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Evaluating thermal response when elderly people using local cooling devices: Correlation among overall and local thermal sensation with skin temperature

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ABSTRACT

The thermal comfort of elderly people in warm indoor environments is important because of their higher risk of heat stress. The use of local cooling devices may help alleviate heat stress. In this study, 26 elderly participants were recruited for climate chamber experiments in neutral (26 °C, 40 % relative humidity (RH)), slightly warm (29 °C, 40 % RH; 28 °C, 60 % RH), and warm (33 °C, 40 % RH; 32 °C, 50 % RH) environments. Three local cooling devices were tested: a table fan, evaporative cooling device, and air-cooled jacket. This study found, in different warm environments, the use of local cooling devices by the elderly results in an mean skin temperature decrease of no more than 0.5 °C. The thermal sensation in the head and torso has the most significant impact on overall thermal sensation. The mean skin temperature (MST) remains an effective physiological indicator for estimating overall thermal sensation after using local cooling devices. The skin temperature in the head, limbs, and extremities plays a substantial role in predicting overall thermal sensation. The thermosensory mean skin temperature (TMST) proposed based on the skin temperature of these parts can more accurately predict overall thermal sensation than MST. This study provides a reference for the development of future local cooling devices. This study has implications for guiding the selection of devices for nursing homes or residential environments for the elderly, and it can be utilized to formulate recommendations for improving device design.

1. Introduction

In the context of global warming, ensuring indoor thermal comfort is crucial for the health and well-being of residents. Commonly used centralized air-conditioning systems have high energy consumption and limited ability to meet individual needs. Therefore, researchers are concentrating on personal comfort systems (PCSs) [1]. PCSs are expected to substitute or provide supplemental solutions for air-conditioning systems under certain conditions [2]. PCSs satisfy the thermal comfort requirements of individuals by creating a microclimate around them [3]. PCSs can be categorized into radiant, convective, and conductive types [4]. For cooling PCS, the most popular type is the convective PCS, which includes ceiling, floor, and desk fans. These common convective PCSs use indoor air, lack air pretreatment systems and air supply ducts, and are usually portable. In particular, using mobile power and attaching a fan to clothing transforms it into a wearable device, such as an air ventilation clothing. This type of PCS is more personalized and portable. Previously, this type of cooling clothing has been widely researched and applied to individuals with high metabolic rates engaged in physical activities [5,6]. Relevant studies have primarily focused on using thermal manikins [7] and recruiting participants for exercise [8,9] to assess the objective cooling effects of cooling clothing; however, there are few studies on the use of air ventilation clothing by indoor individuals with lower metabolic rates [10]. In addition, some convective PCSs, such as devices applying evaporative cooling technology, can reduce the outlet air temperature, but there are also few studies on this topic [11]. Thus, additional investigation into the effects of these cooling convective devices on human in warm indoor environments is required.

The thermal sensation of people exposed to high temperatures can be used as a subjective indicator of heat stress [12,13]. Therefore, an

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Nomenclature Abbreviation definition [unit]

Eva	Evaporative cooling device [−]
Fan	Table fan [−]
Jac	Air-cooled jacket [−]
MST	Mean skin temperature [°C]
PCS	Personal comfort system [−]
PV	Personalized ventilation [−]
RH	Relative humidity [%]
Ta	Room air temperature [°C]
TCV	Thermal comfort vote [−]
TMST	Thermosensory mean skin temperature [−]
T_{sk}	Local skin temperature [°C]
TSV	Thermal sensation vote [−]

evaluation of thermal sensation can provide an important foundation for preventing health risks due to high temperature. However, thermal sensation data are primarily obtained via questionnaires, making dynamic data collection challenging. In hot environments, efforts to enhance the heat dissipation of the human body lead to the dilation of skin blood vessels, resulting in an increased skin blood flow and elevated skin temperature. Consequently, the heightened skin temperature alters the thermal sensation formed by temperature sensors in the skin [14]. Therefore, skin temperature can theoretically serve as a physiological indicator for predicting thermal sensation. Researchers recruited young adults for experiments conducted in uniform environments created by air conditioning systems [15–24]. In steady-state[15,16], step change [17,18], and slope change [19] conditions, the mean skin temperature (MST) can accurately predicted overall thermal sensation. Liu et al. [20] discovered that even in hot environments with relatively high humidity, mean skin temperature could predict overall thermal sensation, with wrist skin temperature being the most accurate predictor. Sim et al. [21] found that using three wrist skin temperatures provided a more accurate estimate of overall thermal sensation compared to estimate based on fingertip skin temperature. Chaudhuri et al. [22] similarly highlighted the significance of hand skin temperature in predicting overall thermal sensation. Tian et al. [23] proposed that the average skin temperature of the nose, cheeks, and chin is the most suitable combination for predicting overall thermal sensation. Choi et al. [24] found significant correlations between skin temperatures of the forehead, arm, wrist, and neck and thermal sensation. However, researchers have observed an increase in the thermal sensation threshold and a decrease in thermal sensitivity in elderly people [25]. This change was most pronounced in the limbs and extremities, following a distal–proximal pattern. This may be due to reduced blood flow to the peripheral nerves, changes in skin properties, and changes in nerve fibers [26]. Variations in skin temperature and thermal sensation and their relationship were different for elderly and young people [27]. Due to abovementioned changes in elderly people, the accuracy of overall thermal sensation predictions based on skin temperature may be compromised. Therefore, investigating the relationship between skin temperature and overall thermal sensation in the elderly is essential. This is beneficial for enhancing the overall thermal comfort of the elderly, and it can assist in the development of relevant cooling technologies to reduce heat stress issues in the elderly.

In contrast to uniform conditions created by an air conditioning system, a PCS typically affects one or more parts of the human body. Most studies on convective PCSs have only analyzed variations in physiological and psychological parameters before and after using different PCSs [28–32]. Few studies have examined the relationship between skin temperature and thermal sensation [33]. Although Jin et al. [34], Zhang et al. [35], and Wang et al. [36] examined this relationship, each experiment focused on cooling only one body part. In practical applications, most convective PCSs affect more than one specific body part, leading to differential changes in skin temperature between target and non-target areas [37]. Therefore, a critical concern is whether there remains a linear correlation between skin temperature and overall thermal sensation after the use of PCSs. The linear relationship between these two factors is a key prerequisite for determining whether skin temperature can serve as a physiological indicator for evaluating thermal sensation after using PCSs.

When investigating non-uniform environments created by PCSs, there is typically a simultaneous focus on local thermal sensation. Local thermal sensation refers to the sensation created in a specific body part. When the same stimulus acts on distinct body parts, the local thermal sensations and their influence on the overall thermal sensation vary [38]. The overall thermal sensation may arise through the cumulative impact of local thermal sensations [34,35]. Some studies divided the human body into sections (each consisting of multiple adjacent body parts), such as the front and back [39], or head, upper body, and lower body [40,41], and then determined the weighting of each section's thermal sensation on the overall thermal sensation. This approach offers two advantages: firstly, it reduces the quantity of questionnaires related to local thermal sensation in future research, facilitating the research; secondly, it provides guidance for the design of PCSs, enabling them to influence specific body regions. However, the division into these sections is typically determined by how the device affects the human body (target and non-target areas). There are no consistent results regarding how to divide the body sections. Therefore, this study plans to further explore this issue based on PCSs that act on different body parts.

The benefits of a PCS capable of local cooling or heating for elderly people include, but are not limited to, being cheap, energy-efficient, user-friendly, and personalized. However, a research gap exists in understanding the thermal responses of elderly people after using local cooling devices. This study conducted a climate chamber experiment on elderly people with three local cooling devices (a table fan, air-cooled jacket, and evaporative cooling device). The novelties of this study are as follows: firstly, it assesses the physiological and psychological effects of three different local cooling devices on elderly people in various warm environments. Secondly, categorize body sections based on local thermal sensation and determine their respective weights in influencing overall thermal sensation. Thirdly, clarifiy that after using local cooling devices, skin temperature remains suitable for evaluating overall thermal sensation, and compare of the accuracy of using different skin temperature to eastimate thermal sensation. The results have benifits on informing the design of future nursing homes or residential environments for the elderly and guiding the selection of devices; meanwhile, it can be used to develop recommendations for device design improvement.

2. Methods

2.1. Climate chamber and facilities

2.1.1. Experimental conditions

The experiment included five conditions: neutral (26 °C, 40 % relative humidity (RH)), slightly warm (29 °C, 40 % RH; 28 °C, 60 % RH), and warm (33 °C, 40 % RH; 32 °C, 50 % RH). The thermal sensation here (neutral, slightly warm, and warm) was calculated by PMV model. The selected conditions are typical indoor conditions encountered in unconditioned spaces [42]. A climate chamber (5.5 m long, 3.8 m wide, and 3.2 m high) was used to achieve the target conditions. It comprised a diffuse-ceiling ventilation system, heated simulation windows, and humidifiers. The system and facilities used in the experiment, as well as the heat load balance method used to achieve the target conditions, are described in detail in a previous article [43]. The air temperature (T_a) and RH in the climate chamber were detected by six TinyTag 2 plus data loggers (T_a accuracy: ±0.5 °C, RH accuracy: ±3 %). The measured environmental data for the chamber conditions are listed in Table 1. The

Table 1
Actual measurements of environmental parameters.

Case (*Ta*/RH)		Test conditions (mean ± SD)		
		Ta	RH	*To*
Neutral	26 °C/40 %	25.7 ± 0.5 °C	42 ± 2 %	25.8 ± 0.3 °C
Slightly warm	29 °C/40 %	29.0 ± 0.5 °C	42 ± 3 %	29.1 ± 0.3 °C
	28 °C/60 %	28.3 ± 0.5 °C	62 ± 5 %	–
Warm	33 °C/40 %	32.6 ± 0.4 °C	38 ± 2 %	–
	32 °C/50 %	31.7 ± 0.6 °C	48 ± 3 %	31.8 ± 0.3 °C

operative temperature (*To*) and air velocity were measured by ComfortSense probes (*To* accuracy: ±0.2 °C, air velocity accuracy: ±0.02 m/s) in 26 °C, 40 % RH, 29 °C, 40 % RH, and 32 °C, 50 % RH. The difference between *To* and T_a was less than 0.5 °C. Air velocity in the occupied zone was less than 0.05 m/s.

2.1.2. Local cooling devices

Three convective local cooling devices were chosen for this study: a table fan (Fig. 1(a)), an air-cooled jacket (Fig. 1(b)), and an evaporative cooling device (Fig. 1(c)). The device specifications are listed in Table 2, and more specific descriptions can be found in a previous article [43]. It is worth noting that the air velocity measurements for different devices and modes in Table 2 are not the same. For table fan and evaporative cooling device, the velocity represents the average velocity near head and chest; for air-cooled jacket, the velocity corresponds to the fan outlet air velocity. The table fan and evaporative cooling device were fixed on a Table 1 m away from the participant at a 45° angle so that the airflow primarily affected the upper torso and limbs (Fig. 1(d)). Air-cooled jackets of three sizes (S, M, and L) were used to fit participants.

2.2. Manikin test

A thermal manikin experiment was conducted in the climate chamber described in Section 2.1.1. The main goals were to determine where local cooling devices act on the human body and quantify the heat dissipation of different devices on different segments.

2.2.1. Thermal manikin

The experiment used a thermal manikin from PT TEKNIK that has 175 cm with 27 segments: top, left side, and right side of head; left and right upper chest; left and right lower chest; front and back of pelvis; left and right upper back; left and right lower back; left and right upper arms; left and right forearms; left and right hands; left and right front thighs; left and right back thighs; left and right front lower legs; and left and right feet. The surface temperature of the segments of the manikin was controlled to be the same as the skin temperature of a person in a state of thermal neutrality.

Table 2
Specifications of three local cooling devices.

Local cooling device	Power (W)	Speed (mode)	Velocity (m/s)
Table fan	0–25	1	0.25
		2	0.31
Evaporative cooling device	0–10	1	0.10
		2	0.12
		3	0.14
		4	0.16
		5	0.18
		6	0.21
		7	0.23
		8	0.25
		9	0.27
		10	0.29
Air-cooled jacket	0–20	1	1.40
		2	2.20
		3	2.60
		4	3.30

2.2.2. Test conditions and procedure

Because the manikin lacks a sweating module, RH has no effect on it; therefore, the experiment was only conducted under three conditions, all at 40 % RH: neutral (26 °C), slightly warm (29 °C), and warm (32 °C). The thermal manikin simulated the participant sitting in a chair, wearing a short-sleeved T-shirt, trousers, socks, and shoes (0.5 clo in total) (Fig. 2). Under the three conditions, using different devices with different powers, the surface temperature and electricity consumption of 27 segments were collected every 10 s by the supporting software until all parameters reached a steady state.

2.2.3. Data analyses

In the present study, the purpose of the thermal manikin test was to confirm which segments were affected when using local cooling devices. Although the outlet air parameters of the local cooling devices varied in the different background environments, the exposed segments were identical. Therefore, only the data from 26 °C/40 % RH was used here as a representative to show the cooling effect of the table fan, evaporative cooling device, and air-cooled jacket at their highest speeds. Under steady-state conditions, the amount of heat supplied to the manikin heating elements was equivalent to the amount of heat lost from the surface. Thus, the heat loss of each segment can be derived from its electricity consumption.

2.3. Elderly people test

An experiment involving elderly people was conducted in the climate chamber described in Section 2.1.1. The main goals were to evaluate the variation in local skin temperature and thermal sensation after using local cooling devices and investigate the relationship between skin temperature and thermal sensation.

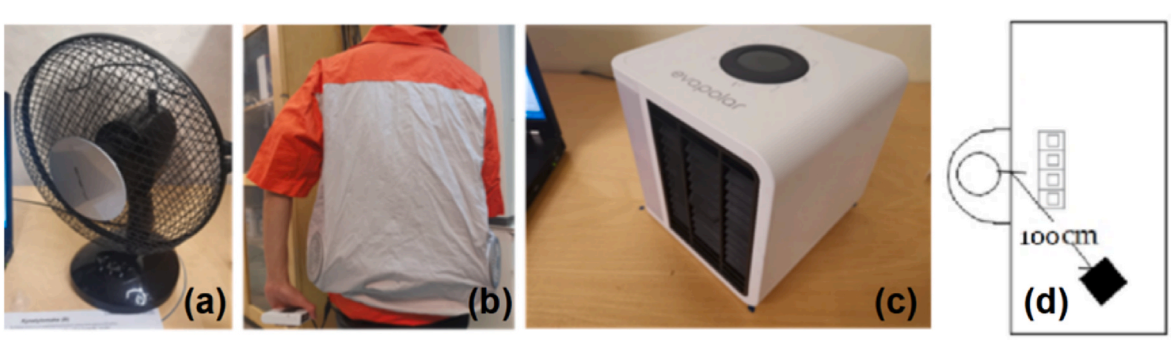

Fig. 1. Local cooling devices: (a) table fan, (b) air-cooled jacket, and (c) evaporative cooling device. (d) Placement of table fan and evaporative cooling device on the table.

Fig. 2. Thermal manikin test with (a) table fan and (b) air-cooled jacket.. (Experiments with the evaporative cooling device fixed in the same position as the table fan were performed as well.)

2.3.1. Participants and test conditions

The Aalto University Research Ethics Committee authorized and supported this study (D/793/03.04/2021, approved on September 23, 2021). Participants included 26 healthy Finnish elderly people, 7 males and 19 females. Table 3 provides information on the participants, each of whom participated in the experiment once per week for 5 weeks. Because not every participant was able to participate each time, the number of test participants (*N*) in each condition varied. The experiment included five conditions: neutral (26 °C, 40 % RH, $N = 26$), slightly warm (29 °C, 40 % RH, $N = 24$; 28 °C, 60 % RH, $N = 26$), and warm (33 °C, 40 % RH, $N = 20$; 32 °C, 50 % RH, $N = 23$).

2.3.2. Test procedure and data collection

The experimental process is illustrated in Fig. 3. Each test lasted 4 h and consisted of six phases, each lasting 40 min. Participants entered the climate chamber 25 min earlier for pre-test preparations, such as clothing changes (clothing insulation was 0.5 clo in all tests) and sensor attachment. During the preconditioning phase, the participants were instructed to remain sedentary to adapt to the test environment. During this period, participants were permitted to use computers or read. During the subsequent local cooling phase, the participants were permitted to rotate the knobs to modify the speed mode of the given local cooling device (Table 2) based on their individual needs; however, they were not permitted to alter the position or angle of the table fan or the evaporative cooling device. The subsequent four phases repeated the first two phases, in which the participants sat for 40 min before using the cooling device for another 40 min. At the end of each local cooling phase, the three participants changed their positions to ensure that they each utilized all three devices. During the final 5 min of each phase, each participant completed a questionnaire and underwent tympanic temperature measurement. Two additional questionnaires and tympanic temperature measurements were done at 15 and 25 min in each local cooling phase. Phases 1, 3, and 5 correspond to a uniform environment, whereas phases 2, 4, and 6 correspond to a non-uniform environment after the use of local cooling devices.

During the experiment, participants' skin temperature was continuously measured using iButton sensors (DS1923, accuracy of ±0.5 °C in the test range of –10–65 °C). The measured body parts were the forehead, chest, pelvis, upper back, lower back, forearm, wrist, palm, thumb, thigh, calf, and foot. Owing to the placement of the table fan and evaporative cooling device, the airflow acted more on the left side of the human body (Fig. 4(a)); hence, the measurement points of the limbs and extremities were all on the left side (Fig. 4(b)). The tympanic temperature was measured using an ear temperature gun (IRT6520, accuracy of ±0.2 °C in the test range of 34–42.2 °C) and was interpreted as the core temperature [44]. The questionnaires used a 7-point scale to describe thermal sensation (−3 to +3: cold to hot) [43]. Thermal sensation included both local thermal sensations (forehead, chest, pelvis, upper back, lower back, forearm, palm, thigh, calf, and foot) and overall thermal sensation. The overall thermal sensation appeared in every questionnaire, whereas the local thermal sensation appeared only in the questionnaires at the end of each phase.

Table 3
Anthropometric data of the elderly participants.

Anthropometric unit (mean ± SD)	Male (7)	Female (19)
Age (years)	70.9 ± 5.5	70.8 ± 6.0
Height (cm)	177.7 ± 4.0	161.8 ± 4.6
Weight (kg)	78.5 ± 8.7	67.6 ± 9.6
Waist circumference (cm)	95.3 ± 7.3	94.0 ± 11.3
Neck circumference (cm)	39.7 ± 1.5	35.6 ± 2.3

2.3.3. Statistical analysis

SPSS 20.0 and GraphPad Prism 8.0 were utilized for statistical analyses. The Shapiro–Wilk test was used for the normal distribution test, the paired *t*-test was used to analyze data before and after using local cooling devices, repeated-measures ANOVA (Greenhouse–Geisser adjustment) was used to analyze data at different time points during the local cooling phase, the Pearson correlation coefficient was used to assess the correlation between two variables, and linear regression was used to describe the quantitative relationships between two or more variables. The significance level was set at $P = 0.05$; "*" and "**" indicate a significant difference of $P < 0.05$ and a highly significant difference of $P < 0.01$, respectively.

Principal component analysis can extract fewer new variables from multiple initial variables while retaining as much information of the initial variables as possible. In addition, there is no correlation between these new variables, which effectively solves the multicollinearity problem [20,45]. However, the main purpose of principal component analysis is data reduction (i.e., translating a variable space into an optimal factor space), not detecting latent constructs or factors. Thus, based on principal component analysis, factor analysis, a correlation-focused approach seeking to reproduce the intercorrelations among variables [46,47], was used to further analyze the local thermal sensation data after using local cooling devices, making the results more interpretable.

3. Results

3.1. Body parts exposed to local cooling in manikin test

Fig. 5 shows the electricity consumption of 27 manikin segments at 26 °C/40 % RH in five cases: no local cooling device used, air-cooled jacket worn but not used, and after using the table fan, evaporative cooling device, and air-cooled jacket at their maximum power.

After using a table fan or an evaporative cooling device, the heat loss (equal to electricity consumption) of the chest, upper arm, forearm, and

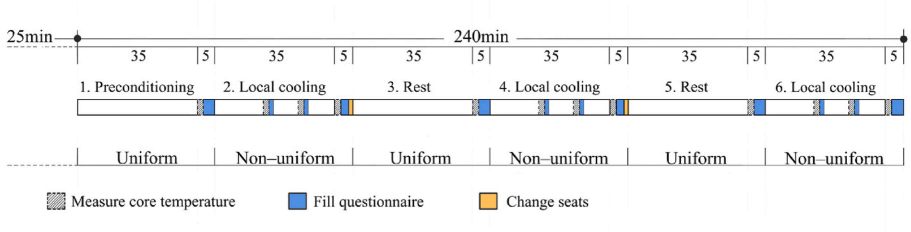

Fig. 3. Schedule of elderly people experiment.

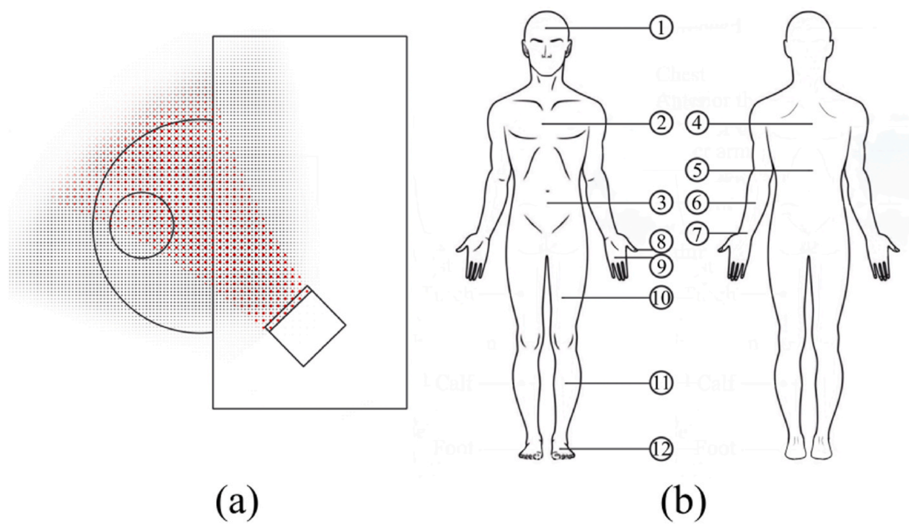

Fig. 4. (a) Air distribution of the table fan and evaporative cooling device; (b) skin temperature measurement points: 1. forehead; 2. chest; 3. pelvis; 4. upper back; 5. lower back; 6. forearm; 7. wrist; 8. thumb; 9. palm; 10. thigh; 11. calf; 12. foot.

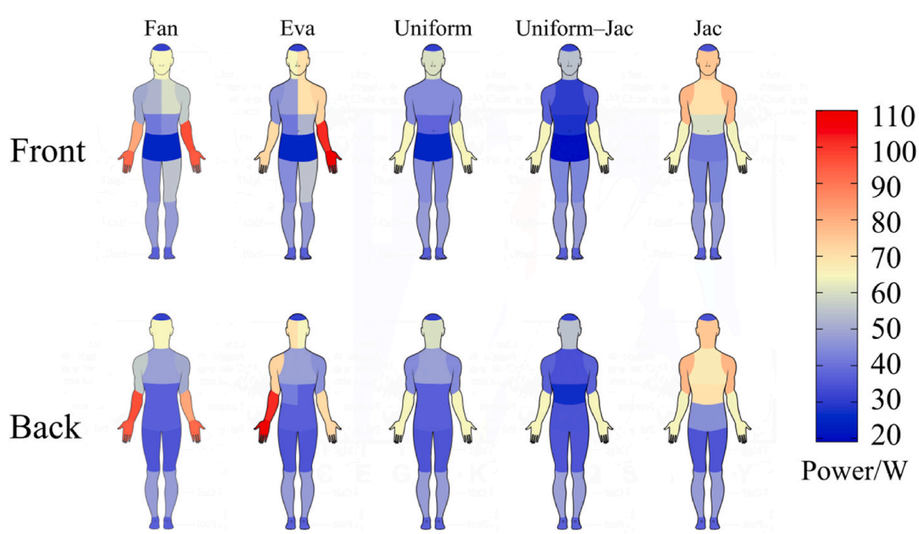

Fig. 5. Electricity consumption of heating element of each segment of thermal manikin under different cases (Fan, table fan; Eva, evaporative cooling device; Uniform, no local cooling device used; Uniform-Jac, air-cooled jacket was worn but not used; Jac, air-cooled jacket).

hand increased substantially compared to the situation without them. This suggests that, as intended, the airflow generated by these devices placed on the table mainly acted on the torso (chest) and limbs. The heat loss of the head and thigh also increased, indicating that they were also influenced by the airflow. As a result of the additional clothing insulation provided by the air-cooled jacket, the heat loss of the chest, back, and upper arm was reduced when the air-cooled jacket was worn without being used compared to when it was not worn. The use of an air-cooled jacket did substantially cool the chest, back, and upper arms. Heat loss from the head also increased, possibly because the airflow released from the collar affected the head.

3.2. Skin temperature change with environmental parameters in uniform steady state

The skin temperature obtained at the end of Phases 1, 3, and 5 in all conditions for all participants was used to analyze the relationship with environmental parameters. T_a significantly affected skin temperature, whereas RH had a small effect on it ($P > 0.05$). The linear regressions between T_a and skin temperature for each local body part are listed in Table 4. The skin temperature of the upper back, forearm, palm, thigh, calf, and foot increased with T_a faster than that of other body parts, particularly the palm and foot, which had the highest coefficients, whereas the temperature of the pelvis and lower back seemed more stable.

The neutral T_a range (24.5 °C < T_a < 27.6 °C) of elderly people with 0.5 clo obtained previously [43] was used to calculate the lower and upper limits of the neutral skin temperature of each body part using the corresponding formula in Table 4. The results are summarized in Table 5. In the neutral state, the skin temperature of the lower back was the highest (T_a = 27.6 °C, T_{sk} = 34.7 °C). By comparing the neutral skin temperatures of elderly [48] and young [49,50] people in other studies (Table 5), we found that the skin temperature of the distal regions (head, hand, and foot) of elderly people was lower than that of young people. This is consistent with the observation that elderly individuals exhibit decreased skin blood flow to their extremities [26]. When the T_a rose, the skin temperature of the palm increased rapidly and reached the highest value (T_a = 32 °C, T_{sk} = 36.1 °C). This suggests that the limbs and extremities heat faster than other body parts and play a role in heat dissipation under warm conditions.

3.3. Skin temperature and core temperature in uniform and non-uniform state

This study examined the changes in mean skin temperature (MST) and core temperature (Tcore) in uniform (only include measurements at the end of uniform phases) and non-uniform state. The MST was calculated using the Dubois 7-point method. MST changed primarily during the first 10 min. The data (average for all participants) were examined using repeated-measures ANOVA. Fig. 6(a) shows the changes in the MST in uniform (t = 0 min) and non-uniform state. Different colors represent different test conditions, and the shaded areas represent the 5th and 95th percentiles of the standard deviations in Fig. 6(a). In this period, significant ($P < 0.05$) drops of MST could be found in all cases except when using the table fan in 33 °C/40 % RH and the evaporative cooling device in 28 °C/60 % RH. After 10 min, only minor fluctuations were observed. After using any of the three devices, the MST decreased by less than 0.5 °C.

Fig. 6(b) shows the core temperature measured at four timepoints: at the end of the uniform condition (t = 0 min) and under nonuniform conditions at t = 15, 25, and 35 min. The core temperature after using the local cooling device was significantly lower ($P < 0.05$) than that under the uniform condition. However, no significant ($P > 0.05$) differences were found among the three measurements (t = 15, 25, and 35 min) during the local cooling phase, indicating that the core temperature changed very slowly and could be considered stable. Thus, combined with the result that MST tended to be stable after 10 min in the local cooling phase, the physiological parameters at the end of the local cooling phase (t = 35 min) can be considered approximately stable.

Fig. 6 also shows that the MST and core temperatures were significantly ($P < 0.05$) different for neutral, slightly warm, and warm conditions. For example, the use of local cooling devices in slightly warm conditions did not lower the MST and core temperatures to their level in the neutral condition. This indicates that the effect of local cooling devices on these physiological parameters was limited.

Table 4
Linear regression between local skin temperature T_{sk} of each body part and T_a.

Local skin temperature (°C)		
Body parts	$y = aT_a + b$	R^2
Forehead	$T_{sk} = 0.291T_a + 26.253$	0.7
Chest	$T_{sk} = 0.276T_a + 26.348$	0.5
Pelvis	$T_{sk} = 0.203T_a + 28.472$	0.1
Upper back	$T_{sk} = 0.369T_a + 23.734$	0.6
Lower back	$T_{sk} = 0.216T_a + 28.749$	0.4
Forearm	$T_{sk} = 0.333T_a + 24.315$	0.6
Palm	$T_{sk} = 0.412T_a + 22.876$	0.6
Thigh	$T_{sk} = 0.344T_a + 23.630$	0.6
Calf	$T_{sk} = 0.328T_a + 23.816$	0.5
Foot	$T_{sk} = 0.451T_a + 19.874$	0.5

Table 5
Neutral skin temperature range of each body part.

Neutral skin temperature (°C)				
Body part	Elderly people		Young people	
	This study	Xiong [48]	Wang [49]	Atmaca [50]
Head	34.3	33.4	34.9	35.6
Chest	34.0	34.0	35.0	33.6
Pelvis	34.1	34.0	35.2	33.4
Upper back	33.9	33.8	34.2	33.2
Lower back	34.7	33.8	34.2	33.2
Forearm	33.5	32.7	32.0	–
Hand	34.2	32.3 (back)	34.0 (back)	35.2
Thigh	33.1	32.7	33.8	33.8
Calf	32.9	32.3	32.2	33.4
Foot	32.3	31.8	32.7	33.9

3.4. Thermal response of local body parts before and after use of local cooling devices

3.4.1. Variation of local skin temperature

The changes in local skin temperature were analyzed using data from the last minute (t = 35 min) of each phase, which represents a steady state. Data were analyzed using the paired t-test. The results are shown in Fig. 7. The dots represent the skin temperature before using the device, the squares represent the skin temperature after using the device (a square containing × inside indicates a significant difference), and the shaded area between them represents the change in skin temperature (the blue area indicates the neutral range of skin temperature based on Table 5).

For all devices, the local skin temperature of each part was within the neutral range at 26 °C, 40 % RH. After using the table fan or evaporative cooling device, the skin temperatures of the chest, forearm, and palm were significantly ($P < 0.01$) reduced under all conditions, and the skin temperatures of the forehead and thigh were significantly ($P < 0.05$) reduced under some conditions. This was consistent with the results of the manikin experiment. After using the air-cooled jacket, the skin temperatures of the chest, lower back, and forearm were significantly ($P < 0.01$) reduced in all conditions, and the skin temperatures of the forehead and upper back were significantly ($P < 0.05$) reduced in some conditions. In contrast to the manikin experiment, the elderly people experiment revealed a significant difference ($P < 0.05$) in the skin temperature of the forearm before and after using the air-cooled jacket. This may be because the forearm of the manikin was always on the table, perpendicular to the upper arm (Fig. 2); thus, the airflow from the cuff did not affect the forearm, and no difference in forearm electricity consumption was found. Therefore, combined with the measurement points of skin temperature in the elderly experiment, this study defined the body parts that were exposed to local cooling owing to the use of devices as shown in Table 6.

Because all body parts were in their neutral range at 26 °C, 40 % RH, only the remaining four conditions were further examined. After using the table fan, the decrease in skin temperature of exposed parts was greater in slightly warm conditions (29 °C, 40 % RH; 28 °C, 60 % RH)

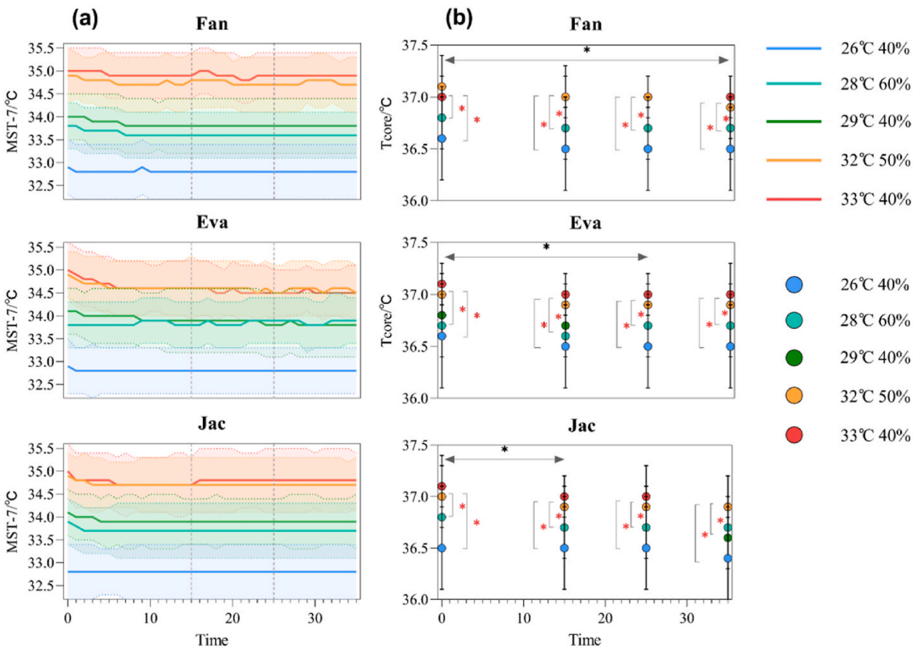

Fig. 6. (a) Trends of the mean skin temperature; (b) core temperature under different conditions with local cooling devices.. (Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

than in warm conditions (33 °C, 40 % RH; 32 °C, 50 % RH). Among exposed parts, the skin temperature of forearm and palm decreased the most of 0.8 °C and 0.6 °C in slightly warm conditions, and 0.4 °C and 0.4 °C in warm conditions, respectively. Among unexposed parts, the upper back, calf, and foot deviated the most from the neutral zone. The foot skin temperature had the greatest deviation (2.1 °C) in warm conditions. For the entire body, the lower back had the highest skin temperature in slightly warm conditions, whereas the palm had the highest skin temperature in warm conditions. The foot and calf had the lowest skin temperatures under all conditions.

After using the evaporative cooling device, the decrease in skin temperature of exposed parts was less in slightly warm conditions (29 °C, 40 % RH; 28 °C, 60 % RH) than in warm conditions (33 °C, 40 % RH; 32 °C, 50 % RH). Among exposed parts, the skin temperatures of the forearm and chest decreased the most by 0.3 °C and 0.3 °C in slightly warm conditions, and 0.9 °C and 1.1 °C in warm conditions, respectively. Among unexposed parts, the upper back, calf, and foot deviated the most from their neutral zone. The foot skin temperature had the greatest deviation (1.8 °C) in warm conditions. For the entire body, the lower back had the highest skin temperatures under all conditions. The foot and calf exhibited the lowest skin temperatures in slightly warm conditions, and forearm had the lowest skin temperature in warm conditions.

After using the air-cooled jacket, the decrease in skin temperature of exposed parts was less in slightly warm conditions (29 °C, 40 % RH; 28 °C, 60 % RH) than in warm conditions (33 °C, 40 % RH; 32 °C, 50 % RH). Among exposed parts, the skin temperatures of the chest and lower back decreased the most, by 0.6 °C and 0.6 °C in slightly warm conditions, and 0.7 °C and 0.7 °C in warm conditions, respectively. Among unexposed parts, the palm, thigh, calf, and foot deviated the most from their neutral zone. The foot skin temperature had the greatest deviation (2.0 °C) in warm conditions. For the entire body, the hand had the highest skin temperature, and the foot and calf the lowest skin temperatures, under all conditions.

Both the evaporative cooling device and air-cooled jacket showed better cooling in warm conditions than in slightly warm conditions, whereas the opposite was true for the table fan. This may be related to the varying speed of the local cooling device under various conditions. All three devices utilize higher speeds in warm conditions than in slightly warm conditions [43]. However, the table fan did not reduce the skin temperature more under warm conditions despite increasing the power, whereas the other two devices were able to reduce the skin temperature more effectively. This may be due to increased convective heat dissipation from the evaporative cooling device, which has cooler outlet air in a warmer environment, thereby decreasing the skin temperature. The outlet air of the air-cooled jacket had the same temperature as the background air, but the velocity was much higher near the skin. It mainly acted on the torso with a higher sweat rate [51,52], leading to higher convective and latent heat dissipation, which resulted in lower skin temperature.

After using the three devices, the skin temperature of the exposed body parts decreased significantly, bringing them closer to their neutral zones, whereas the skin temperature of the unexposed parts remained nearly constant, deviating more from their neutral values than the exposed parts. This indicates that the local cooling devices used in this study can only adjust the skin temperature of the exposed parts. The unexposed parts, including the lower back for the table fan and evaporative cooling device and the palm for the air-cooled jacket, had the highest skin temperature. For the three devices, the body part with the lowest skin temperature was not necessarily an exposed part, but mainly the lower body, including the foot and calf. This may be because staying in a sitting position for a long time reduces the skin temperature of the lower body [53–55].

3.4.2. *Variation of local thermal sensation*

Changes in local thermal sensation were analyzed using data from the last questionnaire of each phase. The results are shown in Fig. 8. The gray line represents the thermal sensation vote (TSV) before using the device, and the red line represents the TSV after using the device. The blue area is the major exposed part, the yellow area is the minor exposed part, and the white area is the unexposed part of three local cooling devices. From top to bottom, the local parts are forehead, chest, pelvis, upper back, lower back, forearm, palm, thigh, calf, and foot.

The effect of the devices on thermal sensation was consistent with that on skin temperature under different conditions; that is, the evaporative cooling device and air-cooled jacket reduced the thermal sensation more in warm conditions, whereas the table fan reduced the thermal sensation more in slightly warm conditions. The TSV of the

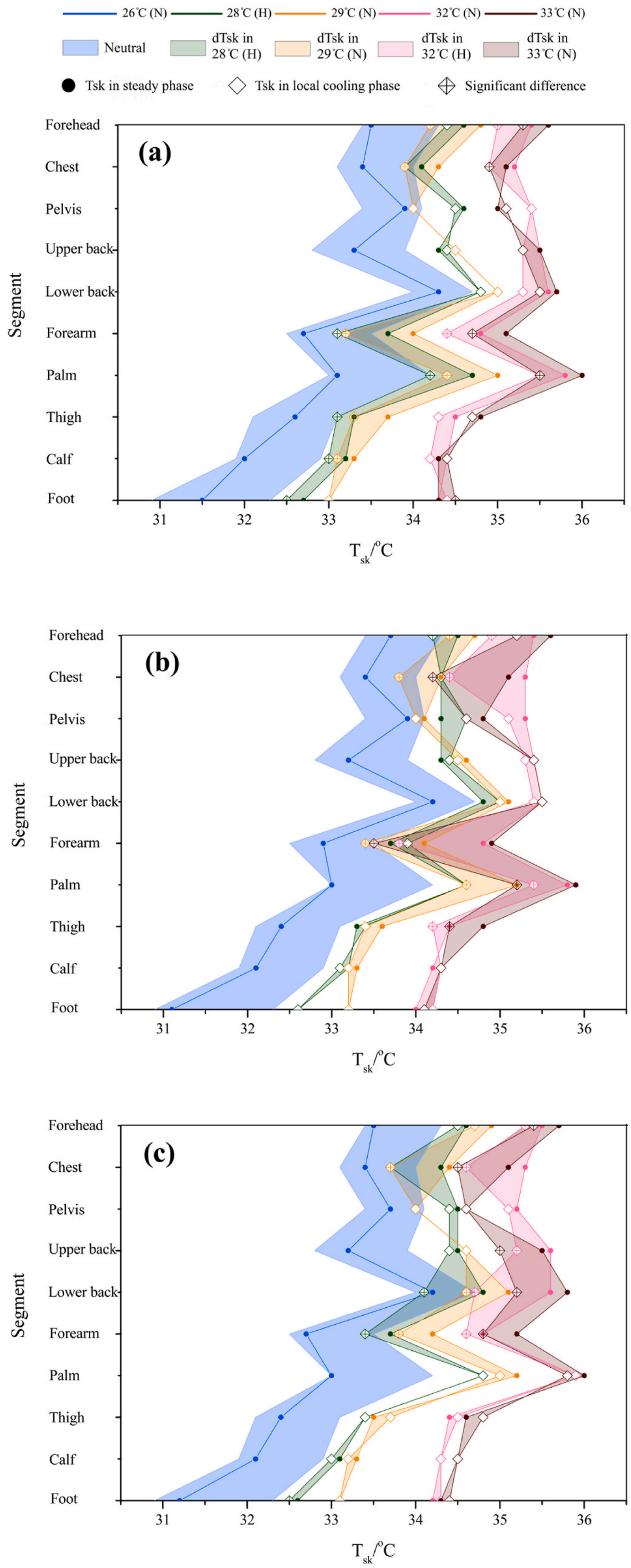

Fig. 7. Local skin temperature before and after using local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

Table 6
Body parts exposed to local cooling devices.

Device	Major exposed parts	Minor exposed parts	Unexposed parts
Table fan Evaporative cooling device	Chest, forearm, and palm (including the wrist and finger, which contact with the palm)	Forehead and thigh	Pelvis, upper back, lower back, calf, and foot
Air-cooled jacket	Chest, upper back, lower back, and forearm	Forehead	Palm, pelvis, thigh, calf, and foot

*Major exposed part: local body part with a significant decrease in skin temperature under all conditions.
*Minor exposed part: local body part with a significant decrease in skin temperature under certain conditions.
*Unexposed parts: local body parts with no significant decrease in skin temperature under any condition.

upper body, which includes the major exposed parts, varied more than that of the lower body. Some unexposed areas also experienced a significant change in thermal sensation. For example, with the set airflow pattern, the table fan and evaporative cooling devices mainly influenced the chest, but the TSV of the pelvis and back changed similarly. The inability of the elderly participants to correctly recognize the thermal sensations of all local body parts may be one of the causes of this unexpected result. However, some comparable experiments conducted on young participants reported similar results [56–58]. Consequently, another possible explanation is that the questionnaires were filled out during the participants' steady state (the final 5 min of each phase), implying that the time interval between the inquiries about local thermal sensation was long; thus, the local thermal sensation may be affected by the overall thermal sensation. The overall TSV was consistent with or even slightly higher than the parts with the highest TSV. This result is consistent with the findings of previous studies [59,60], which concluded that the perception of overall discomfort depends on the local body part that experiences the most intense discomfort. In the present study, the overall TSV may be the collective effect of multiple parts with the highest TSV.

3.5. Weights of local thermal sensation in local cooling phase

Factor analysis was used to further analyze the local TSV data from the local cooling phases. The principal component analysis method was selected for the factor extraction, and Varimax rotation was selected as the rotation method for the factor axis. The results are shown in Fig. 9. Fig. 9(a) shows the component matrix after rotation. The extracted common factors account for more than 90 % of the original variables. The initial variables were sorted in order of factor loadings after rotation. Each original variable could be explained by more than 65 % of the new factors. Fig. 9(b) shows the component score-coefficient matrix.

According to the rotated component matrix, each variable can be expressed as a function of the common factors as follows:

$$TSV_i = \sum \alpha_{ij} * F_j \quad (1)$$

where TSV_i is the thermal sensation vote of local body part i, α_{ij} is the factor loading, and F_j is the four common factor (α_{ij}, F_j are listed in the Fig. 9(a)). For example, the local TSV for the forehead when a fan was used can be calculated as follows:

$$TSV_{forehead} = 0.803F_1 + 0.292F_2 + 0.232F_3 \quad (2)$$

Factor 1 (blue) is an extraction of the variance of the chest, upper back, lower back, and pelvis, and Factor 4 (orange) is an extraction of the variance of the forehead when using the evaporative cooling device and air-cooled jacket. Factors 1 and 4 can be considered combined in the table fan case. In all cases, Factor 2 (green) is an extraction of the

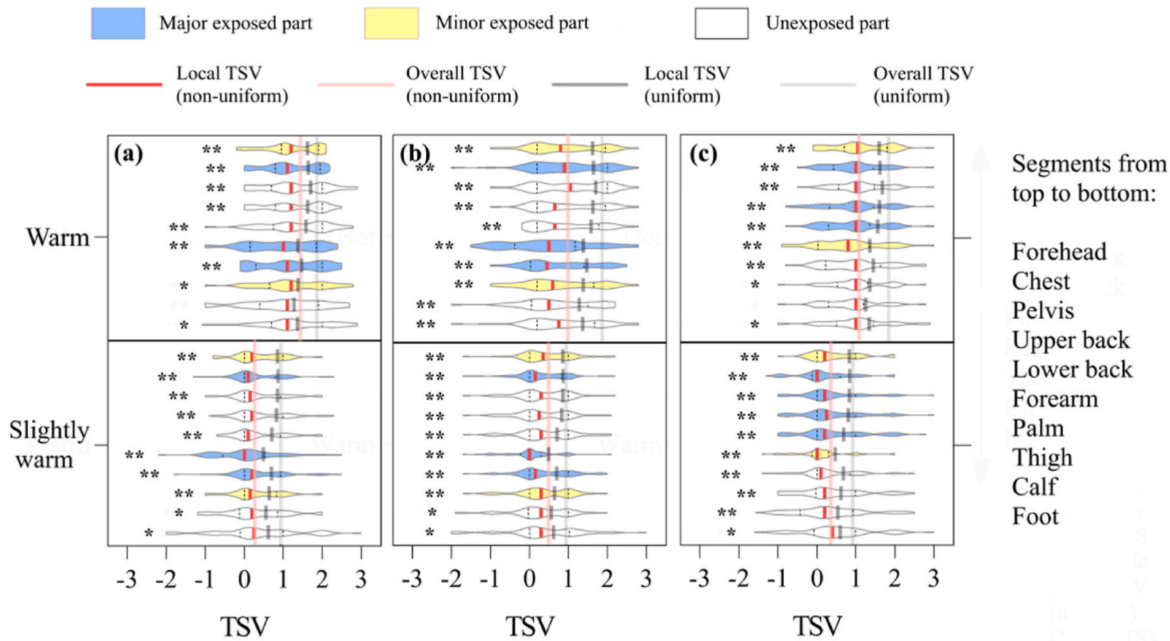

Fig. 8. Local thermal sensation before and after using local cooling devices: (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

(a)

Fan				Eva					Jac				
Rotated Component Matrix				Rotated Component Matrix					Rotated Component Matrix				
Segment	Factor 1	2	3	Segment	Factor 1	2	3	4	Segment	Factor 1	2	3	4
forehead	0.803	0.292	0.232	lower back	0.836	0.398	0.204	0.190	upper back	0.875	0.295	0.175	0.144
chest	0.782	0.314	0.365	upper back	0.828	0.351	0.147	0.309	lower back	0.875	0.369	0.110	0.131
upper back	0.772	0.454	0.234	pelvis	0.818	0.406	0.194	0.169	chest	0.758	0.123	0.385	0.320
pelvis	0.705	0.628	0.360	chest	0.779	0.261	0.238	0.364	pelvis	0.675	0.543	0.172	0.249
lower back	0.656	0.633	0.444	foot	0.220	0.870	0.297	0.129	foot	0.176	0.878	0.265	0.064
calf	0.394	0.857	0.355	calf	0.447	0.829	0.082	0.234	calf	0.338	0.872	0.204	0.135
foot	0.171	0.855	0.207	thigh	0.545	0.708	0.123	0.292	thigh	0.410	0.774	0.242	0.256
thigh	0.521	0.752	0.296	palm	0.167	0.187	0.922	0.167	palm	0.110	0.264	0.914	0.202
palm	0.232	0.352	0.874	forearm	0.609	0.181	0.665	0.035	forearm	0.451	0.327	0.750	0.189
forearm	0.461	0.410	0.705	forehead	0.433	0.367	0.231	0.766	forehead	0.370	0.243	0.356	0.815

(b)

Fan				Eva					Jac				
Component Score Coefficient Matrix				Component Score Coefficient Matrix					Component Score Coefficient Matrix				
Segment	Factor 1	2	3	Segment	Factor 1	2	3	4	Segment	Factor 1	2	3	4
forehead	0.528	-0.285	-0.094	forehead	-0.295	-0.190	-0.010	1.355	forehead	-0.253	-0.069	-0.235	1.367
chest	0.438	-0.273	0.026	chest	0.272	-0.243	-0.043	0.252	chest	0.336	-0.276	0.123	0.056
upper back	0.405	-0.130	-0.117	upper back	0.336	-0.140	-0.154	0.061	upper back	0.474	-0.130	-0.042	-0.265
lower back	0.208	0.100	-0.163	lower back	0.378	-0.047	-0.088	-0.253	lower back	0.459	-0.059	-0.123	-0.251
pelvis	0.192	0.190	-0.280	pelvis	0.375	-0.021	-0.092	-0.293	pelvis	0.185	0.113	-0.164	0.065
forearm	-0.234	0.001	0.573	forearm	0.295	-0.160	0.420	-0.464	forearm	0.080	-0.117	0.571	-0.319
palm	-0.278	-0.198	0.885	palm	-0.293	-0.053	0.870	0.101	palm	-0.174	-0.091	0.780	-0.216
thigh	0.027	0.290	-0.187	thigh	-0.025	0.330	-0.133	0.025	thigh	-0.100	0.349	-0.135	0.167
calf	-0.177	0.452	-0.133	calf	-0.109	0.517	-0.153	-0.104	calf	-0.121	0.459	-0.118	-0.042
foot	-0.515	0.545	0.185	foot	-0.315	0.674	0.143	-0.265	foot	-0.213	0.503	0.004	-0.153

Fig. 9. (a) Rotated component matrix and (b) component score coefficient matrix from factor analysis for three cooling devices.. (Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

variance of the thigh, calf, and foot, and Factor 3 (yellow) is an extraction of the variance of the forearm and palm. According to the parts contained in each factor and human body structure, Factors 1 to 4 (F_1–F_4) are named "torso" (chest, upper back, lower back, pelvis), "lower limbs" (thigh, calf, foot), "upper limbs" (forearm, palm), and "head" (forehead), respectively.

According to the component score coefficient matrix, each common factor can be expressed as a function of the original variables as follows:

$$F_j = \sum \beta_{ij} \cdot \mathrm{TSV}_i \quad (3)$$

where β_{ij} is the coefficient extracted from the initial variable (β_{ij}, TSV_i are listed in the Fig. 9(b)). For example, F_1 when using a fan is calculated as follows:

$$F_1 = 0.528\text{TSV}_{\text{forehead}} + 0.438\text{TSV}_{\text{chest}} + 0.405\text{TSV}_{\text{upper back}} + 0.208\text{TSV}_{\text{lower back}} + 0.192\text{TSV}_{pelvis} - 0.234\text{TSV}_{\text{forearm}} - 0.278\text{TSV}_{\text{palm}} + 0.027\text{TSV}_{\text{thigh}} - 0.177\text{TSV}_{\text{calf}} - 0.515\text{TSV}_{\text{foot}} \quad (4)$$

Linear regression was performed on the overall thermal sensation and the four common factors, as follows:

$$\text{TSV}_{overall} = \sum C_j \cdot F_j, \text{let} \sum C_j = 1 \quad (5)$$

where $\text{TSV}_{overall}$ is the thermal sensation vote of the whole body, and C_i is the coefficient from linear regression.

To enable the representation of each factor using only the part from which the majority of the variance was extracted, the less informative parts were removed. In other words, F_1 contained only the torso, F_2 only the lower limb, F_3 only the upper limb, and F_4 only the head. Although some information was lost, each body part could be better distinguished. As a combination of this new coefficient and the coefficient obtained from the previous linear regression:

$$D_i = C_j * B_{ij}, \text{let} \sum D_i = 1 \text{ (} i \text{ represents the body region classified into common factor } j\text{)} \quad (6)$$

where D_i is the weight of local thermal sensation on overall thermal sensation, C_j is the linear regression coefficient, and B_{ij} is the coefficient extracted from the initial variable.

Table 7 presents the influence weight of the local thermal sensation of each part on the overall thermal sensation.

The results of linear regression showed that it was reasonable to divide the body into four sections. The head had greater influence weight than the rest of the body parts. In the torso, the chest and upper back had greater weight for the table fan, lower back and pelvis had greater weight for the evaporative cooling device, and the upper and lower back had greater weight for the air-cooled jacket. In the upper and lower limbs, greater weight belonged to the extremities, the palm and foot. The part with the greatest weight in each section had a higher thermal sensation, which is consistent with previous results that the overall thermal sensation tended to be the highest local thermal sensation.

3.6. Correlation between skin temperature and thermal sensation

The correlation between the skin temperature and TSV at the end of each phase was analyzed. Fig. 10 shows the results; the value in the cell represents the Pearson correlation coefficient. The finger and wrist skin temperatures correspond to the TSV of the palm.

Table 7
Weight of local thermal sensation on overall thermal sensation after using three local cooling devices and linear regression results (R^2).

Local thermal sensation weight			
Body part	Fan	Eva	Jac
Forehead	0.16	0.19	0.28
Chest	0.13	0.09	0.09
Upper back	0.12	0.11	0.12
Lower back	0.06	0.13	0.12
Pelvis	0.06	0.13	0.05
Forearm	0.10	0.09	0.08
Palm	0.15	0.19	0.11
Thigh	0.05	0.01	0.04
Calf	0.08	0.02	0.05
Foot	0.10	0.03	0.05
R^2	0.74	0.68	0.73

Note: Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.

Fig. 10(a) illustrates the relationship between the local skin temperature and local TSV. All parts except the pelvis and lower back showed a strong correlation between the skin temperature and TSV in a uniform environment. In a nonuniform environment (using a table fan, evaporative cooler, or air-cooled jacket), only the skin temperatures of the limbs and extremities correlated more strongly with their TSV. Fig. 10(b) shows the correlation between the local skin temperature and overall TSV. In all cases, the forehead, limbs, and extremities exhibited stronger correlations than the torso. Fig. 10(c) shows the correlation between changes in the local skin temperature and changes in the overall TSV. The forearm and palm, the parts with the greatest decrease in skin temperature after using the table fan, had a higher correlation with the overall TSV change. The use of an evaporative cooling device or air-cooled jacket yielded the same results, indicating that the exposed parts with a greater reduction in skin temperature were more strongly correlated with the overall TSV change. This suggests that these major exposed parts were responsible for variations in the overall thermal sensation.

The pelvis and lower back showed a low correlation with thermal sensation in both uniform and non-uniform environment. It might because they belong to the core body area, their skin temperatures may remain stable in changing environments. The small linear regression coefficient between their local skin temperature and T_a (Table 4) supports this hypothesis. When significant changes occurred in overall thermal sensation and its intrinsic local thermal sensation (Fig. 8), skin temperature did not undergo substantial alterations (Fig. 7). Consequently, the skin temperature of the pelvic and lower back, in comparison to other parts, fails to reflect thermal sensation. After using local cooling devices, the skin temperatures of the limbs and extremities were strongly correlated not only with their own local TSV but also with the overall TSV, with the highest correlation coefficient found for the finger. This may be because the limbs and extremities, particularly the upper limbs, are exposed to the environment, making their skin temperatures sensitive to T_a (Table 4). In elevated T_a, the human body's extra heat needed to be dissipated through these parts [61], which served as radiators, by vasodilation. The finger, which contains a large number of arteriovenous anastomoses (AVAs), reflects the thermal state of the human body [62]. Although the number of AVAs is reduced in elderly people [63], the present study revealed that the correlation of T_{sk} of the finger with thermal sensation was still higher than that of other parts of the body.

Contrasting the correlation coefficients of skin temperature for each body part with overall thermal sensation and the weights of local thermal sensation on overall thermal sensation, it is evident that the head and hand possess higher coefficients and greater weights compared to other parts. This suggests that using local cooling devices in a warm environment, the thermal sensation of the head and hands will more significantly influence overall thermal sensation, and their skin temperatures can be used as indicators for assessing overall thermal sensation.

3.7. Mean skin temperature for reflecting overall thermal sensation after using local cooling devices

In studies conducted in a uniform environment [15–18,20–24,34], researchers made use of mean skin temperature (MST) to predict the overall thermal sensation and found that MST can accurately predict the

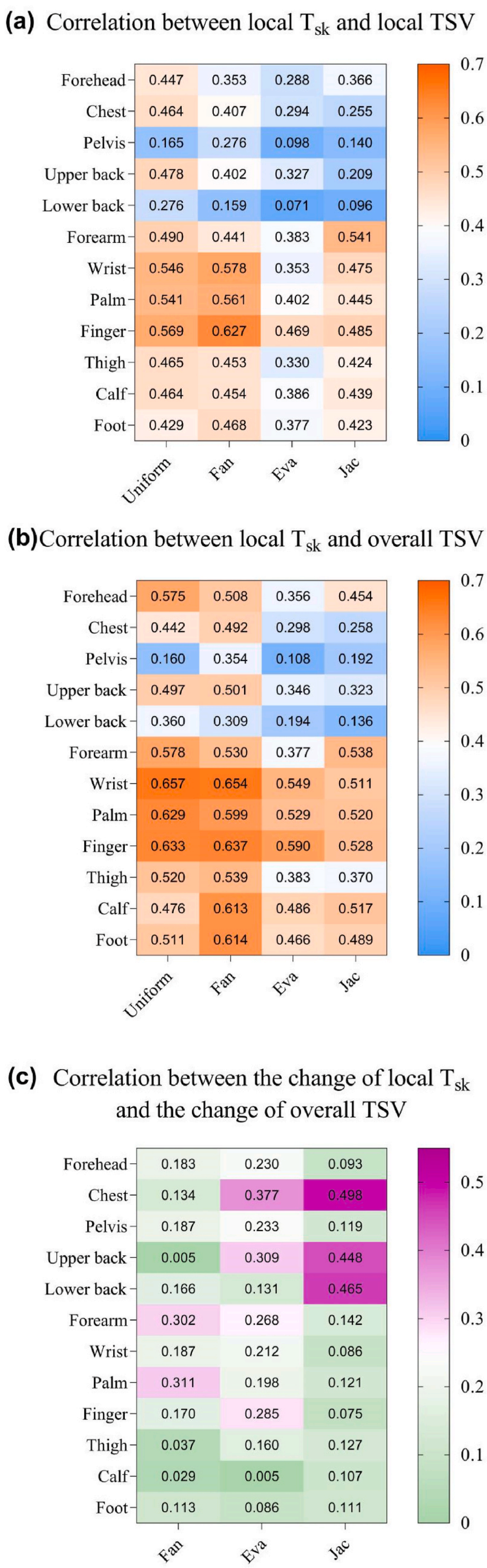

Fig. 10. Correlation between (a) local skin temperature T_{sk} and local thermal sensation vote (TSV), (b) local T_{sk} and overall TSV, and (c) the change in local T_{sk} local and the change in overall TSV.. (Uniform, no cooling device used; Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

overall thermal sensation [15,18]. According to ISO 9886 and ISO 13731, the mean skin temperature is always defined as the "sum of the products of the area of each regional surface element and its mean temperature divided by the total body surface area". Therefore, MST can reflect the heat exchange occurring on the body surface, thus reflecting overall thermal sensation. Taylor et al. [45] proposed that weighting coefficients based on thermoreceptor density or regional skin thermal sensitivity may be useful for determining the relationship between skin temperature and overall thermal sensation in transient and nonuniform environments. Thus, the MST assuming uniform distribution of skin thermoreceptors may not be applicable in non-uniform conditions created by a PCS. This issue will be explored in this section.

Researchers have provided a thorough summary of existing MST formulas [15]. Because the local body parts chosen for measuring skin temperature in this study were based on the 7-point formula, formulas including more than seven parts were omitted owing to the lack of data for the corresponding parts. Thus, useable MST formulas with fewer than seven measurement points were selected as listed in Table 8. Another purpose of this section is to establish a new weighted skin temperature calculation method, enhancing its correlation with overall thermal sensation in non-uniform environments created by PCS. To distinguish this type of weighted skin temperature formula, which is primarily designed to reflect overall thermal sensation rather than overall exchange, we named it the thermosensory mean skin temperature (TMST).

where W_i is the weithing factor of the local skin temperature Tsk_i

In Section 3.5, we observed that the Torso section has the highest weight on overall thermal sensation, followed by the Upper Limbs, Head, and Lower Limbs sections. While this reflects the substantial influence of torso thermal sensation on overall thermal sensation, considering that the Torso section includes four body parts may contribute to its higher weight. For individual part, the forehead and palm are the two heaviest weighted parts. Furthermore, in Section 3.6, we found that the forehead, limbs, and extremities exhibit higher correlations with both their own local thermal sensation and overall thermal sensation compared to other parts. Therefore, in constructing TMST, we included the forehead, forearm, finger, and foot as components. We assume that the skin temperature of these parts can entirely reflect their thermal sensations and thn predict overall thermal sensation through local thermal sensations. Thus, the weights of TMST are obtained using the previously calculated weights of local thermal sensation influencing overall thermal sensation (Table 7), as follows:

$$W_i = D_i \Big/ \sum D_i$$

where W_i is the weighting coefficient of local skin temerature in TMST, D_i is the weight of local thermal sensation on overall thermal sensation in Table 7, $\sum D_i$ is the sum of the weights for the selected local parts.

One study revealed that the correlation with the overall thermal sensation increased as the weight of the exposed part in the formula increased [36]. Thus, the forehead, forearm, finger (only for the table fan and evaporative cooling device, as the air-cooled jacket had no influence on the finger), and foot were selected to establish the TMST formula for each local cooling device.

Table 8 lists the formula for the TMST, and Fig. 11 depicts the results of the linear regression performed on the MST and TMST calculated from Table 8 and the overall TSV. Both MST and TMST were significantly ($P < 0.01$) correlated with the overall TSV; however, TMST was more accurate. MST-3b had the highest correlation with the overall TSV among the MST formulas, probably because it utilized the forehead, forearm, and foot variables like TMST.

Table 8
Local skin temperature coefficients in various weighted mean skin temperature formulas.

Local weights of mean skin temperature												
Formula		Forehead	Forearm	Hand	Palm	Finger	Back	Chest	Pelvis	Anterior thigh	Anterior calf	Foot
MST [15]	3a		0.14					0.50			0.36	
	3b	0.25	0.50									0.25
	4		0.15					0.34		0.33	0.18	
	5	0.07		0.05				0.50		0.18	0.20	
	6a	0.14	0.11		0.05		0.19	0.19		0.32		
	6b	0.14	0.11	0.05				0.19	0.19	0.32		
	7	0.07	0.14		0.05			0.35		0.19	0.13	0.07
TMST	Fan	0.31	0.20			0.30						0.19
	Eva	0.38	0.18			0.38						0.06
	Jac	0.67	0.20									0.13

Note: Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.
MST and TMST are calculated by: MST or TMST = $W_i * Tsk_i$.

4. Discussion

4.1. Key parts that affect overall thermal sensation after using local cooling devices

In this study, it was found that the body could be divided into four sections for local weight analysis, regardless of the type of local cooling device used, when it acted mainly on the upper body. Based on Table 8 and previous results under uniform conditions [43], Fig. 12(a) depicts the weights of the four sections for various cases. The weight of each section was different for different devices. This may be due to the different outlet air parameters of the three devices.

Compared with the situation without local cooling devices, the weights of the head and upper limbs increased, and those of the torso and lower limbs decreased after using local cooling devices. In all cases, the torso had the greatest weight, whereas the lower limbs had the smallest weight (the head, with only one part, was not compared). This may be because the human torso contains the most vital organs and is the heat-producing center of the body. The torso accounts for approximately 30% of the body's total surface area [64]. Thermal signals from this area serve as important auxiliary feedback signals in the control of autonomic thermoeffectors, which influence thermal sensation in the steady state of the human body [61]. In contrast, the lower limbs are sufficiently far from the core region [65] such that the lower body contributes less to the overall thermal sensation [39]. Although the surface area of the face accounts for approximately 4 % of the total surface area, it contributes significantly to the total skin signal driving certain thermoeffectors [66,67], making the head a critical section. Fig. 12(b) depicts the changes in warm and cold thresholds of various parts of elderly people compared to young people obtained by Stevens et al. [68]. This indicates only a minor increase in the warm and cold thresholds on the face of the elderly people, thus rendering the face more resistant to the effects of aging on thermal sensitivity [26]. The four-section division of the body proposed in this study may serve as a guide for simplifying local thermal sensations in the future.

Although this study found that the change in overall thermal sensation was most correlated with the change in skin temperature in the major exposed sections (Fig. 10(c)), which refers to the torso and upper limbs, the sections with the greatest correlation with the overall thermal sensation were still the head, upper limbs, and lower limbs (Fig. 10(b)). This may be because when predicting thermal sensation by skin temperature, not only the thermoreceptor density distribution but also the rate and amount of skin temperature changes with environmental parameters should be considered. Therefore, it is reasonable to establish the TMST formula using the head, upper limbs, and lower limbs, which have high thermoreceptor densities and are sensitive to changes in environmental parameters as well as high thermal sensation weights.

In summary, the head and torso, which account for approximately 70 % of the weighting, are the sections with the most influence on the overall thermal sensation after using local cooling devices. When designing local cooling devices, the primary consideration chould be cooling for these two sections.

4.2. Limitations and future research

Local skin temperatures and thermal sensation were analyzed in detail in this study; however, because of the placement and directed flow pattern of the table fan and evaporative cooling device, the environmental parameters of the left and right sides of the human body were asymmetrical, which may have affected the results. The thermal manikin used in this experiment simulates an adult male with a height of 175 cm, so the effective areas of the devices may differ for females. In addition, changes in skin temperature and thermal sensation over time were analyzed. However, the questionnaire was completed 15 min after the start of the local cooling phase, which is a slightly long interval for transient responses. Although it was challenging for the elderly participants to complete the questionnaire frequently, future research should attempt to shorten the time interval, particularly immediately following changes. It is important to note that in this study, convective local cooling used air at room temperature, and even for evaporative cooling, the temperature was slightly above the wet-bulb temperature. Therefore, these results may not be suitable for cases involving stronger local cooling. In addition, this study recruited 26 participants, including 7 males and 19 females. Therefore, the results may be influenced by the imbalance in the sample. The impact of gender differences needs to be considered in future research.

5. Conclusion

The thermal comfort of elderly people in warm environments is of great concern, and local cooling devices may be an important solution for reducing heat stress. Regarding changes in skin temperature and thermal sensation of elderly people in warm conditions after using local cooling devices, the following conclusions can be drawn:

- Elderly people, after using local cooling devices in different thermal environments, exhibited stable physiological parameters within 10 min. The mean skin temperature decreased by no more than 0.5 °C, with a local skin temperature reduction ranging from 0.5 °C to 1.1 °C. Skin temperature significantly droped in exposed body parts, while the it in unexposed parts remained nearly unchanged.
- Local thermal sensations in both exposed and unexposed body parts of the elderly significantly decreased. However, this may be attributed to the longer questionnaire interval, causing the overall thermal sensation influence local thermal sensation.
- Results from factor analysis of local thermal sensations reveal the human body can be divided into four sections after using three

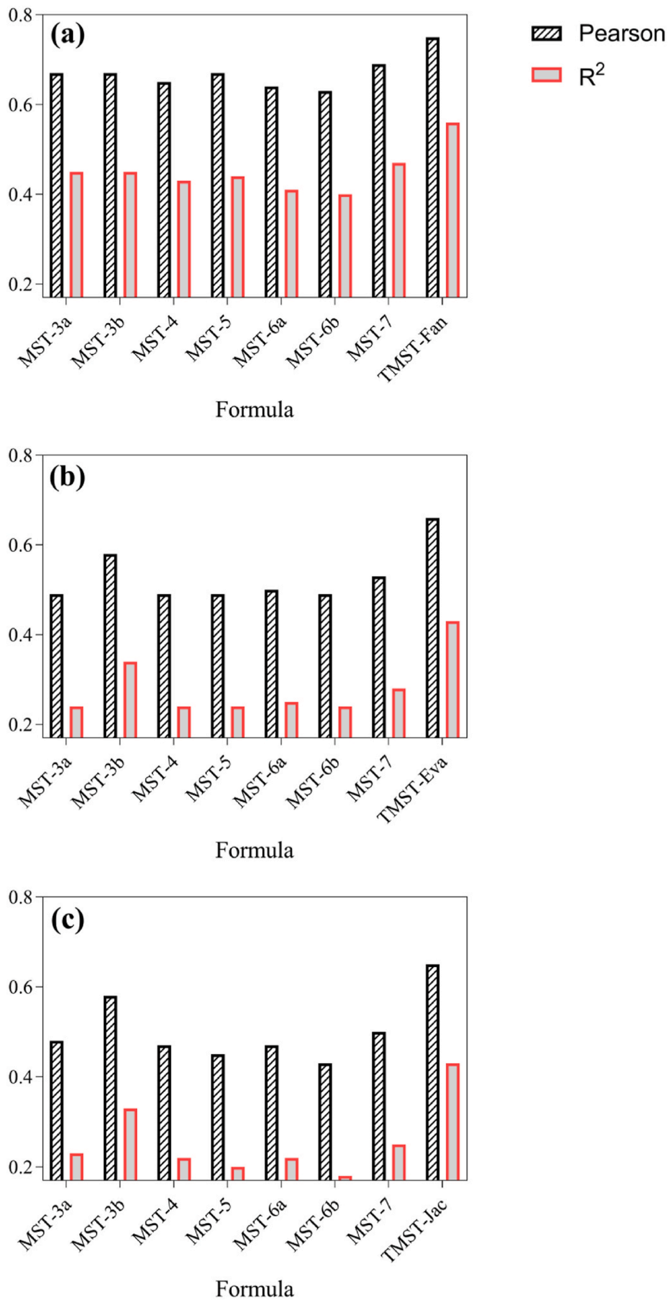

Fig. 11. Correlation between weighted mean skin temperature and overall thermal sensation for (a) table fan, (b) evaporative cooling device, and (c) air-cooled jacket.

different devices: head (forehead), torso (chest, pelvis, upper back, lower back), upper limbs (forearm, palm), and lower limbs (thigh, calf, and foot). The thermal sensation weights of the head and torso sections have the greatest impact on overall thermal sensation, constituting approximately 70 %. When designing local cooling devices, priority should be given to cooling these areas. For individual parts, the head and palm have the highest weights. If only cooling a specific part, consideration chould be given to the head or hand.

- Skin temperatures of the head, limbs, and extremities exhibited stronger correlation with thermal sensation, indicating the importance of considering sensitive extremities when predicting thermal sensation in non-uniform environments. Changes in skin temperature in exposed areas show a strong correlation with changes in overall thermal sensation.

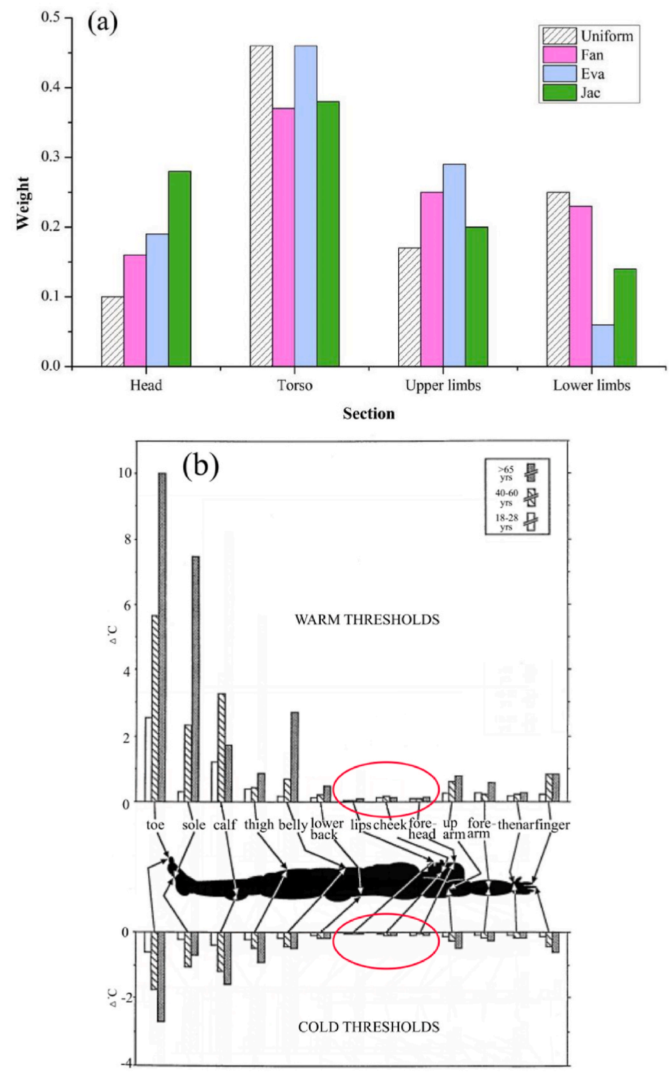

Fig. 12. (a) Section weights of thermal sensation; (b) warm and cold thresholds changes in different age groups [68]. (Fan, table fan; Eva, evaporative cooling device; Jac, air-cooled jacket.)

- After using local cooling devices, the mean skin temperature (MST) remained significantly correlated with overall thermal sensation, serving as an effective physiological indicator for estimating thermal sensation.
- To enhance the correlation between skin temperature and overall thermal sensation, this study introduced the thermosensory mean skin temperature (TMST). Constructed from the skin temperatures of the forehead, forearm, finger, and foot, along with the weights derived from factor analysis, TMST demonstrated higher correlation and accuracy in predicting overall thermal sensation compared to MST.

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CRediT authorship contribution statement

Minzhou Chen: Writing – original draft, Data curation, Conceptualization. **Jaafar Younes:** Writing – review & editing, Validation, Data curation. **Azin Velashjerdi Farahani:** Writing – review & editing, Data curation. **Simo Kilpeläinen:** Writing – review & editing, Project administration, Methodology. **Risto Kosonen:** Writing – review & editing, Project administration, Funding acquisition. **Nesreen Ghaddar:** Writing – review & editing, Supervision, Project administration. **Kamel Ghali:** Writing – review & editing, Supervision. **Arsen Krikor Melikov:** Writing – review & editing, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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