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Gender differences in thermal sensation and skin temperature sensitivity under local cooling

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ABSTRACT

Local cooling has proven to be an alternative to traditional comfort air conditioning to ensure users' thermal comfort while conserving energy. Few studies have investigated the gender differences in the applicable cooling temperatures and the applicable cooling locations and the differences in the sensitivity of skin temperature to thermal sensation under local cooling. Based on the design of orthogonal experiment, nine chamber experiments were conducted through different combinations of ambient temperature, cooling temperature, and cooling location. The subjective questionnaires and objective measurements were obtained in each experimental case. The results showed that the ambient temperature and the cooling location significantly affect the human overall thermal sensation of both genders under local cooling, while cooling temperature and cooling location significantly affect the local thermal sensation. For female, a neutral thermal sensation can be achieved by cooling the back at 24–26 °C when the ambient temperature is 31 °C. Back cooling at 22–26 °C is effective for male when the ambient temperature is 28 °C and 31 °C, and sole cooling with a higher cooling temperature is more acceptable at 34 °C. Moreover, female skin temperature is more sensitive to thermal sensation than that of males under local cooling. The upper arm skin temperature is most sensitive to thermal sensations for female, while the forearm skin temperature is most sensitive for male.

1. Introduction

Compared to traditional HVAC systems that condition the entire space and create a uniform indoor environment, Personal Comfort System (PCS) is designed to change the microclimate around the occupants or transfer heat and cold directly to the users (Song et al., 2022). This localized and individualized system makes it easier for users to suit their various thermal needs (Lyu et al., 2021; Pallubinsky et al., 2016; Wang et al., 2011; Xia et al., 2020; B. Yang et al., 2021; Yang et al., 2019). Local cooling of the human body is a popular topic in the field of PCS research (He et al., 2015; Lan et al., 2018; Pallubinsky et al., 2016; Schellen et al., 2012; Van Craenendonck et al., 2019; Zhang, 2003). The contact local cooling supplies the cooling directly to the body through thermal conduction. The building ambient temperature using local cooling can be higher than the range of indoor setting temperature recommended in current standards to achieve energy savings (Song et al., 2022; Veselý and Zeiler, 2014). This makes local cooling effective in saving energy while achieving improved human thermal comfort (Luo et al., 2020). Local cooling is expected to be an important adjunct to traditional HVAC systems, reducing building energy consumption and improving occupant thermal comfort during the cooling seasons (Tang et al., 2022).

One of the main topics explored in the in-depth study of thermal comfort is gender differences. At present, there is no formed consistent conclusions on the significance and the size of gender differences in neutral temperature. Fanger (1970) found that there were differences between two genders in their satisfaction with the thermal environment, but these differences were deemed insignificant. However, many studies have found that females are more sensitive to ambient temperature changes and are more prone to feel uncomfortable in cold and hot environment than males (Beshir and Ramsey, 1981; Cao et al., 2021; Federspiel, 1998; Griefahn and Künemund, 2001; Xiong et al., 2019; Xu et al., 2021). These studies are mostly based on traditional uniform indoor environments. For local cooling of PCS, only few studies have explored in depth the potential thermal comfort differences between the two genders in its application (listed in Table 1). Among them, Yang et al. (2019) and Pasut et al. (2015, 2012) found no significant

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Nomenclature

$T_{forehead}$	Skin temperature of the forehead, °C
$T_{upperarm}$	Skin temperature of the upper arm, °C
$T_{forearm}$	Skin temperature of the forearm, °C
T_{hand}	Skin temperature of the hand back, °C
T_{back}	Skin temperature of the back, °C
T_{breast}	Skin temperature of the breast, °C
T_{belly}	Skin temperature of the belly, °C
T_{thigh}	Skin temperature of the thigh, °C
T_{calf}	Skin temperature of the calf, °C
T_{foot}	Skin temperature of the foot, °C

Abbreviation

ANOVA	Analysis of variance
Correlation coef	Correlation coefficient
IQR	Interquartile range
MST	Mean skin temperature, °C
PCS	Personal Comfort System
Regression coef	Regression coefficient
RH	Relative humidity, %
TCV	Thermal comfort vote
TSV	Thermal sensation vote

difference in thermal sensation and thermal comfort between males and females when using local cooling. Pallubinsky et al. (2016) found no significant difference in thermal sensation and thermal comfort between two genders when constant cooling temperatures of underarm cooling, face cooling, sole cooling, and back cooling were given in a 32 °C ambient environment. The insignificant differences in thermal comfort between the two genders in these studies maybe because cooling devices are controlled by the occupants, who were able to autonomously adjust the cooling power to make themselves comfortable during the experiment, allowing the thermal requirements of both genders to be satisfied to the greatest extent (Song et al., 2022). In addition, if the experimental condition is single, significant differences between the genders may not be observed, which proves that both genders have similar thermal preferences in this condition only. It does not mean that their thermal preferences will be similar in other common local cooling conditions. Due to the different thermophysiological characteristics of both genders, such as hormone secretion (Charkoudian and Stachenfeld, 2016), vasoconstriction/vasodilation (Daanen, 2003), etc., males and females may have different preferences in terms of cooling temperatures, cooling sites, etc. Therefore, the gender differences in thermal sensation under local cooling conditions still require continued research. Although gender differences were not analyzed in studies of Zhai et al. (2015) and Yang et al. (2021) due to the small number of subjects, they both pointed out that gender differences are still a topic that needs further exploration.

The perception of temperature in human body is achieved by cold-sensitive and warm-sensitive nerve endings under the skin that send signals to the hypothalamus via the sympathetic nervous system. Thermal stimulation of skin, and some tissues drives autonomic thermoregulatory responses in human body (Cotter and Taylor, 2005). These responses to such cooling and heating quantifies the thermal sensitivity of that tissue. It is well established that skin thermal sensitivity is lower than that of the body core in driving sensory responses (Nadel et al., 1971; Stolwijk and Hardy, 1966). However, the much larger temperature fluctuations skin experiences can still drive the sensory responses (Bothorel et al., 1991; Cabanac et al., 1972; Cotter and Taylor, 2005). In traditional comfortable air conditioning environment (Wang et al., 2022), the skin temperature of specific areas of the human body, such as wrist (Choi and Yeom, 2017), arm (Xiong et al., 2016), and face (Jia et al., 2022) is correlated to the overall thermal sensation. There are a

Table 1
Previous studies on gender differences in personal cooling device applications.

	Subjects number	Ambient temperature	Cooling temperature or cooling power	Cooling device	Cooling location	Heat transfer mechanism	Gender differences	Notes
Yang et al. (2019)	females: n = 10; males: n = 10	28 °C, 30 °C, 32 °C	No fixed	Thermoelectric cooling chair	Upper back, Lower back, Chest, Abdomen	Conduction	No difference in psychological response	–
Pasut et al. (2012)	females: n = 16; males: n = 14	16 °C, 18 °C, 25 °C, 29 °C	No fixed	Thermoelectric cooling chair	Back, Pelvis	Conduction	No difference in psychological response	–
Pasut et al. (2015)	females: n = 12; males: n = 11	16 °C, 18 °C, 29 °C	No fixed	Ventilated chair, Ventilated chair + fan	Face, Back, Pelvis	Conduction, Convection	No difference in psychological response	–
Pallubinsky et al. (2016)	females: n = 8; males: n = 8	32.3 ± 0.29 °C	22.7 ± 0.81°C for face-underarm cooling and underarm cooling; 21.8 ± 0.62°C for sole cooling; 30 °C for back cooling	Cooling panel, Cooling chair	Underarm, Face, Sole, Back	Conduction	No difference in psychology response; Difference in physiological response	In warm conditions, women had higher mean and distal skin temperatures compared with men.
Verhaart et al. (2018)	females: n = 6; males: n = 5	27.5 °C	No fixed	Personalized ventilation system	Face, Chest, Arms, Hands	Convection	Difference in psychological response	The males tend to increase the air velocity while females tend to reduce the air velocity.
Schellen et al. (2012)	females: n = 10; males: n = 10	25.5 ± 0.2 °C	Asymmetric radiation: ceiling = 18 °C; floor = 29 °C	Cold radiant panel (ceiling)	Upper body	Asymmetric radiation	Difference in psychology response; Difference in physiological response	Mean, distal, and proximal skin temperatures of the females were significantly lower. Females are more uncomfortable and dissatisfied

few studies on the differences in skin temperature sensitivity of two genders in traditional uniform air-conditioned environments (Chaudhuri et al., 2018; Choi and Yeom, 2019, 2017; Dai et al., 2017; Jia et al., 2022; L. Yang et al., 2021; Yeom and Delogu, 2021). Several studies have concluded that female skin has more cold-sensitivity than male skin (Choi and Yeom, 2019, 2017; L. Yang et al., 2021). Zhang (2003) pointed out that the human physiological response to local cooling differs from that in a uniform thermal environment because of the local thermoregulatory mechanisms of human body. Existing studies have found greater cold sensitivity of skin temperature in the face and torso when local cooling is applied to body (Cotter and Taylor, 2005; Stevens and Choo, 1998). However, only few studies have explored the potential differences in skin temperature sensitivity between the two genders under local cooling conditions. Existing studies have found that the differences in skin temperature sensitivity between genders appeared to be more pronounced than that in psychological sensations during local cooling. Pallubinsky et al. (2016) in their experiment did not observe significant gender differences in thermal sensation and thermal comfort, but found that females had higher mean and distal skin temperatures compared with males. Similarly, Schellen et al. (2012) did not find any gender differences in thermal sensation in an environment with asymmetric cooling radiation, but found that mean, distal and proximal skin temperatures of the females were significantly lower than that of males. The experiments conducted in these existing studies rarely take ambient temperature, cooling temperature, and cooling location as experimental variables to analyze the difference in skin temperature sensitivity between genders under multiple local cooling conditions, which makes further research necessary. Skin temperature sensitivity relates skin temperature to human psychological sensations, making it practical to investigate skin temperature sensitivity by gender in a variety of local cooling conditions. On the one hand, based on the results, it is possible to establish overall thermal sensation prediction model using skin temperature applicable to each gender. This will support the automation and intelligent practical application of cooling devices. On the other hand, it may contribute to explain the difference in psychological feelings of men and women under local cooling.

In order to overcome the above limitations, various local cooling conditions in the climate chamber were conducted in this study. The subjective questionnaires and objective measurements were used to obtain the thermal sensation and skin temperature of males and females. The main objectives include: (1) analyzing the differences in thermal sensation between two genders before and under local cooling, as well as the factors that influence this; and (2) comprehensively investigating the sensitivity of skin temperature in response to thermal sensation in various body areas of males and females under local cooling condition.

2. Methodology

2.1. Experimental conditions

Cooling temperature, ambient temperature, and cooling location are important factors that influence the effect of local cooling. Therefore, these three factors were considered as variables in this study. This experiment aimed to obtain the overall thermal sensation, local thermal sensation, local thermal comfort, and skin temperature of males and females under multiple conditions with combinations of these variables.

Local cooling can be applied in hotter environments, since it directly cools the specific part of human body. Therefore, the ambient temperature in this experiment was set at 28–34 °C, which is similar to the ambient temperature setting of Yang et al. (2019). For cooling locations, back and forehead cooling are currently of great interest due to their high practical applicability. For example, based on back cooling research, some scholars have now developed cooling undershirts and back chairs. Foot sole heating to improve human thermal comfort in winter is an effective and energy-efficient solution (Oi et al., 2011; Zhang et al., 2010). The feasibility of foot sole cooling has already been focused on, but the related studies need to be explored further (Zhou et al., 2022). In order to make the results of the study better applied in real life, the cooling locations in this study are determined to be the forehead, back, and foot sole. In the pre-experiment, the subjects generally reported that the cooling temperature below 22 °C was unacceptable due to strong stimulation. Some studies have pointed out that when the neutral temperature is within +6 °C, the acceptance range of the local cooling temperature is 22–30 °C (Yang et al., 2020). Considering that, the cooling temperature is set at 22–26 °C in this study. An L9 (3^4) orthogonal experimental design was adopted for the experiment. There are nine experimental cases in total, and the specific parameters of each case are shown in Table 2.

2.2. Description of climate chamber and cooling device

The experiments were conducted in an artificial climate chamber at Shanghai Jiao Tong University, China. The climate chamber layout is shown in Fig. 1. The dimensions of the chamber were 6.7 m (length) × 3.8 m (width) × 2.8 m (height). The chamber has three interior walls and one exterior wall. In order to reduce the thermal radiation asymmetry between the interior walls and the exterior wall caused by high outdoor temperature, polyurethane insulation layer (thermal conductivity less than 0.02 W/m K^{-1}) is installed on the inner surface of the wall. Two windows are installed on the exterior wall. During the experiment, the inner curtain was used to avoid the impact of direct solar radiation. The door and windows were closed during the experiment. The temperature difference between each wall surface was less than 0.3 °C, the ambient temperature fluctuation was less than 0.5 °C, the relative humidity (RH) was maintained at 55–60%, and the indoor air velocity was less than 0.1 m/s during the experiment controlled by a ceiling-mounted air conditioner with low-speed air supply and return. The infrared ray thermometer (FLUKE 62 max+; A Fluke Company, USA) was used to monitor the wall surface temperature (range: 30–650 °C, accuracy: ±1% readings). The omnidirectional anemometer system (SWEMA; SWEMA AB, Sweden) equipped with a temperature sensor (range: 10–40 °C, accuracy: ±0.2 °C), RH sensor (range: 10–90%, accuracy: ±1%) and velocity sensor (range: 0–10 m/s, accuracy: ±0.01 m/s) were located at the measuring point to monitor the ambient temperature, RH and air velocity.

A custom-made cooling device was used for local cooling in the experiment, as seen in Fig. 2. The cooling source of this cooling device was provided by one semiconductor cooling plates (40 mm × 40 mm × 3.8 mm) with a rated cooling capacity of 54 W. In order to spread the cooling generated by the semiconductor cooling plate over a larger area, the cold surface of semiconductor cooling plate was attached to a thermal conductive aluminum plate (180 mm × 90 mm × 3 mm). A thermally conductive silicone gel sheet (180 mm × 90 mm × 3 mm, thermal conductivity of 6.0 W/m K^{-1}) was installed on the aluminum plate to make the plate more comfortable for the subjects. The heat

Table 2
Experimental conditions.

Case number	Indoor air temperature	Cooling location	Cooling temperature (heat flow [a])
Case 1	28 °C	Forehead	24 °C (422 ± 20.7 W/m^2)
Case 2	28 °C	Back	22 °C (566 ± 19.7 W/m^2)
Case 3	28 °C	Foot sole	26 °C (380 ± 22.3 W/m^2)
Case 4	31 °C	Forehead	22 °C (580 ± 21.5 W/m^2)
Case 5	31 °C	Back	26 °C (530 ± 14.1 W/m^2)
Case 6	31 °C	Foot sole	24 °C (495 ± 35.4 W/m^2)
Case 7	34 °C	Forehead	26 °C (395 ± 34.2 W/m^2)
Case 8	34 °C	Back	24 °C (455 ± 12.9 W/m^2)
Case 9	34 °C	Foot sole	22 °C (590 ± 14.1 W/m^2)

[a] The heat flow of each local cooling condition was measured for one subject using a heat flow meter (RHTF-1; TSINGHUA TONGFANG, Beijing, China) (range: 700–4000 W/m^2, accuracy: ±5% readings).

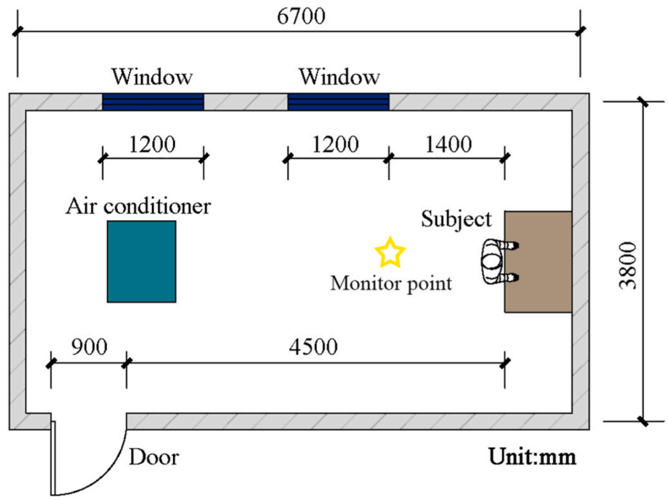

Fig. 1. Layout of the climate chamber.

dissipation system of the cooling device consisted of a heat exchanger with three copper tubes (30 mm × 90 mm × 90 mm), and two cooling fans. The heat generated by the semiconductor cooling plate would be discharged into the surrounding environment. A microcomputer electronic thermostat was equipped to adjust the surface temperature of cooling plate. The difference between the actual temperature and the design temperature of cooling plate surface during operation had been tested to within 0.5 °C. The electric power of the cooling device is about 50 W when the operating voltage is 12 V (including the power of the semiconductor cooling plate and cooling fans). The overall size of the local cooling device was small (180 mm × 90 mm × 130 mm, weight: 0.6 kg), making it convenient to achieve forehead cooling, back cooling, and foot sole cooling.

2.3. Experimental subjects and procedure

The number of subjects was determined by referring to the research of Yang et al. (2019), and ten males and ten females were selected, respectively. All subjects were healthy college students whose basic information is shown in Table 3. They were all asked to avoid caffeine, alcohol, and vigorous physical activity before the experiment. Subjects were asked to wear summer clothing, including short-sleeved T-shirts, pants, socks, and shoes during the experiment. The thermal resistance of the clothing is approximately 0.50 clo. During the experiment, subjects were allowed to read books or work on laptops. The metabolic rate of these types of activities is about 1.1 MET. The ethics committee for science and technology of Shanghai Jiao Tong University approved the research proposal and the related informed consent, which conformed to standards set forth by the committee. Written informed consent was provided by all subjects before participation in the study.

A repeated measure design was adopted in the study. Each participant was required to experience nine conditions for a total of 180 experiments. To eliminate the order effect, each subject experienced a random sequence of cases and there should be at least one day of rest between two cases. To avoid the effects of circadian rhythm, each person was tested at a fixed time. The experimental process is shown in Fig. 3. Before each experiment, the environmental parameters of the climate chamber were adjusted and stabilized for 60 min, and then the subjects entered the climate chamber and adapted to the indoor environment for 15 min. At the end of adaptation, the subjects completed the first questionnaire to give the thermal sensation before local cooling. This study adopts the 7-point thermal sensation vote (TSV) and 5-point thermal comfort vote (TCV) specified in ASHARE-55 (ASHRAE, 2017). After completing questionnaire 1, subjects were given local cooling. One minute before the end of cooling, the subjects completed the subjective questionnaire 2 to give their overall TSV, local TSV, and local TCV under local cooling. According to existing studies (Qian et al., 2017; Xiong et al., 2016; Yang et al., 2020, 2021), the subjects' thermal sensation and thermal comfort can reach a steady state within 20 min under local cooling conditions. In order to ensure the skin temperatures can also reach steady states within 20 min, a pre-experiment was conducted. The details of pre-experiment can be found in supplementary materials. Supplementary Fig. S1 gives the skin temperature at 10 body locations and MST during pre-experiment. When subjects were exposed to the local cooling condition, their skin temperature had begun to gradually steady after 13 min and was generally stable after 15 min. Therefore, it is assumed that a 20-min local cooling period allows the subjects to reach a steady thermal state.

2.4. Skin temperature measurement

In the experiment, Thermochron iButtons (DS, 1923-F5#; Maxim, USA) (range: 20–85 °C, accuracy: ±0.5 °C, resolution: 0.0625 °C) were used to measure the skin temperatures of the subjects during the experiment. The sampling interval was 15 s. The skin temperature measurement points adopted the 10-point method, including forehead, breast, belly, back, upper arm, forearm, hand back, thigh, calf, and foot. The specific positions are shown in Fig. 4. It should be noted that for

Table 3
Basic information of subjects.

Gender	Number	Age	Height (cm)	Weight (kg)	BMI (kg/cm^2)
Male	10	24.9 ± 1.5	177.3 ± 3.6	67.4 ± 4.9	21.4 ± 1.5
Female	10	24.2 ± 1.8	162.4 ± 3.7	53.1 ± 4.6	20.1 ± 1.5

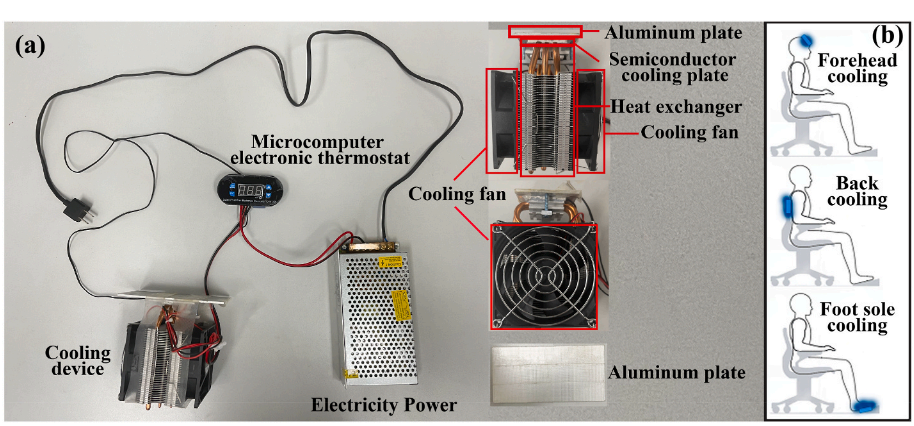

Fig. 2. Local cooling device and cooling locations.

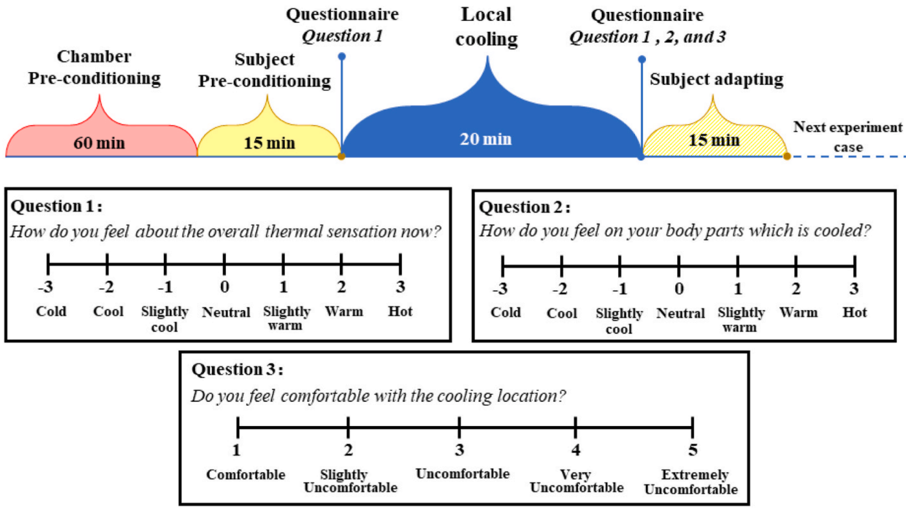

Fig. 3. Detail procedure of the experiment.

areas where local cooling is applied, including the forehead, back, and foot sole, the measuring points are located at positions not covered by the cooling device. The whole-body mean skin temperature (MST) is calculated by equation 2 (Liu et al., 2011).

$$MST = 0.06T_{forehead} + 0.08T_{upperarm} + 0.06T_{forearm} + 0.06T_{hand} + 0.12T_{back} + 0.12T_{breast} + 0.12T_{belly} + 0.19T_{thigh} + 0.13T_{calf} + 0.07T_{foot} \quad (1)$$

2.5. Statistical analysis

This experiment was an orthogonal experiment, and analysis of variance (ANOVA) was used to determine whether the effect of the variables on the experiment results was significant. Independent sample T-test was used to analyze the gender difference in thermal sensation under the same experimental condition. Paired sample T-test was used to analyze the difference between thermal sensation before local cooling and thermal sensation under local cooling. The sensitivity of the skin temperature response to thermal sensation was evaluated with Pearson correlation analysis. The Pearson coefficient between the two variables were strongly correlated at greater than 0.6, moderately correlated at 0.4–0.6, and weakly correlated at 0.2–0.4. It was considered statistically significant at $p < 0.05$ (repeated measures using Greenhouse-Geisser adjustment). The symbol "*" indicates significant difference ($p < 0.05$), "**" indicates significant difference ($p < 0.01$). All data were statistically analyzed using the SPSS software (version 26.0; SPSS, Inc., Chicago, IL, USA).

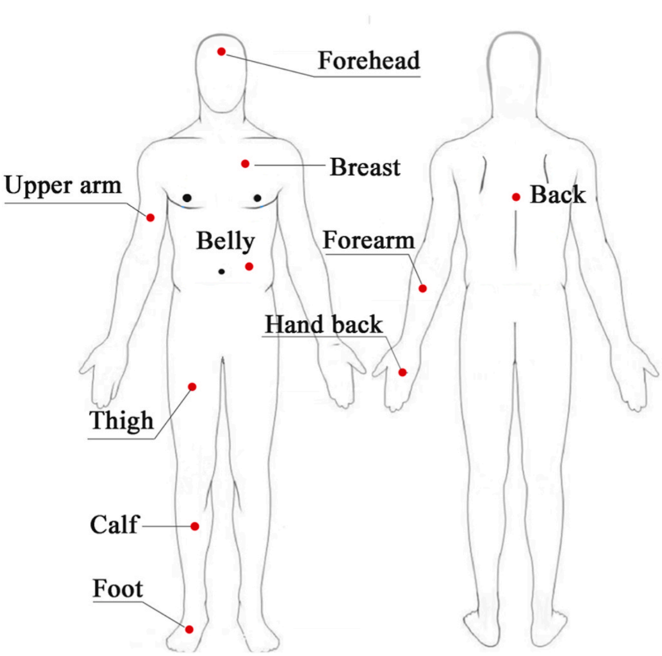

Fig. 4. Locations of the skin temperature sensors.

3. Results

3.1. Effect of local cooling on thermal sensation

3.1.1. Effect of local cooling on overall thermal sensation

Fig. 5 shows the overall TSV of males and females before local cooling. No difference in thermal sensation was observed between two genders at ambient temperatures of 28 °C and 31 °C. At an ambient temperature of 28 °C, both genders reached neutral thermal states. When the ambient temperature raised to 31 °C, the thermal sensation of males and females increased correspondingly, but no gender difference was observed. There were significant gender differences in overall TSV at an ambient temperature of 34 °C, and overall TSV was much higher in

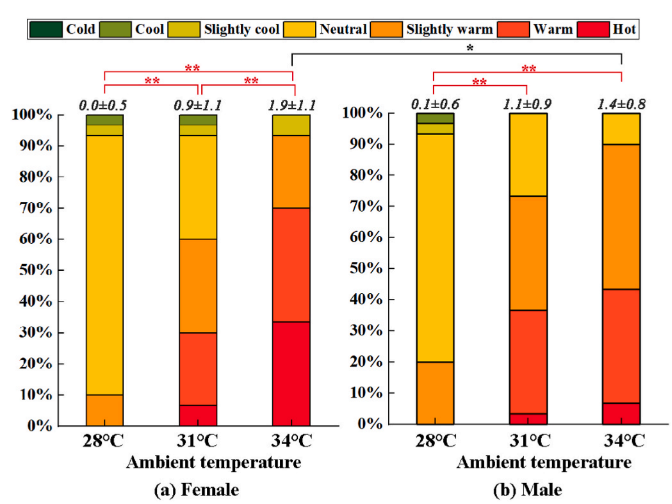

Fig. 5. Overall thermal sensation votes before local cooling for males and females.

females than in males.

ANOVA was performed on the factors affecting the overall TSV under local cooling, and the results are presented in Table 4. The ANOVA results showed that for both genders, ambient temperature, and cooling location significantly affected the overall thermal sensation. The overall thermal sensation of males and females under local cooling condition is given in Fig. 6. Compared to pre-cooling, local cooling can reduce the overall thermal sensation of the subjects. The overall TSV was more varied in females compared to the overall TSV concentrated at 0 (neutral) and 1 (slightly hot) in males. When the ambient temperature is 28–31 °C, the male overall TSV under cooling was generally within the range of −1 (slightly cool) – 1 (slightly warm), whereas females felt cool at a 28 °C ambient temperature. When local cooling was applied in a high temperature environment of 34 °C, the overall TSV of both genders were generally higher than that in other ambient temperature environments.

At an ambient temperature of 34 °C, the overall TSV was significantly higher in males under cooling the back than it under cooling forehead. Similar characteristics were observed among the female subjects. At other ambient temperatures, no significant difference in thermal sensation was observed in both genders when the local cooling locations were different.

3.1.2. Effect of local cooling on local thermal sensation

The factors impacting the local TSV under cooling were studied by ANOVA, and the results are presented in Table 5. The results revealed that the cooling location and cooling temperature had significant effects on the local TSV of males and females. The local thermal sensation at the cooling location of two genders is given in Fig. 7. The local TSV of all subjects was below 0 (neutral) under local cooling, and that of more than half of the subjects was below −2 (cool). In both genders, the local TSV was higher when cooling the back than cooling the forehead or foot sole. For males, forehead cooling at all three ambient temperatures resulted in an intense local cold feeling, which was particularly pronounced at a cooling temperature of 22 °C. When cooling the foot sole at a cooling temperature of 22 °C, the similar intense local cold sensation occurred. However, it is noted that this can be effectively relieved by raising the cooling temperature of the foot sole. For females, the local TSV was below −1 for both foot sole cooling, and forehead cooling at a temperature of 22–26 °C.

3.2. Skin temperature sensitivity analysis

3.2.1. Skin temperature sensitivity on cooling location

The sensitivity of skin temperature is represented its correlation with the overall TSV. Fig. 8 depicts skin temperature of cooling parts and its correlation with overall TSV. Female sensitivity of skin temperature at the cooling parts was significantly higher than that of males. The correlation coefficient between the skin temperature and the overall TSV was 0.49 ($P < 0.01$) for both back cooling and foot sole in females, and 0.44 ($P < 0.05$) for that when cooling the forehead. For males, the correlation coefficients between skin temperature at all three cooling parts and overall TSV were not statistically significant.

Table 4
ANOVA of factors influencing the overall thermal sensation under local cooling.

Source	Gender	Sum of Squares	Df	Mean Square	F value	P value
Ambient temperature	*Male*	1.949	2	0.975	159.430	< 0.01
	Female	5.627	2	2.813	843.121	< 0.01
Cooling location	*Male*	0.336	2	0.168	27.454	< 0.01
	Female	0.140	2	0.070	20.979	< 0.01
Cooling temperature	*Male*	0.001	2	0.004	-[a]	–
	Female	0.007	2	0.003	-[b]	–
Error	*Male*	0.016	2	0.008		
	Female	0.007	2	0.003		
Corrected Error	*Male*	0.025	4	0.006		
	Female	0.013	4	0.003		
Total	*Male*	2.309				
	Female	5.780				

a, b: The mean square value is not greater than error term, which is also considered as the error term.

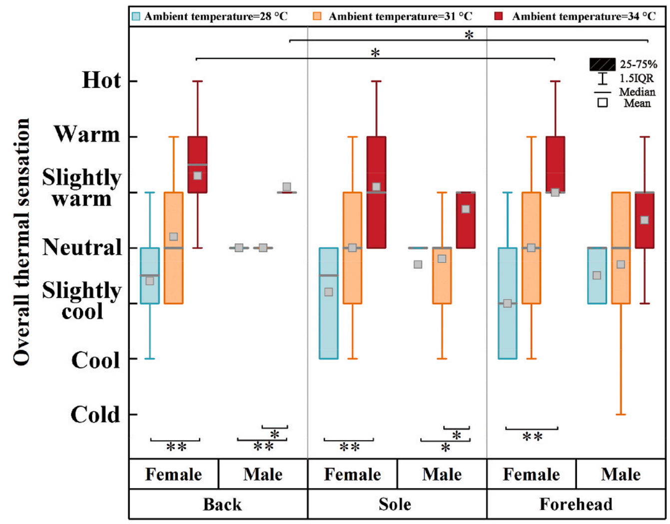

Fig. 6. Overall thermal sensation votes at different cooling locations and ambient temperatures.

Table 5
ANOVA of factors influencing the local thermal sensation under local cooling.

Source	Gender	Sum of Squares	Df	Mean Square	F value	P value
Ambient temperature	*Male*	0.127	2	0.063	2.715	0.27
	Female	0.062	2	0.031	-[a]	–
Cooling location	*Male*	0.960	2	0.480	20.568	< 0.01
	Female	1.070	2	0.535	13.636	< 0.05
Cooling temperature	*Male*	0.607	2	0.303	12.996	< 0.05
	Female	0.549	2	0.274	0.701	< 0.05
Error	*Male*	0.047	2	0.023		
	Female	0.095	2	0.048		
Corrected Error	*Male*	0.047	2	0.023		
	Female	0.157	4	0.039		
Total	*Male*	1.700				
	Female	1.662				

[a] The mean square value is not greater than error term, which is also considered as the error term.

3.2.2. Skin temperature sensitivity on non-cooling location

The mean values of skin temperatures at non-cooled body locations during the 3 min before the end of cooling in five overall thermal sensation classification are shown in Fig. 9. Overall, the temperature of the limbs was lower than that of the torso. The correlation and linear regression coefficients of non-cooled location skin temperature and overall TSV are given in Table 6.

The sensitivity of skin temperature at non-cooled locations was also significantly higher in females than in males. For forehead and back local cooling, only forearm skin temperature correlated statistically with overall TSV in males (Correlation coefficients are 0.45 and 0.43, respectively, $P < 0.05$), and for foot sole cooling, none of the non-cooled

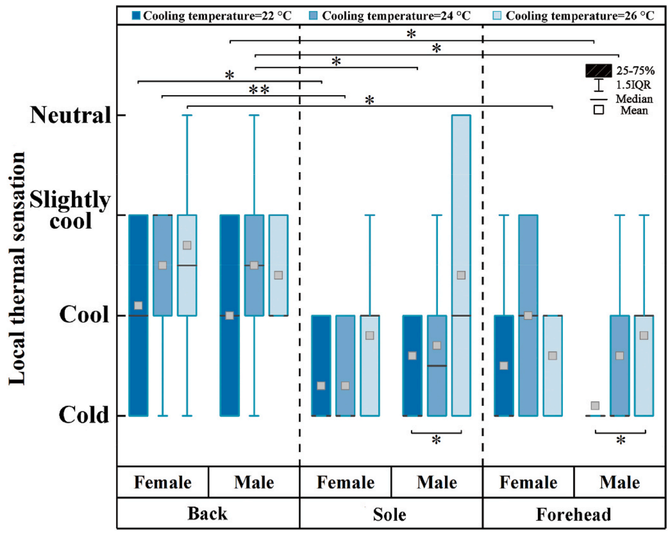

Fig. 7. Local thermal sensation votes at different cooling location and cooling temperature.

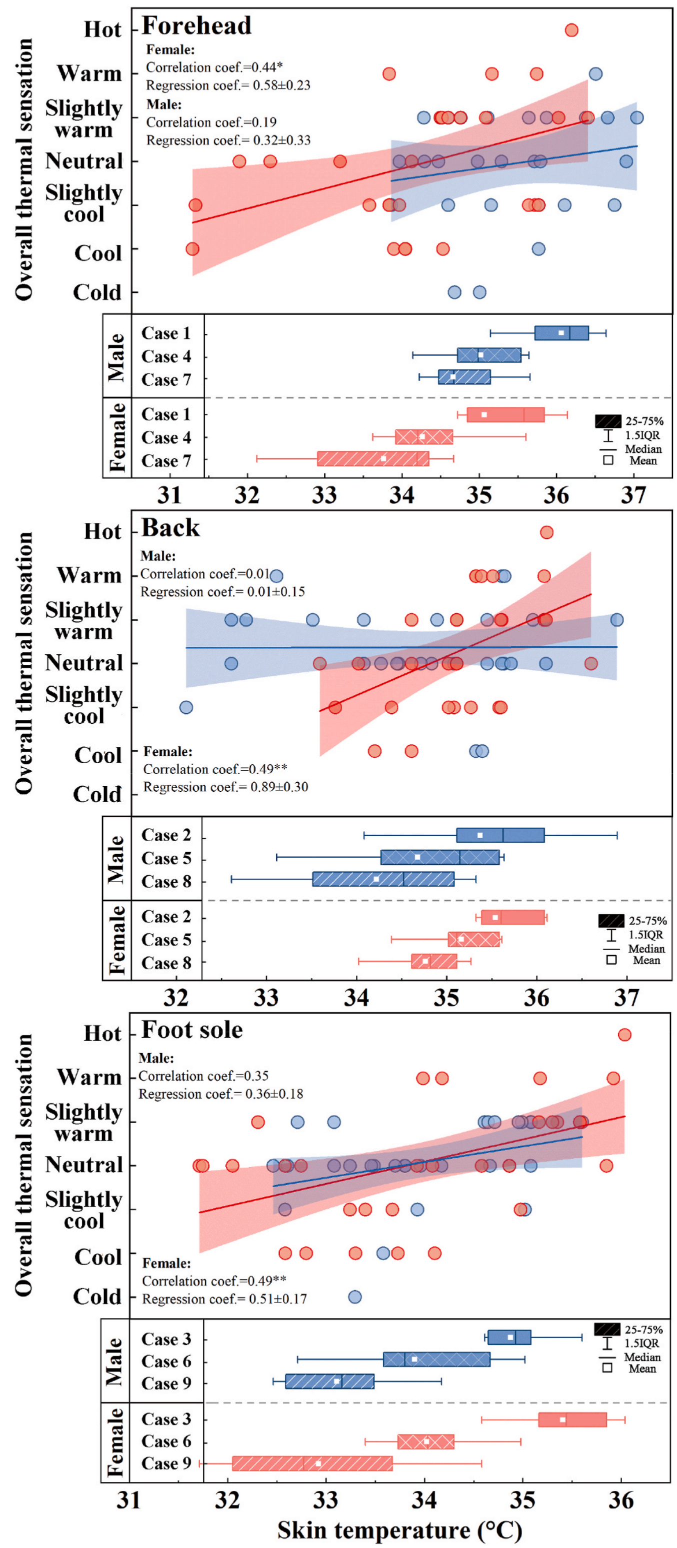

Fig. 8. Skin temperature of cooling location and its correlation coefficient with overall thermal sensation. Red dots represent skin temperature at the cooled location for females and blue dots represent skin temperature at the cooled location for males; solid lines are linear fit results and shading is 95% confidence interval.

locations showed correlation with overall TSV. For females, all skin temperature of non-cooled locations showed significant correlations with overall TSV, except for the belly. Among these, the correlation coefficients were higher for MST, calf, and forearm.

The differences in skin temperature at each body location between two genders in different overall TSV classification were analyzed, and the statistically significant results are listed in Table 7. The findings revealed that at an overall TSV of −2 (cool), skin temperature in males and females differed significantly in several areas, with males having a higher skin temperature than females. As overall TSV increased, the number of body areas with significant gender differences in skin temperature decreased. Significant gender differences in breast and belly skin temperatures were observed when overall TSV ranged from −1 (slightly cool) to 2 (warm), and skin temperature was higher in females than in males.

4. Discussion

The overall thermal sensations before local cooling had gender differences, with significantly higher thermal sensation in females at ambient temperature of 34 °C. A study by Xiong et al. (2015) found relatively small gender differences in thermal sensation in the thermoneutral environment, with females having lower thermal sensation than males at low ambient temperatures (22 °C) and higher thermal sensation than males at high ambient temperatures (32 °C and 37 °C). This is consistent with the results we observed. Xiong et al. (2015) suggested that this gender difference can be demonstrated in relation to skin temperature. Female skin temperature is lower than male skin temperature in cooler environments and higher in warmer environments, resulting in relatively larger variations in thermal sensation for females.

The overall thermal sensation was achieved at a relatively neutral level without any local cooling in an indoor environment with ambient temperature of 28 °C. Furthermore, because the temperature difference between the cooling temperature and the ambient temperature of 28 °C was minimal, the effect of local cooling on the overall thermal sensation was improved but not noticeable. In an indoor environment at 31 °C, the overall thermal sensation could be improved to be neutral by local cooling. As the ambient temperature raised to 34 °C, local cooling at an acceptable cooling power could improve the human overall thermal sensation to a certain extent, but it was difficult to eliminate the negative impact of the high ambient temperature, making occupants unable to reach a relatively neutral or cool state. Existing studies have pointed out that the overall thermal sensation is usually dominated by the most

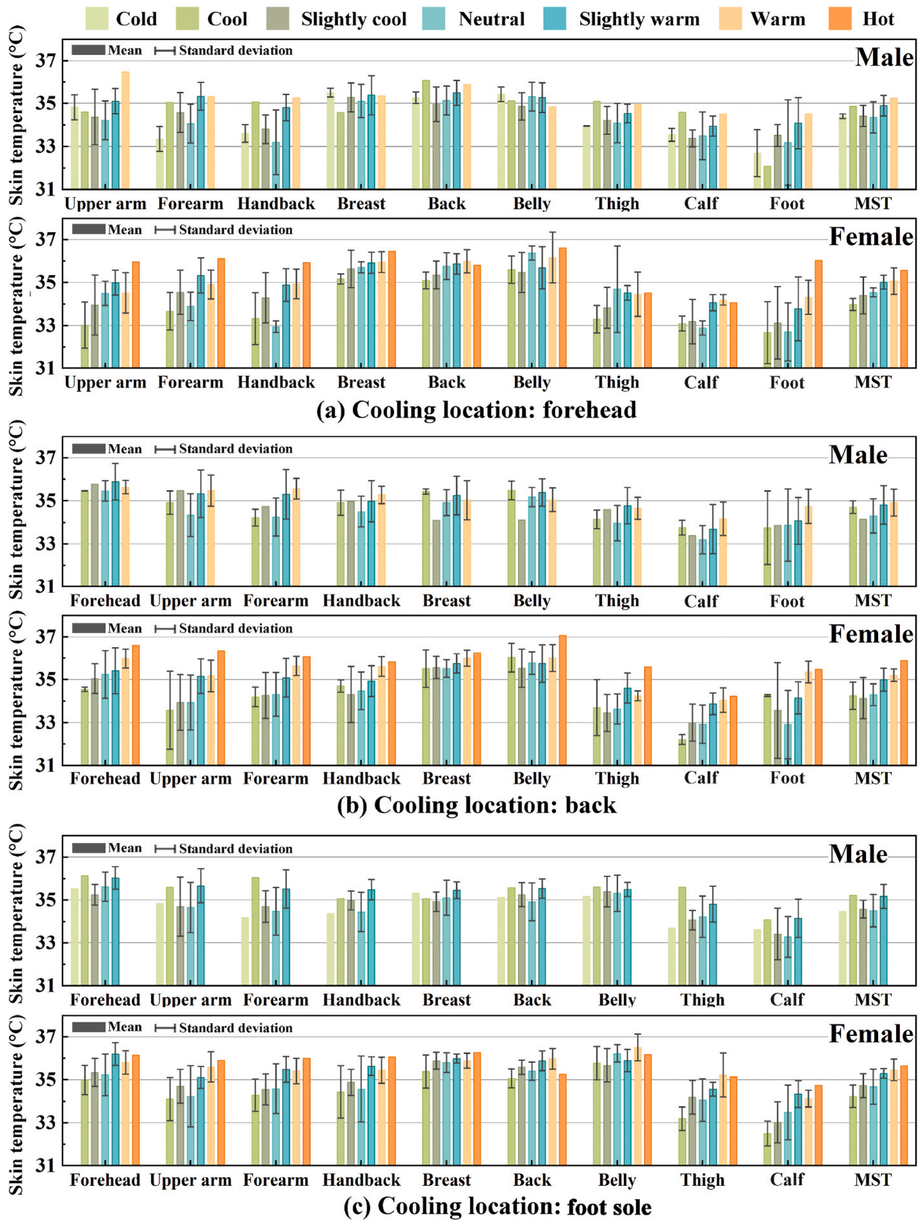

Fig. 9. The mean values of skin temperatures at non-cooled body locations in five overall thermal sensation classification.

unneutral or uncomfortable body areas, and the overall TSV is highly correlated with the distal skin temperature (Luo et al., 2018; Zhou et al., 2019). The distal end of the human body includes the feet and forehead, while the proximal end includes the back. Therefore, compared with back cooling, cooling the foot sole and forehead greatly improved the occupants' overall thermal sensation, and this effect was more significant when the indoor ambient temperature was high.

Although local cooling could give occupants with a favorable overall thermal sensation, it could also create local discomfort due to an overly intense local cooling sensation. Fig. 10 illustrates the correlation of local TCV and local TSV for males and females. In this figure, the darker the color of the blocks, the greater the number of subjects who reported having this sensation. When the local TSV reached −2 (cool), both males and females began to feel local uncomfortable. With the further decline of the local TSV, this discomfort was further exacerbated. This risk was primarily caused by the cooling of the forehead and foot sole. According to existing research, the brain nerve center is in the head, which requires a lot of energy on a daily basis (Riccitelli, 1933). This, combined with the thin skin and dense blood veins, results in a high heat exchange rate between the head and outer environment (Monahan-Earley et al., 2013). This may make the local cold sensation more pronounced when cooling the head at the same cooling temperature, and the cold sensation increases further as the cooling temperature decreases. The results showed that the back has a higher local cooling threshold and withstand higher cooling intensities, which is consistent with the findings of previous studies (Yang et al., 2020; Zhao et al., 2021). Notably, the weight of the local cooling device and the way it is fixed may affect the comfort of the user (Song et al., 2022). In this study, the back cooling device was placed between the subject's back and the seat, and was fixed to the backrest of the seat. Although users did not have to carry the cooling device, they were asked to keep their backs in full contact with the cooling plate. Holding such a position for a long time may cause their discomfort. Head cooling is conducted by fixing the device on the subject's head and the pressure of the device may also affect their thermal comfort and cause complaints. Although cooling the foot sole could also caused local discomfort, increasing the cooling temperature could considerably reduce this problem. Combined with the overall TSV results, it is clear that local cooling has good cooling effects on males at the three ambient

Table 6
Correlation and linear regression coefficients of non-cooled location skin temperature and overall thermal sensation.

Cooling location	Body location	Male			Female		
		Correlation coef.	Regression coef. (mean ± SD)	P value	Correlation coef.	Regression coef. (mean ± SD)	P value
Forehead	Upper arm	0.27	0.34 ± 0.23	N/A	0.52	0.62 ± 0.19	**
	Forearm	0.45	0.57 ± 0.21	*	0.53	0.73 ± 0.22	**
	Hand back	0.30	0.31 ± 0.19	N/A	0.44	0.52 ± 0.20	*
	Breast	0.05	0.08 ± 0.31	N/A	0.44	1.01 ± 0.39	*
	Back	0.17	0.31 ± 0.34	N/A	0.48	1.17 ± 0.41	**
	Belly	0.05	0.10 ± 0.36	N/A	0.25	0.43 ± 0.31	N/A
	Thigh	0.20	0.36 ± 0.33	N/A	0.37	0.51 ± 0.24	*
	Calf	0.21	0.34 ± 0.30	N/A	0.55	1.00 ± 0.29	**
	Foot	0.32	0.28 ± 0.16	N/A	0.42	0.39 ± 0.16	*
	MST	0.30	0.62 ± 0.37	N/A	0.61	1.31 ± 0.33	**
Back	Forehead	0.18	0.29 ± 0.29	N/A	0.46	0.64 ± 0.23	*
	Upper arm	0.25	0.23 ± 0.17	N/A	0.52	0.54 ± 0.17	**
	Forearm	0.43	0.40 ± 0.16	*	0.54	0.67 ± 0.20	**
	Hand back	0.19	0.24 ± 0.23	N/A	0.45	0.60 ± 0.23	*
	Breast	0.06	0.09 ± 0.25	N/A	0.39	1.04 ± 0.47	*
	Belly	0.05	0.08 ± 0.33	N/A	0.23	0.40 ± 0.32	N/A
	Thigh	0.29	0.34 ± 0.21	N/A	0.52	0.77 ± 0.24	**
	Calf	0.21	0.23 ± 0.21	N/A	0.61	0.88 ± 0.22	**
	Foot	0.16	0.12 ± 0.13	N/A	0.36	0.29 ± 0.14	*
	MST	0.20	0.25 ± 0.22	N/A	0.60	1.02 ± 0.26	**
Foot sole	Forehead	0.25	0.37 ± 0.28	N/A	0.44	0.73 ± 0.28	*
	Upper arm	0.22	0.19 ± 0.16	N/A	0.43	0.53 ± 0.21	*
	Forearm	0.22	0.20 ± 0.16	N/A	0.49	0.70 ± 0.24	**
	Hand back	0.30	0.33 ± 0.20	N/A	0.37	0.44 ± 0.21	*
	Breast	0.18	0.27 ± 0.27	N/A	0.37	1.05 ± 0.50	*
	Back	0.13	0.17 ± 0.24	N/A	0.46	1.26 ± 0.46	*
	Belly	0.07	0.10 ± 0.27	N/A	0.31	0.70 ± 0.41	N/A
	Thigh	0.19	0.20 ± 0.19	N/A	0.61	0.87 ± 0.21	**
	Calf	0.19	0.18 ± 0.18	N/A	0.59	0.75 ± 0.19	**
	MST	0.24	0.33 ± 0.25	N/A	0.59	1.14 ± 0.30	**

Table 7
Differences in skin temperature between males and females at the same overall thermal sensation.

Overall thermal sensation	Body area	Skin temperature (°C)		Mann-Whitney *U* test *P value*
		Male	Female	
Cool	Forehead	35.7 ± 0.3	34.5 ± 0.7	0.010
	Upper arm	35.0 ± 0.5	33.6 ± 1.1	0.029
	Back	35.6 ± 0.3	35.0 ± 0.4	0.050
	Thigh	37.8 ± 0.7	33.3 ± 0.6	0.015
	Calf	34.1 ± 0.4	32.7 ± 0.5	0.005
Slightly cool	Breast	35.1 ± 0.6	35.7 ± 0.6	0.024
	Belly	34.9 ± 0.7	35.5 ± 0.8	0.031
Neutral	Breast	35.1 ± 0.7	35.7 ± 0.4	0.000
	Belly	35.3 ± 0.7	36.1 ± 0.6	0.000
Slightly warm	Breast	35.4 ± 0.7	35.8 ± 0.4	0.011
	Belly	35.4 ± 0.6	35.8 ± 0.7	0.009
Warm	Breast	35.1 ± 0.7	36.0 ± 0.4	0.029
	Belly	35.0 ± 0.4	36.2 ± 0.7	0.021

temperature levels in this study. When the ambient temperatures are 28 °C and 31 °C, back cooling is suggested. In a hot indoor environment at 34 °C, it is more appropriate to use foot sole cooling with a relatively high cooling temperature. In this study, the best appropriate ambient temperature level for local cooling for female is 31 °C. In this environment, back cooling at 24 °C to 26 °C will make females reach a neutral thermal sensation state. It is worth noting that for females, foot sole and forehead cooling are likely to cause discomfort due to the intense local cold sensation.

The sensitivity of skin temperature to the overall thermal sensation changes at different body areas during local cooling, and there are some differences between the genders. Compared with males, female skin temperature could make more sensitive physiological response to their own thermal sensation. For males, skin temperature in all parts of the body did not show sensitivity to thermal sensation when using foot sole cooling. Skin temperature of the male forearm was correlated with their thermal sensation to some extent during forehead cooling and back cooling, but this still needs more studies to support. The temperature of the arm and calf can better characterize the female overall thermal sensation under local cooling. It needs to be noted that Schellen et al. (2012) found a significant correlation between overall TSV and skin temperature of female hand, forearm, and upper arm under non-uniform cooling, which is consistent with our findings. However, their research points out that there is no correlation between male skin temperature at each point and overall TSV, which is different from our research results. This could be due to the fact that the experimental settings are different. A non-uniform environment through the cooling radiant ceiling was conducted in their experiment, with ambient temperature of 24 °C. The overall TSV of the male subjects during the experiment was mainly focused at 0 (neutral) with few variations. This may have led to a less significant response of skin temperature to thermal sensation in males in their study.

In the study of uniform cooling environment, Yeom and Delogu (2021) discovered that male breasts have higher skin temperatures than that of female, which is different from the findings of our experiment. This may be related to the effect of airflow velocity on local skin temperature. According to Wang et al. (2011), the stronger the draft sensation, the lower the local skin temperature at the exposed area of the airflow. Considering that females have a larger breast skin area than males generally, skin temperature may be more affected by air velocity.

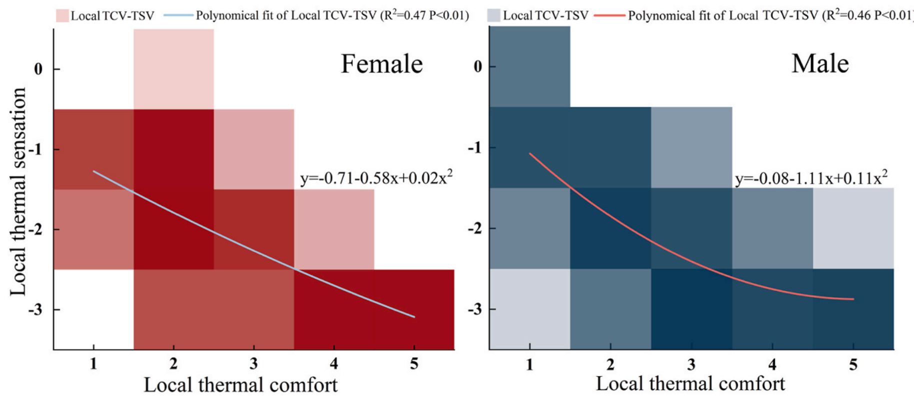

Fig. 10. Local thermal sensation and corresponding local thermal comfort.

As a result, in a convection-cooled environment, female breast skin temperatures are lower. This also explains why in Yeom's study, males had greater breast temperatures but lower belly skin temperatures than females (the belly is not part of the direct airflow area in the sitting position). Local cooling was achieved in this study through conduction, and the indoor air velocity was strictly controlled within 0.1 m/s to avoid airflow to influence local skin temperature.

5. Future perspective and practical applications

In this study, TSV was collected after human thermal sensation reached steady state under local cooling condition. This study did not gather much TSV in the non-stable stage since subjects may develop unpleasant subjective sentiments when filling out the questionnaire with high frequency. In the future, the experimental design can be improved to investigate the difference in thermal sensitivity and skin temperature change rate between males and females in a non-steady situation. This could broaden the scope of research into the gender differences in human psychological and physiological responses to local cooling. Furthermore, while one of the goals of this study was to find body areas of males and females with high sensitivity to thermal sensation response under local cooling, the skin temperature-thermal sensation association model was not thoroughly discussed. In the future, the skin temperature of these locations could be used as an input for a machine learning algorithm to construct a thermal sensation prediction model.

For the practical application of local cooling, the portability, cost, aesthetics, the fixing location, the application scenario of the cooling devices, and the design cooling temperature are all important factors. The accepted comfortable indoor environment temperature is 26 °C, and this paper demonstrates that local cooling of the back is effective in improving thermal sensation in both men and women in a higher temperature environment. Back cooling can be easily applied to domestic or office chairs, and for special occupations where heat insecurity is a concern (e.g. doctors and nurses in medical protective clothing, construction workers, couriers, etc.), back cooling can be combined with work clothing to provide portable, real-time cooling. In addition, for men, foot sole cooling is worth exploring in the future, especially in hot environments. Foot sole cooling can easily be combined with foot heating devices to form a complete thermal sensation improvement system. This study also investigated the sensitivity of human skin temperature under different local cooling conditions. With the development of automation technology, the intelligence of cooling equipment has become popular. The non-contact temperature measurement sensor is used to evaluate the human thermal sensation and thus achieve the automatic adjustment of the device. According to the results of this study, the forearm temperature of males reflects to some extent their thermal sensation during forehead cooling and back cooling. In females, the calf and forearm skin temperatures reflect their thermal sensation during forehead cooling, back cooling, and foot sole cooling. In future studies, mathematical models of "ambient temperature - cooling temperature – overall TSV" for three cooling location can be further developed based on the results of this study, and relevant automatic control strategies can be proposed.

6. Conclusion

The conclusions of this study are as follows:

(1) Under local cooling, female has a greater variation in thermal sensation than male. In this experiment, male overall TSV is concentrated between 0 (neutral) and 1 (slightly warm), but female overall TSV is dispersed between −2 (cool) and 2 (warm).
(2) For both males and females, ambient temperature and cooling location have a significant impact on overall thermal sensation under local cooling, while cooling temperature and cooling location have a significant impact on local thermal sensation.
(3) In the three environments with different ambient temperature set up in this study, the best applicable indoor environment with local cooling for female is 31 °C. In this environment, back cooling at 24–26 °C achieves a neutral thermal sensation.
(4) Local cooling is applicable for male in all three environments with different ambient temperature set up in this study. Back cooling at 22–26 °C is recommended in 28 °C and 31 °C indoor environments. In a 34 °C environment, foot sole cooling with a higher cooling temperature is preferable.
(5) The skin temperatures of female are more sensitive to thermal sensation than that of males under local cooling. The skin temperature of female upper arm is the most sensitive, whereas that for male is the skin temperature of forearm.

Author contribution statement

Qiantao Zhao: Experiment, Data curation., **Junmeng Lyu:** Investigation, Data analysis, Writing - original draft, Visualization.

Heng Du: Writing – review & editing., **Zhiwei Lian:** Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing., **Zisheng Zhao:** Writing – review & editing.

Declaration of competing interest

We declare no conflict of interest. This manuscript is approved by all the authors for publication.

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jtherbio.2022.103401.

References

Ashrae, S., 2017. Thermal Environmental Conditions for Human Occupancy. In: ANSI/ASHRAE Standard 55-2004, vol. 145. American Society of Heating, Refrigerating and Air conditioning Engineers.

Beshir, M.Y., Ramsey, J.D., 1981. Comparison between male and female subjective estimates of thermal effects and sensations. Appl. Ergon. 12, 29–33. https://doi.org/10.1016/0003-6870(81)90091-0.

Bothorel, B., Galeou, M., Dewasmes, G., Hoeft, A., Candas, V., 1991. Leg skin temperature and thigh sweat output: possible central influence of local thermal inputs. Eur. J. Appl. Physiol. Occup. Physiol. 62, 405–409. https://doi.org/10.1007/BF00626611.

Cabanac, M., Massonnet, B., Belaiche, R., 1972. Preferred skin temperature as a function of internal and mean skin temperature. J. Appl. Physiol. 33, 699–703. https://doi.org/10.1152/jappl.1972.33.6.699.

Cao, T., Lian, Z., Ma, S., Bao, J., 2021. Thermal comfort and sleep quality under temperature, relative humidity and illuminance in sleep environment. J. Build. Eng. 43, 102575 https://doi.org/10.1016/j.jobe.2021.102575.

Charkoudian, N., Stachenfeld, N., 2016. Sex hormone effects on autonomic mechanisms of thermoregulation in humans. Auton. Neurosci. 196, 75–80. https://doi.org/10.1016/j.autneu.2015.11.004.

Chaudhuri, T., Zhai, D., Soh, Y.C., Li, H., Xie, L., 2018. Random forest based thermal comfort prediction from gender-specific physiological parameters using wearable sensing technology. Energy Build. 166, 391–406. https://doi.org/10.1016/j.enbuild.2018.02.035.

Choi, J.-H., Yeom, D., 2019. Development of the data-driven thermal satisfaction prediction model as a function of human physiological responses in a built environment. Build. Environ. 150, 206–218. https://doi.org/10.1016/j.buildenv.2019.01.007.

Choi, J.-H., Yeom, D., 2017. Study of data-driven thermal sensation prediction model as a function of local body skin temperatures in a built environment. Build. Environ. 121, 130–147. https://doi.org/10.1016/j.buildenv.2017.05.004.

Cotter, J.D., Taylor, N.A.S., 2005. The distribution of cutaneous sudomotor and alliesthesial thermosensitivity in mildly heat-stressed humans: an open-loop approach. J. Physiol. 565, 335–345. https://doi.org/10.1113/jphysiol.2004.081562.

Daanen, H.A.M., 2003. Finger cold-induced vasodilation: a review. Eur. J. Appl. Physiol. 89, 411–426. https://doi.org/10.1007/s00421-003-0818-2.

Dai, C., Zhang, H., Arens, E., Lian, Z., 2017. Machine learning approaches to predict thermal demands using skin temperatures: steady-state conditions. Build. Environ. 114, 1–10. https://doi.org/10.1016/j.buildenv.2016.12.005.

Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analy. Appl. Environ. Eng.

Federspiel, C.C., 1998. Statistical analysis of unsolicited thermal sensation complaints in commercial buildings. Transactions-American Society Of Heating, Refrigerating And Air Conditioning Engineers 104, 912–926.

Griefahn, B., Künemund, C., 2001. The effects of gender, age, and fatigue on susceptibility to draft discomfort. J. Therm. Biol. 26, 395–400. https://doi.org/10.1016/S0306-4565(01)00050-X.

He, Y., Li, N., Huang, Q., 2015. A field study on thermal environment and occupant local thermal sensation in offices with cooling ceiling in Zhuhai, China. Energy Build. 102, 277–283. https://doi.org/10.1016/j.enbuild.2015.05.058.

Jia, M., Choi, J.-H., Liu, H., Susman, G., 2022. Development of facial-skin temperature driven thermal comfort and sensation modeling for a futuristic application. Build. Environ. 207, 108479 https://doi.org/10.1016/j.buildenv.2021.108479.

Lan, L., Qian, X.L., Lian, Z.W., Lin, Y.B., 2018. Local body cooling to improve sleep quality and thermal comfort in a hot environment. Indoor Air 28, 135–145. https://doi.org/10.1111/ina.12428.

Liu, W., Lian, Z., Deng, Q., Liu, Y., 2011. Evaluation of calculation methods of mean skin temperature for use in thermal comfort study. Build. Environ. 46, 478–488. https://doi.org/10.1016/j.buildenv.2010.08.011.

Luo, M., Arens, E., Zhang, H., Ghahramani, A., Wang, Z., 2018. Thermal comfort evaluated for combinations of energy-efficient personal heating and cooling devices. Build. Environ. 143, 206–216. https://doi.org/10.1016/j.buildenv.2018.07.008.

Luo, Y., Lian, Z., Xuan, Y., Zhang, W., 2020. Research on more effective local cooling ways to human thermal comfort in hot environment. In: Wang, Z., Zhu, Y., Wang, F., Wang, P., Shen, C., Liu, J. (Eds.), Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019). Springer Singapore, Singapore, pp. 563–572.

Lyu, J., Feng, X., Cheng, Y., Liao, C., 2021. Experimental and numerical analysis of air temperature uniformity in occupied zone under stratum ventilation for heating mode. J. Build. Eng. 43, 103016 https://doi.org/10.1016/j.jobe.2021.103016.

Monahan-Earley, R., Dvorak, A.M., Aird, W.C., 2013. Evolutionary origins of the blood vascular system and endothelium. J. Thromb. Haemostasis 11, 46–66.

Nadel, E.R., Bullard, R.W., Stolwijk, J.A., 1971. Importance of skin temperature in the regulation of sweating. J. Appl. Physiol. 31, 80–87. https://doi.org/10.1152/jappl.1971.31.1.80.

Oi, H., Yanagi, K., Tabata, K., Tochihara, Y., 2011. Effects of heated seat and foot heater on thermal comfort and heater energy consumption in vehicle. Ergonomics 54, 690–699. https://doi.org/10.1080/00140139.2011.595513.

Pallubinsky, H., Schellen, L., Rieswijk, T.A., Breukel, C.M.G.A.M., Kingma, B.R.M., van Marken Lichtenbelt, W.D., 2016. Local cooling in a warm environment. Energy Build. 113, 15–22. https://doi.org/10.1016/j.enbuild.2015.12.016.

Pasut, W., Zhang, H., Arens, E., Zhai, Y., 2015. Energy-efficient comfort with a heated/cooled chair: results from human subject tests. Build. Environ. 84, 10–21. https://doi.org/10.1016/j.buildenv.2014.10.026.

Pasut, W., Zhang, H., Arens, E.A., Kaam, S., Zhai, Y., 2012. Effect of a heated and cooled office chair on thermal comfort. HVAC R Res. 19, 574–583.

Riccitelli, L., 1933. Regulation of blood cells by nerve centres. DMW (Dtsch. Med. Wochenschr.) 59.

Schellen, L., Loomans, M.G.L.C., de Wit, M.H., Olesen, B.W., Lichtenbelt, W.D. van M., 2012. The influence of local effects on thermal sensation under non-uniform environmental conditions — gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling. Physiol. Behav. 107, 252–261. https://doi.org/10.1016/j.physbeh.2012.07.008.

Song, W., Zhang, Z., Chen, Z., Wang, F., Yang, B., 2022. Thermal comfort and energy performance of personal comfort systems (PCS): a systematic review and meta-analysis. Energy Build. 256, 111747 https://doi.org/10.1016/j.enbuild.2021.111747.

Stevens, J.C., Choo, K.K., 1998. Temperature sensitivity of the body surface over the life span. Somatosens. Mot. Res. 15 1, 13–28.

Stolwijk, J.A., Hardy, J.D., 1966. Partitional calorimetric studies of responses of man to thermal transients. J. Appl. Physiol. 21, 967–977. https://doi.org/10.1152/jappl.1966.21.3.967.

Tang, Y., Yu, H., Zhang, K., Niu, K., Mao, H., Luo, M., 2022. Thermal comfort performance and energy-efficiency evaluation of six personal heating/cooling devices. Build. Environ. 217, 109069 https://doi.org/10.1016/j.buildenv.2022.109069.

van Craenendonck, S., Lauriks, L., Vuye, C., Kampen, J., 2019. Local effects on thermal comfort: experimental investigation of small-area radiant cooling and low-speed draft caused by improperly retrofitted construction joints. Build. Environ. 147, 188–198. https://doi.org/10.1016/j.buildenv.2018.10.021.

Verhaart, J., Li, R., Zeiler, W., 2018. User interaction patterns of a personal cooling system: a measurement study. Sci Technol Built Environ 24, 57–72. https://doi.org/10.1080/23744731.2017.1333365.

Veselý, M., Zeiler, W., 2014. Personalized conditioning and its impact on thermal comfort and energy performance – a review. Renew. Sustain. Energy Rev. 34, 401–408. https://doi.org/10.1016/j.rser.2014.03.024.

Wang, Y., Lian, Z., Lan, L., 2011. The effect of turbulence intensity on local skin temperature and subjective responses to draft. Energy Build. 43, 2678–2683. https://doi.org/10.1016/j.enbuild.2011.06.021.

Wang, W., Wang, F., Lai, D., Chen, Q., 2022. Evaluation of SARS-COV-2 transmission and infection in airliner cabins. Indoor Air 32 (1), e12979. https://doi.org/10.1111/ina.12979.

Xia, L., Lan, L., Tang, J., Wan, Y., Lin, Y., Wang, Z., 2020. Bed heating improves the sleep quality and health of the elderly who adapted to no heating in a cold environment. Energy Build. 210, 109687 https://doi.org/10.1016/j.enbuild.2019.109687.

Xiong, J., Lian, Z., Zhou, X., You, J., Lin, Y., 2015. Investigation of gender difference in human response to temperature step changes. Physiol. Behav. 151, 426–440. https://doi.org/10.1016/j.physbeh.2015.07.037.

Xiong, J., Ma, T., Lian, Z., de Dear, R., 2019. Perceptual and physiological responses of elderly subjects to moderate temperatures. Build. Environ. 156, 117–122. https://doi.org/10.1016/j.buildenv.2019.04.012.

Xiong, J., Zhou, X., Lian, Z., You, J., Lin, Y., 2016. Thermal perception and skin temperature in different transient thermal environments in summer. Energy Build. 128, 155–163. https://doi.org/10.1016/j.enbuild.2016.06.085.

Xu, X., Lian, Z., Shen, J., Lan, L., Sun, Y., 2021. Environmental factors affecting sleep quality in summer: a field study in Shanghai, China. J. Therm. Biol. 99, 102977 https://doi.org/10.1016/j.jtherbio.2021.102977.

Yang, B., Lei, T.-H., Yang, P., Liu, K., Wang, F., 2021. On the use of wearable face and neck cooling fans to improve occupant thermal comfort in warm indoor environments. Energies 14. https://doi.org/10.3390/en14238077.

Yang, H., Cao, B., Ju, Y., Zhu, Y., 2019. The effects of local cooling at different torso parts in improving body thermal comfort in hot indoor environments. Energy Build. 198, 528–541. https://doi.org/10.1016/j.enbuild.2019.06.004.

Yang, H., Deng, Y., Cao, B., Zhu, Y., 2020. Study on the local and overall thermal perceptions under nonuniform thermal exposure using a cooling chair. Build. Environ. 176, 106864 https://doi.org/10.1016/j.buildenv.2020.106864.

Yang, L., Zhao, S., Gao, S., Zhang, H., Arens, E., Zhai, Y., 2021. Gender differences in metabolic rates and thermal comfort in sedentary young males and females at various temperatures. Energy Build. 251, 111360 https://doi.org/10.1016/j.enbuild.2021.111360.

Yeom, D.J., Delogu, F., 2021. Local body skin temperature-driven thermal sensation predictive model for the occupant's optimum productivity. Build. Environ. 204, 108196 https://doi.org/10.1016/j.buildenv.2021.108196.

Zhai, Y., Zhang, Y., Zhang, H., Pasut, W., Arens, E., Meng, Q., 2015. Human comfort and perceived air quality in warm and humid environments with ceiling fans. Build. Environ. 90, 178–185. https://doi.org/10.1016/j.buildenv.2015.04.003.

Zhang, H., 2003. Human Thermal Sensation and Comfort in Transient and Non-uniform Thermal Environments. University of California, Berkeley.

Zhang, H., Arens, E., Kim, D., Buchberger, E., Bauman, F., Huizenga, C., 2010. Comfort, perceived air quality, and work performance in a low-power task–ambient conditioning system. Build. Environ. 45, 29–39. https://doi.org/10.1016/j.buildenv.2009.02.016.

Zhao, Q., Lian, Z., Lai, D., 2021. Thermal comfort models and their developments: a review. Energy Built Environ. 2, 21–33. https://doi.org/10.1016/j.enbenv.2020.05.007.

Zhou, X., Liu, Y., Luo, M., Zhang, L., Zhang, Q., Zhang, X., 2019. Thermal comfort under radiant asymmetries of floor cooling system in 2 h and 8 h exposure durations. Energy Build. 188–189, 98–110. https://doi.org/10.1016/j.enbuild.2019.02.009.

Zhou, X., Liu, Y., Zhang, J., Ye, L., Luo, M., 2022. Radiant asymmetric thermal comfort evaluation for floor cooling system – a field study in office building. Energy Build. 260, 111917 https://doi.org/10.1016/j.enbuild.2022.111917.