/cooling devices. Finally, the results identified the conductive heat flux of skin as a useful physiological parameter in examining human thermal sensation.

1. Introduction

In a space with only a few occupants present, localized heating or cooling can be an energy-efficient strategy because it does not require the entire space to be conditioned. Stepping further, if occupants' comfort can be maintained by heating or cooling their specific body segment using Personal Environmental Control (PEC) systems, greater energy saving potential can be achieved. However, the challenge involves the identification of the segments of the human body that should be targeted for localized (or personalized) heating or cooling.

It is well known that there are large variations in the density of cutaneous cold and warm thermoreceptors (Hensel, 1981). Not surprisingly, human thermal sensations on local body parts can be considerably different even in the same environmental conditions. Therefore, significant research efforts have been devoted to understand human local thermal characteristics. The results indicated that in a uniform/stable environmental condition, hands and feet generally felt colder than other body parts in cool environments, while the head was insensitive to cold but sensitive to warm conditions (Arens et al., 2006). In other environmental chamber studies that simulated dynamic thermal conditions, local thermal sensation on the arm and forehead showed a stronger influence on overall thermal sensation than the other local segments of the body (Choi and Yeom, 2017a). Literature studies indicated that in the offices with the cooled ceiling, some body parts (e.g. head, hand, leg, and foot) acquired noticeable effects on the subjective warmth of an occupant (i.e. thermal sensation), while head and leg influenced occupants' overall thermal comfort (He et al., 2015). In the simulated airplane cabin conditions, both the upper and lower body determined the subjects' overall thermal comfort in the cold environment (Park et al., 2011). Other studies have reported that face cooling could improve thermal acceptability and shift the upper boundary of the acceptable room temperature (Ghaddar et al., 2011; Melikov, 2004; Zhang and Zhao, 2007). The literature studies indicate that the overall thermal sensation is influenced by local sensation, in particular, by

hand, foot, and head; and therefore human thermal acceptance can be improved by changing thermal conditions at the local body level. Notably, for asymmetrical environments, Zhang et al. (Zhang et al., 2010a, 2010b, 2010c) developed several models for predicting the local thermal sensation and local comfort of different parts of the human body, and also the whole-body sensation and comfort response.

Humans tend to express 'cold' discomfort in the metabolic zone; satisfaction or acceptability in the thermoneutral zone; and 'warm' discomfort in the sudomotor regulatory zone (Parkinson et al., 2016). A cold signal from the skin primarily governs vasoconstriction in the vascular bed of the skin and thus reduces the blood flow from core to the skin. In contrast, a warm signal from the skin plays a more important role in regulating the body temperature by governing sweating than that by vasodilation (Gagge et al., 1971). The human body is governed by the thermoregulation principle to balance the heat flux between the ambient thermal condition and the body itself; therefore, the skin temperature plays a significantly important role in maintaining this physiological principle (Choi and Yeom, 2017b). Thus the skin temperature is regarded as one of the key bio-indexes to reveal thermally sensitive body parts (Xiong et al., 2016). However, the skin temperature is not equal to heat flux, which is actually affected by the temperature gradient. P. R. Hoppe (1993) reported that energy balance is the only way for providing comprehensive description of the effects of thermal environment on the human body. Therefore, the heat flux should be considered as a key index as it is directly associated with energy balance.

PEC can be used to improve the comfort of building occupants by heating or cooling their specific body segment. The common types of PEC devices that appear in literature reports are summarized in Table 1. Cooling/heating garment as a PEC works by blowing dry air onto the body, pumping liquid inside a suit or vest, or using phase change material in pockets. They are typically used to reduce the risk of heat/cold stress and related injuries in harsh environments; however, the sweat evaporation of the body can worsen the thermal sensation (Mokhtari Yazdi and Sheikhzadeh, 2014). Hand/foot warmers have practical use to relieve local discomfort (Lakic, 1988; Smith, 1951); nonetheless, they have the disadvantage of limiting occupants' movement because hands and feet are restricted to an exact posture (e.g. touching the hand/foot warmers) to receive heat from such devices. If the users move away by changing their posture (e.g. hands on chin thinking and cross-legged sitting), the local heating is no longer available. Use of chair or desk heater/coolers is an effective way to improve thermal comfort of occupants by heating/cooling back and thigh (Habchi et al., 2016; Hweij et al., 2016; Pasut et al., 2015; Sun, 2010; Watanabe et al., 2009), without involving the confinement of the occupants' hands and feet.

Literature studies indicate that the dominant PEC method is that which provides the heating/cooling to local body segments (Habchi et al., 2016; Hweij et al., 2016; Pasut et al., 2015; Sun, 2010; Tsuzuki et al., 1999; Watanabe et al., 2009). However, the body segments targeted by the PEC devices/systems are not necessarily the most effective parts in providing thermal comfort (Choi and Yeom, 2017a; He et al., 2015).

In order to overcome the above mentioned issue, in this study, seven local body parts (i.e. upper arm, chest, back, belly, waist, thigh, and leg) were investigated. The local parts of hand, foot, neck, head, and

forearm were excluded because of the following reasons: 1) Local thermal sensations at these parts affect the thermal sensation of the entire body; however, these parts impose difficulty in using PEC for some facilities, such as a common chair; 2) During work, these parts need flexible movement and cannot be fixed in one posture. Once they move away from PEC devices, the practical effects of local heating or cooling become weak; 3) They have small surface areas; and therefore they gain little heating or cooling capacity from PEC; 4) Hand, foot, and head have different boundaries from the main segments of the body which are constantly covered with clothes in the office building context; and therefore have different thermal characteristics from other parts. The local conductive heat flux, local skin temperature, and thermal sensation were tested to define the predominant body segments ideal for the application of localized heating or cooling. By comparing the changes of thermal characteristics at these body segments both in winter and summer scenarios, the main objective of this study was to derive crucial body segments for local heating and cooling.

2. Methodology

2.1. Subjects

A total of 24 college students (12 male and 12 female students) were recruited for the experiment. The means (standard deviation (SD)) of the subjects' age, height, and weight were 23.5 (± 3.5) years, 1.68 (± 0.13) m, and 58.5 (± 4.5) kg, respectively. All the subjects were healthy, non-smokers who did not have any symptoms of skin disease, fever, and disorders. Consent from each of the participants was obtained after they were briefed on the experimental procedure. Moreover, the subjects were also required to avoid strenuous exercise and consumption of coffee or alcohol within 12 h prior to the experiment. During the experiment, they remained sedentary and were asked to simulate office work (reading) in a climate chamber.

2.2. Thermal parameters

The key physiological parameters this study focuses on are the skin temperature and heat flux. Human body temperature consists of the skin temperature and the core temperature. The former is commonly used in thermal comfort research as indicated in our literature review, while the latter is more specifically used in the studies involving physical activity (Weinert and Waterhouse, 2007) or transient stimulation (Zhang, 2003). In order to compare the thermal characteristics of the different local body segments, only the skin temperature was monitored during the previous experiments.

Heat flux is divided into three parts, namely, radiation, convection, and conduction. According to the third boundary condition of thermal transfer, the conductive heat flux should be equal to the sum of radiative and convective heat fluxes on the surface of an object. The local radiative and convective heat fluxes on the clothes surface can be easily measured or calculated (Wang et al., 2016), however, it becomes hard when the skin surface is covered with clothes. Owing to the reasons stated above, the current experiment focuses on the conductive heat flux of skin.

ASHRAE seven-point thermal sensation scale (i.e. −3 cold, −2 cool, −1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, and +3 hot) was used to assess the subjects' thermal sensation (ASHRAE, 2017), and they were recorded as Thermal Sensation Vote (TSV) in the experiment performed herein.

2.3. Instrumentation

Human skin temperature and conductive heat flux were measured using a low heat flow sensor shown in Fig. 1 (KM1, Kyoto Electronics Manufacturing), which was linked to a multi-channel data collector (HFM-215N, Kyoto Electronics Manufacturing). The outer diameter of

Table 1
The practices of personal environmental control.

Method/device	Literature
Cooling/heating garment	(Choi et al., 2008; Ke et al., 2018; Nishihara et al., 2002)
Hand/foot warmer	(Lakic, 1988; Smith, 1951)
Chair heater/cooler	(Sun, 2010; Habchi et al., 2016; Hweij et al., 2016; Pasut et al., 2015; Watanabe et al., 2009)
Desk heater/cooler	(Habchi et al., 2016; Tsuzuki et al., 1999)
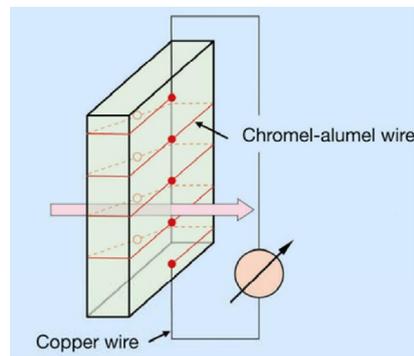
(a) Structure of KM1(KEM, 2018)   (b) KM1 attached to the skin

Fig. 1. The illustration of low heat flow sensor KM1 (KEM, 2018).

the sensor was $30 \times 15 \, \text{mm}^2$ and the thickness was 1.7 mm. The temperature range was from -40 to $150 \, °C$, and heat flow measurement range was from 11.6 to $3480 \, \text{W m}^{-2}$. Accuracy and resolution were 3% and $3.48 \, \text{W m}^{-2}$, respectively.

The air temperature, global temperature, air speed, and relative humidity (RH) were measured using a thermal comfort meter (MI6401, Metrel). The specifications of the instrument including range, accuracy, and resolution are summarized in Table 2. The measurements were taken in the occupied zone, in proximity to the subject (see Fig. 2). In accordance with ASHRAE 55 (section 7) measurement protocol for a seated occupant, the air temperature and air speed were measured at the 0.1, 0.6, and 1.1 m levels. The RH and global temperature were measured at the 0.6 m level.

2.4. Climate chamber

The experiment was carried out in a climate chamber at Xi'an Polytechnic University in Xi'an city, China. Fig. 2 shows the schematic illustration of the climate chamber. It was set up by King Tech. It could control air temperature from 0 to $40 \, °C$ with the accuracy of $\pm \, 0.3 \, °C$, and RH from 15% to 85% with the accuracy of $\pm \, 4\%$. The chamber was protected from direct solar radiation.

2.5. Clothing insulation

The subjects were required to wear prescribed two types of clothing, i.e. summer and winter styles. The summer clothing included thin straight trousers, long-sleeve dress shirt, thin-soled shoes, ankle-length athletic socks, and undergarments (brassiere and panties for female subjects, and men's brief for male subjects). The winter clothing included long underwear bottom, long underwear top, thick straight trousers, thick long-sleeve sweater, ankle-length socks, thick-soled shoes, and undergarments (brassiere and panties for female subjects, and men's brief for male subjects).

The clothing insulation was tested using an electrically heated manikin housed in a chamber. High quality thermal manikin including 22 segments was manufactured by PT TEKNIK. Its heat loss was set between 0 and $200 \, \text{W m}^{-2}$, with the solution of $0.1 \, \text{W m}^{-2}$ and

Table 2
Instrument specification (MI6401).

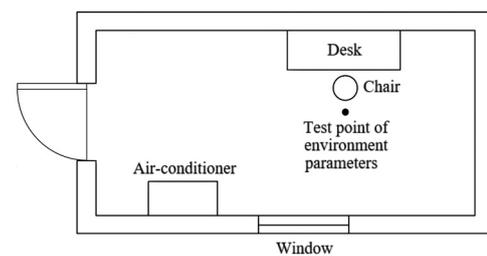| Item	Range	Accuracy	Resolution
Air temperature	-20–$60 \, °C$	$\pm \, 0.2 \, °C$	$0.1 \, °C$
Global temperature	10–$50 \, °C$	$\pm \, 0.5 \, °C$	$0.1 \, °C$
Air speed	0.1–$9.99 \, \text{m s}^{-1}$	5% of the reading value	$0.01 \, \text{m s}^{-1}$
RH	10–90%	$\pm \, 2\%$	0.1%

Fig. 2. Schematic illustration of the climate chamber.

precision of 1%; and skin temperature was set between 18 and $42 \, °C$, with the solution of $0.1 \, °C$ and precision of $0.2 \, °C$.

The experimental procedure was carried out according to ISO 9920 (ISO, 2007). The air temperature in the chamber was set at $23.5 \, °C$. The mean radiant temperature was calculated to be within less than $0.5 \, °C$ of air temperature. The air velocity was less than $0.15 \, \text{m s}^{-1}$, and RH was between 30% and 70%. The parallel method and thermal comfort model were used for the calculation of clothing insulation. The results are presented in subsection 3.2.

2.6. Experimental procedure

In order to define the key local body segments both in hot and cold environments, the experiment was divided into two groups. The first round of the experiment (Group 1) was carried out in summer, and the second group of experiment (Group 2) was conducted in winter. For the Group 1 experiment (6 males and 6 females, summer clothing), the air temperature was increased from 25 to $31 \, °C$ at an interval of $2 \, °C$ (see Fig. 3). According to ASHRAE 55, environment with $25 \, °C$ was considered to be in comfort zone with *clo*-value of 0.5 clo (summer clothing), RH of 50%, air speed of less than $0.2 \, \text{m s}^{-1}$, and light activity (sitting and reading). This group represented the change from 'neutral' to 'hot' conditions. Comparative analysis of the local thermal characteristics between the two conditions became the basis for defining the predominant body segments for cooling. That is, the segments that deviated further from the neutral condition than other body parts during the transition from 'neutral' to 'hot' were determined as predominant segments for cooling. For the Group 2 experiment (6 males and 6 females, subjects different from Group 1, winter clothing), the air temperature inside the testing chamber was decreased from 21 to $15 \, °C$ at an interval of $2 \, °C$ (see Fig. 3). According to ASHRAE 55, environment with $21 \, °C$ was in comfort zone with *clo*-value of 1.0 clo (winter clothing), RH of 44%, air speed of less than $0.2 \, \text{m s}^{-1}$, and light activity (sitting and reading). Thus Group 2 experienced 'neutral' to 'cold' conditions. Similarly, by contrasting the thermal characteristics of local body parts between the two conditions, the key segments for heating could be determined.

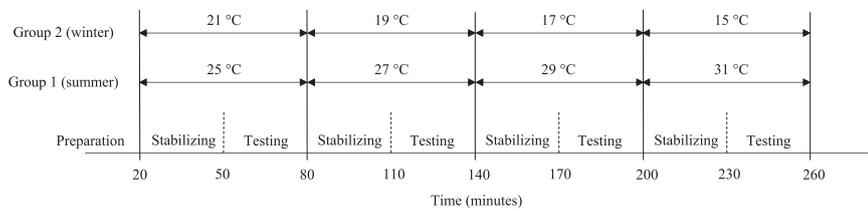Group 1 and 2 experiments were carried out in June and December

| | 21 °C | 19 °C | 17 °C | 15 °C |

Group 2 (winter)

Group 1 (summer)

| | 25 °C | 27 °C | 29 °C | 31 °C |

| Preparation | Stabilizing | Testing | Stabilizing | Testing | Stabilizing | Testing | Stabilizing | Testing |

20   50   80   110   140   170   200   230   260

Time (minutes)

Fig. 3. A schematic illustration of the experiment process.

in 2017, respectively. Only the data recorded during stable environmental conditions were used for our analysis. According to literature (De Dear et al., 1993; Huizenga et al., 2004; Liu et al., 2011; Zhao, 2007), when the change in environmental temperature was less than 10 °C, mean skin temperature and thermal sensation stabilized within 40 min. In this study, the control period (i.e. the duration shown in Fig. 3) was one hour for each of the temperature conditions. When the condition became stable (within 30 min), the objective (instrumental) and subjective (thermal sensation) data were collected. Once all the measurements at one exposure temperature were completed, the temperature was set to the next value (at 2 °C interval as described above). During the entire experiment, the subjects remained sedentary and were engaged in light activity (i.e. reading). The chair on which the subject sat was wooden side-arm chair, which is used in most of the basic studies on thermal comfort, with the insulation of 0.00 clo (ASHRAE, 2017).

2.7. Test point of the human body

The local skin temperature is typically tested by 4 sites, 6 sites, 7 sites, 10 sites, 21 sites, and 32 sites methods (Choi et al., 1997; De Dear et al., 1993; ISO, 1992; Liu et al., 2013a, 2013b; Mitchell and Wyndham, 1969). Each method specifies the exact test points on the human body. The objective of this research was to compare the thermal characteristics of main body segments with large surface area. The body segments with small surface areas (e.g. hand, foot, face, neck, and forearm) were excluded because of the reasons explained in Section 1. In this experiment, the test points were selected in relatively large body segments, i.e. upper arm, chest, back, belly, waist, thigh, and leg for the summer experiment, as shown in Fig. 4. In order to contrast the values in the same place, the test points for the winter experiment remained the same. All the test points did not contact the chair during the test.

3. Results

3.1. Environmental parameters

The average values of air temperature, mean radiant temperature, and RH during each experimental condition (recorded when environmental parameters were stable) are summarized in Table 3. The air
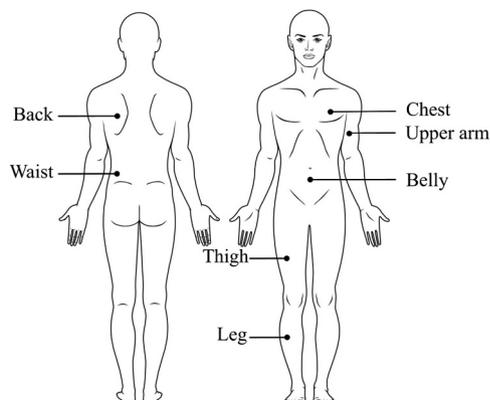

Fig. 4. Seven test points selected for the experiment.

temperature difference between head level (1.1 m) and ankle level (0.1 m) was less than 0.5 °C. The operative temperature was calculated based on the arithmetic mean of air temperature and mean radiant temperature at 0.6 m (ASHRAE, 2017).

3.2. Clothing insulation

During the test of clothing insulation, air temperature (23.4 ± 0.1 °C), mean radiant temperature (23.1 ± 0.1 °C), RH (57.8 ± 3.8%), and air velocity (0.07 ± 0.03 m s^{-1}) corresponded to the conditions proposed by ISO 9920 (2007). Fig. 5 presents the typical clothing types worn by the subjects, and the corresponding clo-values. The mean clo-value was 0.47 clo for female subjects and 0.49 clo for male subjects for the summer experiment (Group 1), and 0.78 for female subjects and 0.79 for male subjects for the winter experiment (Group 2). The clothing insulation for the male subject was a little higher than that for female subjects, but the difference (i.e. 0.02 clo) was negligible falling within the error range.

3.3. Local thermal characteristics

The p values (the level of significance was set at $p < 0.05$) in the output of two-way ANOVA indicated that, both in summer and winter experiments, a significant difference was observed between all the parameters (i.e. TSV, skin temperature, and conductive heat flux), between gender, and also between segment groups. The mean values of the thermal parameter at each local part are summarized in Table 4. TSV, skin temperature, and conductive heat flux of the local body parts of the subjects for Group 1 (summer condition) are shown in Figs. 6–8, respectively. Figs. 9–11 illustrate these parameters for Group 2 (winter condition).

3.3.1. Mean value

Table 4 summarizes that the conductive heat flux showed patterns that were different from those of the skin temperature and TSV at local parts of the body. The mean skin temperatures and mean TSVs at the leg and thigh were lower than those at the other parts both for summer and winter results, but the corresponding conductive heat fluxes were different (i.e. the conductive heat fluxes of leg and thigh in summer were lower than those of other parts; however, higher than those of other parts (except for back) in winter, see Table 4).

Besides, the results of mean skin temperatures and mean TSVs of belly and chest were almost similar both in summer and winter, which also occurred between back and waist. However, again the mean conductive heat fluxes at these body parts were different. The results indicated that the conductive heat flux was more sensitive than the skin temperature and TSV in identifying the thermal response of the belly and chest, and also of back and waist.

Table 4 further presents that leg and thigh showed the minimum mean conductive heat flux in summer when people require more heat loss, while leg and back exhibited the maximum mean conductive heat flux in winter when people need less heat loss. These body parts might be the key segments that could dominate overall thermal sensation because their heat losses were much different from other parts, which is further discussed in the subsequent Sections 3.3.2 and 3.3.3.

The mean conductive heat fluxes of all the local parts in summer were lower than those in winter, which might be the reason that people

Table 3
Summary of environmental parameters during the experiments.

Group	Case	Air temperature (°C)	Mean radiant temperature (°C)		Relative humidity (%)	Operative temperature (°C)	Air speed (m s⁻¹)
1 (summer)	1	25 ± 0.2	25 ± 0.4	50 ± 2		25 ± 0.3	≤0.2
	2	27 ± 0.3	27 ± 0.5	52 ± 3		27 ± 0.4	
	3	29 ± 0.2	29 ± 0.4	53 ± 2		29 ± 0.3	
	4	31 ± 0.2	31 ± 0.4	56 ± 2		31 ± 0.3	
2 (winter)	1	21 ± 0.3	21 ± 0.5	44 ± 3		21 ± 0.4	
	2	19 ± 0.2	19 ± 0.3	43 ± 2		19 ± 0.3	
	3	17 ± 0.2	17 ± 0.4	42 ± 3		17 ± 0.3	
	4	15 ± 0.2	15 ± 0.3	40 ± 3		15 ± 0.3	

0.47±0.01 clo   0.49±0.01 clo   0.78±0.01 clo   0.79±0.01 clo

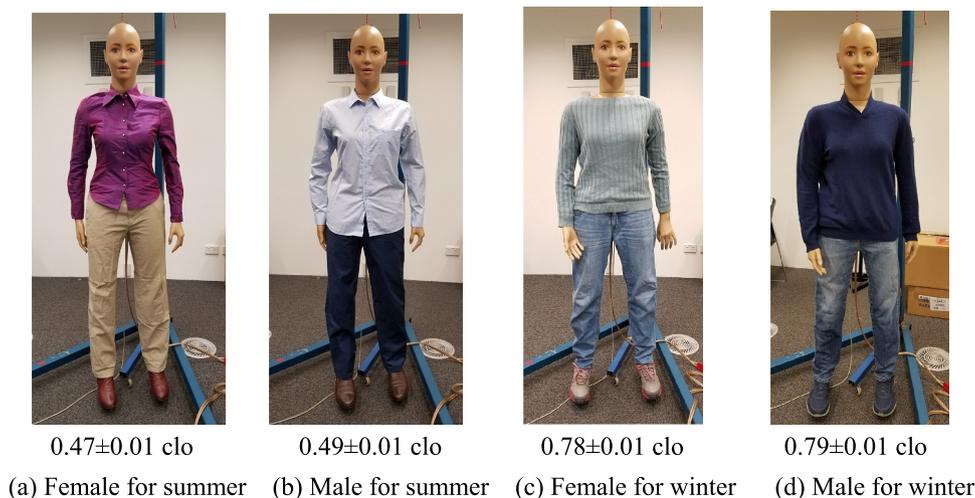(a) Female for summer   (b) Male for summer   (c) Female for winter   (d) Male for winter

Fig. 5. Estimation of clothing insulation for summer and winter experiments.

usually feel hot in summer (e.g. less heat loss leading to heat accumulation) and cold in winter (e.g. more heat lost resulting in heat deficit). Our results indicated that the conductive heat flux could be a useful index to explain the variation in thermal sensation.

3.3.2. Summer results

Fig. 6 exhibits that the mean whole-body TSVs for both female and male subjects at 25 °C are very close to 0, indicating 'neutral' condition in the summer experiment. In general, an upward trend is observed; i.e., TSVs increase with the increase in the operative temperature. At 31 °C, the TSV of male subject was a little higher than that of the female subjects. Fig. 6 also shows that the local TSVs between different body parts tend to concentrate at a single value with the increase in the operative temperature. For example at 31 °C, the maximum difference between local TSVs was less than 0.5, which is even less than SD. All the local TSVs were almost similar in the hot environment, thus they were not significantly different to distinguish the key body segment. Although the TSV of the leg was a little lower than that of the other parts,

the difference was only marginal. Therefore, whether or not it is the predominant part to be cooled could not be determined.

Fig. 7 illustrates how the skin temperatures of local body segments change across the four different temperature conditions. At 25 °C, the TSVs of the whole body are near "0" ('neutral' condition) both for female and male subjects. The local skin temperatures vary between different body parts for both the female and male groups. The skin temperatures recorded in 'neutral' conditions for chest, belly, upper arm, back, waist, thigh, and leg were 32.5, 32.4, 32.1, 31.8, 31.2, 30.4, and 27.9 °C, respectively, for the female subjects; and 33.4, 33.2, 32.0, 31.9, 32.5, 29.6, and 28.1 °C, respectively, for the male subjects. The chest and belly skin temperatures were higher than those of other parts of the body, and statistically significant differences were observed between the two segments and other segments, $p < 0.01$. The leg and thigh skin temperatures were lower than those of the other parts, and they also exhibited significant differences from other segments, $p < 0.01$. The maximum temperature differences between the investigated body segments occurred between the chest and leg, and they

Table 4
The mean values of the thermal parameter at the local part.

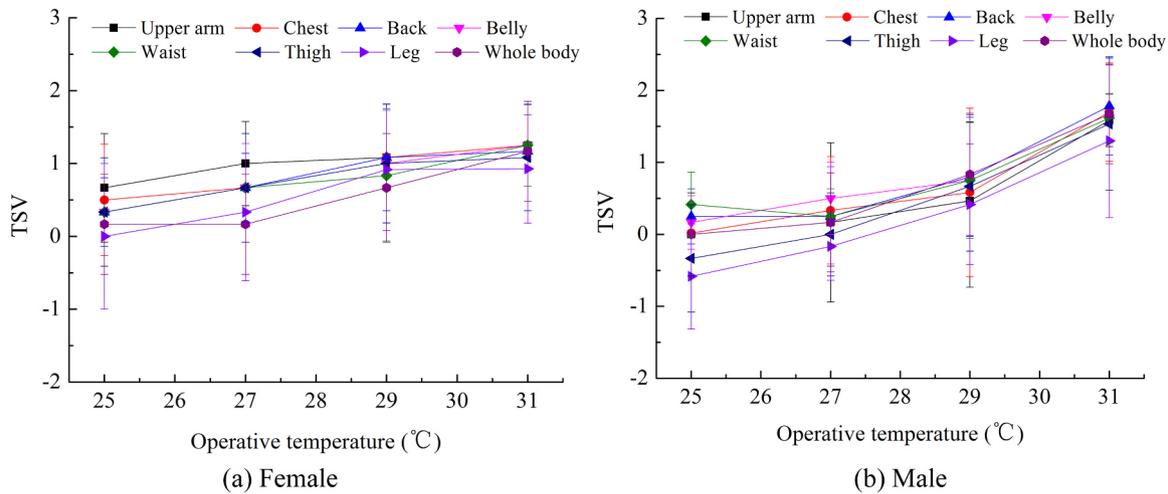|	Summer results (Group 1)			Winter results (Group 2)		
	Conductive heat flux (W m⁻²)	Skin temperature (°C)	TSV	Conductive heat flux (W m⁻²)	Skin temperature (°C)	TSV
Leg	27.9	29.5	0.4	85.4	26.9	− 1.6
Thigh	24.7	31.0	0.6	64.3	26.9	− 1.2
Belly	27.9	34.0	0.8	44.8	33.6	− 0.7
Waist	38.8	32.9	0.8	56.4	32.4	− 0.9
Chest	33.6	33.7	0.8	52.2	33.0	− 0.6
Back	54.7	32.7	0.8	81.2	32.2	− 1.0
Upper arm	36.7	32.6	0.8	53.3	31.2	− 1.1

Fig. 6. Whole body and local body thermal sensations under summer conditions (Group 1).

were 4.7 °C (female) and 5.3 °C (male).

With the increase in the operative temperature from 25 to 31 °C, the local skin temperatures gradually increased as well. For the female group, the skin temperatures of leg, waist, belly, thigh, and back increased greater than those of the other body segments (increased by 3.0, 2.7, 2.5, 2.4, and 1.9 °C, respectively). For the male subjects, the trend was a little different to their counter part, females. Skin temperatures of their leg, thigh, and back increased more than those of the other parts (increased by 3.1, 2.4, and 1.9 °C, respectively). The skin temperature increments of waist and belly for the female group were greater than those for the male group. The skin temperatures of leg, thigh, and back for both groups showed the similar increment. Based on these results on the skin temperature, the key body segments that are common for both females and males, are leg, thigh, and back in summer conditions.

Conductive heat flux of skin is directly proportional to thermal conductivity and temperature gradient under the skin. In higher ambient temperatures, vessel expands and blood flow capacity increases under the skin, resulting in higher thermal conductivity. However, Fig. 8 shows the decrease in the conductive heat fluxes attributed to the decrease of the temperature gradient under the skin. The data showed statistically significant differences between the back and other segments, $p < 0.01$. In the temperature range from 25 to 31 °C, the top three decrements of conductive heat flux were reported for the leg, back, and thigh for both female and male subjects. The corresponding values were 39 (leg), 35 (back), and 28 W m^{-2} (thigh) for the female

subjects; and 67 (leg), 47 (back), and 29 W m^{-2} (thigh) for the male subjects. The reduction of conductive heat flux causes an accumulation of heat in the human body. According to literature (Wang et al., 2016), the average bare areas of head, neck, chest (including chest and back), abdomen (including belly and waist), upper arm, forearm, hand, thigh, leg, and foot were 0.117, 0.029, 0.221, 0.157, 0.129, 0.116, 0.066, 0.451, 0.267, and 0.108 m^2, respectively. Apparently, the areas of leg and thigh were much larger than other body parts. Considering both conductive heat flux and surface area together, leg, back, and thigh were found to be better at dissipating heat than the other parts. Hot discomfort at 31 °C could be mainly attributed to the fact that leg, back, and thigh did not dissipate heat as much as that at 25 °C.

As a result, based on the local thermal characteristics observed in the summer scenario, leg, back, and thigh should be considered as the predominant body segments to be cooled in order to maintain comfort. These segments lead to more reduction in conductive heat fluxes than other body parts. Furthermore, they account for the much larger area of the whole body. According to the measurements done on Chinese subjects, their proportion in the total surface area is about 53% (Wang et al., 2016). Our experimental results indicate that these three segments should be cooled down in hot environments in order to maintain thermal comfort.

3.3.3. Winter results

At the operative temperature of 21 °C, the TSV of the entire body was close to 0 for females; however, it was − 1.2 for males (Fig. 9). This
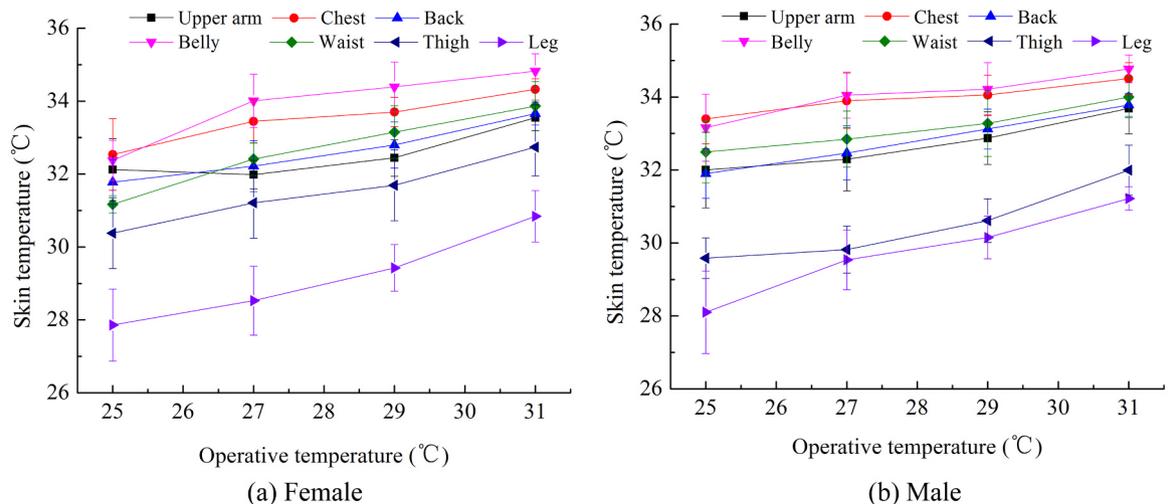

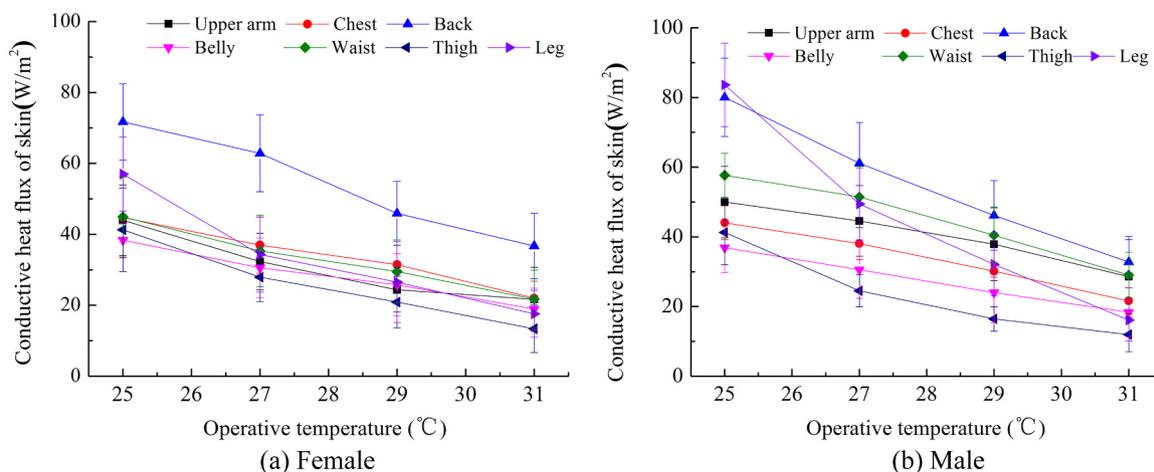**Fig. 7.** Local skin temperatures under summer conditions (Group 1).

Fig. 8. Local conductive heat flux under summer conditions (Group 1).

indicates that the 21 °C experimental condition was close to 'slightly cool' for the male subjects, while it was nearly 'thermal neutrality' for the female subjects. The main objective herein was to find out the key segments for heating by comparing different thermal sensation; therefore, 'slightly cool' at 21 °C was acceptable because the subjects felt 'cool' (19 °C) or 'cold' (15 °C) at other operative temperatures (Fig. 9(b)). With the decrease in the operative temperature from 21 to 15 °C, local TSVs decreased and became dispersed, showing somewhat different patterns from those observed in the summer experiment. In the temperature range from 21 to 15 °C, the TSV decrements of the thigh, leg, upper arm, and back were greater than the other parts for both female and male groups. The TSV decrements for thigh, leg, upper arm, and back were 1.7, 1.4, 1.4, and 1.3, respectively, for the female subjects; and 2.7, 2.3, 2.2, and 2.2, respectively, for the male subjects. In particular at 15 °C, the subjects felt colder on their leg, thigh, upper arm, and back, compared to the other body segments. Based on the TSV of the subject, thigh, leg, upper arm, and back are the key body segments that should be warmed in winter.

Fig. 10 clearly shows that the skin temperatures of different body segments are more scattered at low-temperature conditions, compared to that at high-temperature conditions. The thigh, leg, and upper arm skin temperatures are significantly lower than that of the other body segments. With the decrease in the operative temperature from 21 to 15 °C, the decrements of skin temperatures measured at the subjects' leg and thigh are greater than that of other local body parts for the two

sexes. The skin temperature decrements were 4.0 °C (leg), and 3.1 °C (thigh) for the females, and 4.1 °C (leg), and 3.8 °C (thigh) for the males. The skin temperature of upper arm showed the third biggest decrement at 1.4 °C for the females and 0.9 °C for the males. Our investigation based on the decrements of local skin temperature indicates that the leg, thigh, and upper arm are the key body parts to be warmed in winter.

In winter, the greater the conductive heat flux, the more heat the human body loses. Fig. 11 demonstrates that the conductive heat flux at low temperatures is greater than that at high temperatures. The subjects' leg, back, and thigh registered greater conductive heat fluxes than other body parts, and the three parts exhibited significant differences from other segments ($p < 0.05$). At 15 °C, the corresponding values were 89 W m^{-2} (leg), 89 W m^{-2} (back), and 77 W m^{-2} (thigh) for the females; and 98 W m^{-2} (leg), 99 W m^{-2} (back), and 66 W m^{-2} (thigh) for the males. In other words, leg, back, and thigh released abundant heat from the subject's body in the cold environments. For this reason, leg, back, and thigh are deemed to be the primary segment to be warmed in winter.

The results of the experiments simulating the winter condition reveal that leg, thigh, back, and upper arm have cooler skin temperature in low temperature conditions than the other body parts, and they account for a great amount of heat loss. The proportion of conductive heat loss from these four body segments is about 75% of the total of the seven parts investigated at 15 °C. Moreover, these segments account for
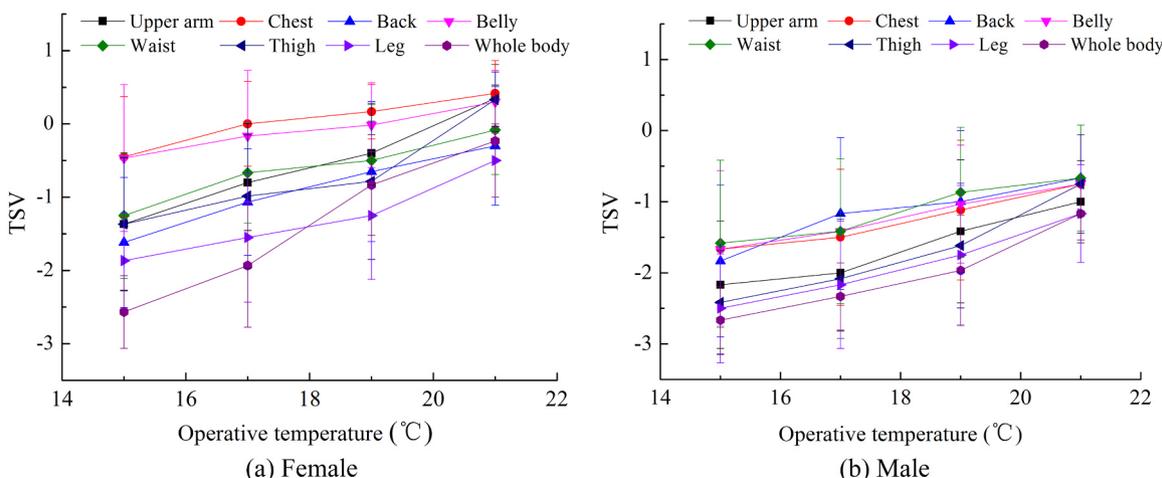

Fig. 9. Whole body and local thermal sensations under winter conditions (Group 2).
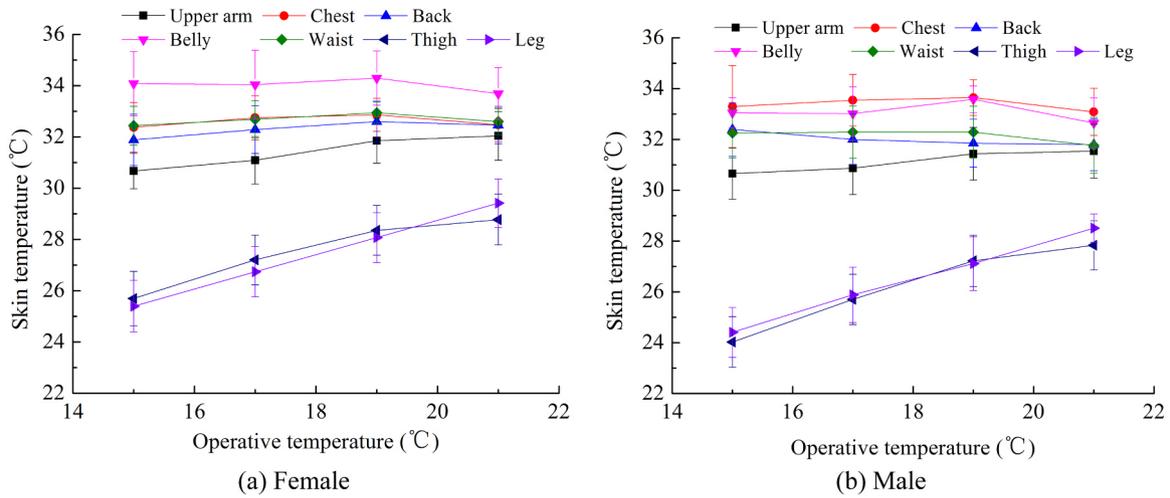
Fig. 10. Local skin temperatures under winter conditions (Group 2).

a large area of the entire body (about 60%) (Wang et al., 2016). Therefore, if these four segments are effectively warmed in a cold environment, the whole body 'comfort' can be achieved.

4. Discussion

4.1. Key body segments and application to personal environmental control

According to the analysis of the results, the key body segments for local heating were found to be leg, thigh, back, and upper arm, while the key parts for cooling were leg, thigh, and back. In the context of office buildings, most occupants are sedentary at their workstations. It is possible to make use of the desk and chairs to apply local heating or cooling to these key body segments defined in our analysis. Fig. 12 provides a conceptual diagram of a PEC system applied to a typical office workstation. The zone A, B, and C (Fig. 12) could be equipped either with fans to cool back, thigh, and leg by convection in a hot environment; or by heat radiating plates or heating film to heat back, upper arm, leg, and thigh by radiation or conduction in a cold environment. In other contexts, where people remain seated for a long time (e.g. students, elderly in a wheelchair, etc.), the local heating/cooling chair/desk can be a useful method to solve the problems associated with thermal discomfort.

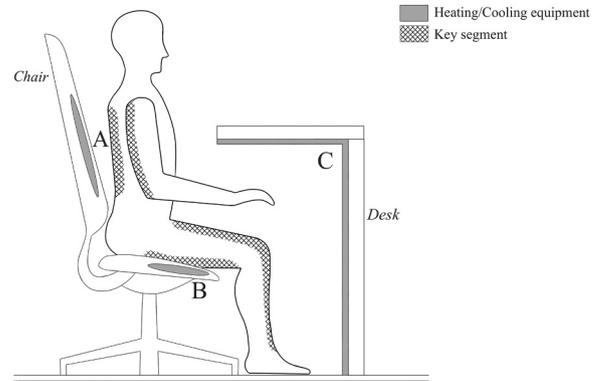Heating or cooling chair as PEC was tested by Pasut et al. (2015) to

Fig. 12. Conceptual diagram of local heating or cooling applied to office workstation, based on the key body segments derived in this study (A, B, and C are heating or cooling zones: A: chair heating or cooling for the back and upper arm, B: chair heating or cooling for the thigh, and C: desk heating or cooling for the thigh and leg).

evaluate its effect on thermal sensation and comfort. The chair (zones A and B in Fig. 12) was equipped with fan and heating elements. They reported that the heated/cooled chair strongly influenced the thermal sensation of the subjects and improved the thermal comfort and
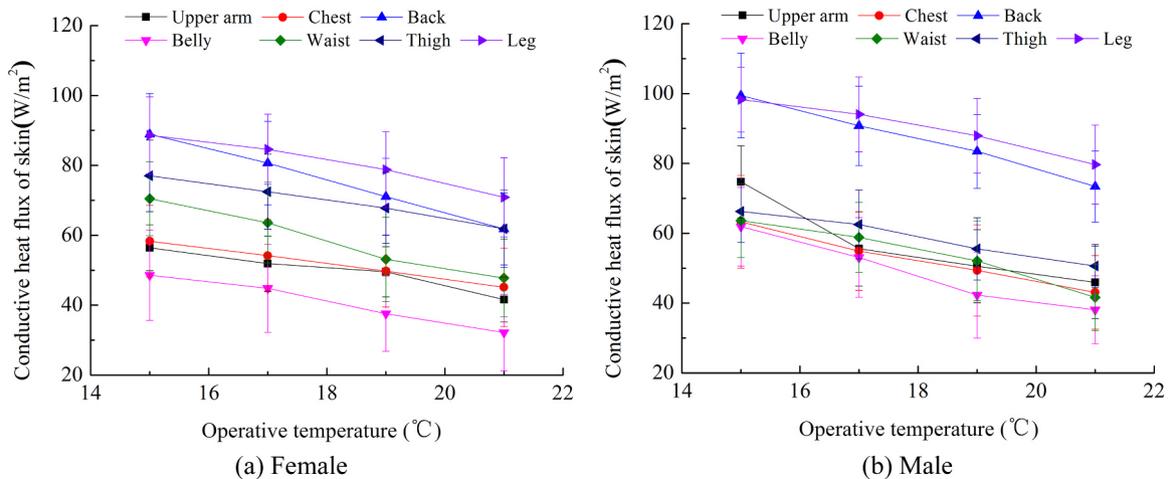

Fig. 11. Local conductive heat flux under winter conditions (Group 2).

perceived air quality. Their inference of back and thigh as the key segments for heating or cooling was in line with the result of our analysis. Our results also indicate that the key body segments should also include leg and upper arm for heating, and leg for cooling. This implies that the local heating or cooling strategies could go beyond zones A and B (see Fig. 12) of the chair, applied to other zones such as under a desk (i.e. zone C in Fig. 12).

4.2. Conductive heat flux as a physiological index

In previous studies, local thermal response of occupants has usually been examined by measuring the skin temperature and TSV; however, the conductive heat flux has rarely been adopted. The current study presented that the conductive heat flux is a sensitive index to identify the local thermal response of the human body (Table 4, Figs. 8 and 11). It could also be used to explain the human thermal sensation. 'Hot' thermal sensation corresponded to the low conductive heat flux lost from the skin, while 'cold' thermal sensation correlated to high heat dissipation of conductive heat flux. Given its correlation to thermal sensation, the conductive heat flux can be recommended as an important physiological parameter for research on human thermal comfort.

Wang et al. (2016) calculated other heat fluxes (radiative, convective, diffusive, and evaporative heat losses) of ten segments (namely head, neck, chest, abdomen, upper arm, forearm, hand, thigh, leg, and foot). They found that in low temperatures environment, significantly more heat loss was observed from thigh, leg, and upper trunk than that from other parts, which was in accordance with the present results indicating that leg, thigh, and back had more conductive heat flux than other parts in winter conditions.

4.3. Limitations of this study

The main limitations of this study are as follows: (a) Only seven points were tested on the main local body; (b) In the present study, the skin temperature, conductive heat flux, and thermal sensation vote (TSV) were mainly taken into account; however, there could be other parameters affecting the thermal characteristics of local body segments; and (d) The practicality of applying PEC system to key segments leg and upper arm was not verified. Undeniably, a lot more systematic explorations are demanded to test the effect of these body segments on overall thermal sensation and comfort, which will be pursued in future.

5. Conclusion

In order to derive the local body segments that can predominantly affect human thermal comfort, variables such as local thermal sensation, local skin temperature, and local conductive heat flux were measured in a climate chamber simulating the summer- and winter-conditions, respectively. The following conclusions were drawn.

1) In hot environments, leg, thigh, and back were found to be the key body segments to be cooled. In cold environments, leg, thigh, back, and upper arm were the principal segments which required warming.
2) The skin conductive heat flux changed clearly with the variation in the indoor operative temperature. Its value in low temperature environment was significantly higher than that in high temperature environment. The implication is that the conductive heat flux can be a useful physiological parameter to reflect human thermal sensation.
3) Gender differences were observed both in the change of the skin temperature and conductive heat flux. Especially in cold environments, local conductive heat fluxes of most of the female subjects were smaller than those of the male subjects. On the other hand, the local skin temperatures of the female group were higher than those of the male group.

4) Human local thermal sensations tended to converge at high-temperature conditions, while they tended to disperse at low-temperature conditions. The local thermal sensations of the female subjects were more dispersed than those of the males at low-temperature conditions.

These findings can have important implications for the design of low-energy cost-effective personal heating/cooling devices.

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