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Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment

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A B S T R A C T

The study aimed to examine the effect of a hybrid personal cooling garment (PCG) on improvement of thermal comfort of office workers in a hot indoor environment. Eleven male subjects underwent two 90-min trials with one in PCG (i.e., with the hybrid personal cooling garment) and another with no cooling (i.e., CON). The trials were performed in a climate chamber with an air temperature of 34.0 ± 0.5 °C, relative humidity of 65 ± 5% and an air velocity of 0.15 ± 0.05 m/s. It was found that the hybrid PCG could remarkably improve the whole-body thermal sensations (TSs), skin wetness sensations (WSs) and comfort sensations (CSs) during most of time of the trials compared with CON (i.e., from the 10th min to the 40th min and from the 70th min to the 80th min for TSs, from the 10th min and the 20th min to the end of the test for WSs and CSs, respectively) ($p < 0.05$). The upper-body and lower-body TSs, WSs and CSs were all significantly improved in PCG from the 10th min to the end of the test ($p < 0.05$). In addition, mean skin temperatures and the total sweat production were also significantly reduced in PCG ($p < 0.05$). In summary, the hybrid PCG was highly anticipated to improve thermal comfort of office workers while doing office work in the studied hot and moderate humid indoor environment.

1. Introduction

Office workers generally spend more than 90% of their time indoors [1]. Indoor thermal environments (e.g., the air temperature, relative humidity, air velocity, radiation) [2] together with the air quality and illumination significantly affect the performance and health of office workers in indoor environments [3,4]. In recent years, indoor thermal conditions have been worsened due to global warming and frequently emergent and intensified heat waves [5]. This tends to consume more energy to provide acceptable thermal conditions for office workers [5]. Thus, a great deal of attention has been paid to improve indoor thermal comfort of office workers without significant compromise of energy consumption [6].

Theoretically, indoor human thermal comfort can be improved by either adjusting the environmental condition through the Heating Ventilation and Air Conditioning (HVAC) system [6], or using personal comfort systems (PCSs) [7]. Adjusting the HVAC system to maintain the indoor environment in a standard defined comfort limit range does not always lead to a high level of comfort [8,9]. On the contrary, numerous anecdotal experiences of the overcooled buildings caused by the modern HVAC system have reflected the inflexibility of the system [9]. Furthermore, HVACs are most likely to bring about tremendous energy cost as well as environmental pollutions [6]. Considering the above problems and the widely accepted fact that great individual differences exist between genders and different age groups [10], using PCSs has been regarded as the most effective and flexible approach to fulfil individual thermal comfort needs [11]. For instance, electric fans directing at the whole body (such as ceiling fans and opposing air jets) or local body parts (such as front desk fans and fans incorporated into chairs) were widely examined by researchers on their effectiveness in improving human thermal comfort in hot indoors [12–18]. PCSs were proved to be effective in maintaining human thermal comfort in warm indoor environments without HVAC (e.g., $T_{air} < 32.0$ °C) [12,16]. However, it seems difficult to keep the human body in thermal neutral state using PCSs in hot indoors where the

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Nomenclature

HVAC	Heating, Ventilation and Air Conditioning
PCS	Personal comfort systems
PCG	Phase change garment
CON	No cooling condition
PCM	Phase change material
LCG	Liquid cooling garment
ACG	Air cooling garment
HR	Heart rate
T_c	Core temperature
$\overline{T_{sk}}$	Mean skin temperature
T_b	Mean body temperature
ΔS	Body heat storage
TS	Thermal sensation
CS	Comfort sensation
WS	Wetness sensation

air temperature is higher than 34.0 °C [12,16] and particularly in hot humid indoor environments [12,14,18]. Moreover, using PCSs may induce body discomfort (due to drought) [17,18], and bring such ergonomic problems as high noise, more energy cost and space occupation [17]. In addition, PCSs such as electric fans were not portable and could not be able to provide sustained thermal comfort.

Many researchers have discovered that human indoor thermal comfort could be improved by self-adjusting clothing [19–21]. Unfortunately, this is not always feasible for office workers because they have to wear vocational clothing even in hot summer due to social etiquette requirements. Moreover, self-adjustment of clothing had a limited benefit in improving human indoor thermal comfort, particularly in extreme harsh indoor environments [20] combined with high/low air velocities and humidity [21]. In order to solve above issues, personal cooling and heating clothing systems have been developed. Compared to the conventional clothing adjustment method, personal heating/cooling systems have shown evident ability in improving individual thermal comfort [22].

Currently, the effectiveness of personal cooling garments (PCGs) in alleviating body heat strain while exercising in hot environments has been widely examined [23–25]. PCGs have already been applied to such special fields as military training, firefighting, medical operations and sports. In general, PCGs may be divided into four categories based on the types of cooling sources, i.e., liquid cooling garments (LCGs) [26], air cooling garments (ACGs) [26–28], garments incorporated with phase change materials (PCMs) [28] and hybrid cooling garments that combine two or more of the aforementioned cooling techniques [29,30]. Literature review studies demonstrated that LCGs and cold-air ACGs could provide greater cooling benefits compared to other types of PCGs [22,23]. Nevertheless, LCGs and cold-air ACGs have many obvious drawbacks of high cost, complexity and non-portability due to the refrigeration systems connected, thus restricting them to a small range of application [23]. In contrast, PCGs incorporated with PCMs, ACGs using ventilation fans and the hybrid cooling garments combining the PCMs and ventilation fans are relatively cheap and portable, and thus they have a great potential to be applied to various work settings including indoor office work [24,25,30].

Few studies have attempted to examine the effect of PCGs in improving human thermal comfort indoors [31–34]. Several studies explored on the effectiveness of PCM cooling clothing in improving thermal comfort of special personnel such as surgeons [32,33]. Two studies were retrieved for investigating the performance of PCM cooling clothing in improving thermal comfort of office workers [31,34]. Nishihara et al. [31] examined the effects of a commercial ice vest and a PCM cooling garment in improving thermal comfort of office workers in a warm and dry environment. Gao et al. [34] examined the effect of a PCM cooling vest on an already overheated body while conducting office work in a hot environment. Results illustrated that PCM cooling vests had significant effects on local body regions rather than the whole body [31,34]. In view of ongoing research, more studies should be conducted to find out better PCGs to improve the thermal comfort of office workers in hot indoor environments, e.g., during severe heat wave incidents.

More recently, a hybrid PCG (clothing incorporated with air ventilation fans and PCMs) was developed to give full consideration of the cooling effect and ergonomic design. Thermal manikin studies have evidently showed that the hybrid PCG presented larger and prolonged cooling effect compared to single cooling methods [30]. It is of great interest to examine the hybrid PCG on its effectiveness in improving thermal comfort of office workers in hot indoor environments where the HVAC system is not available. It was hypothesized that the hybrid PCG could greatly improve both physiological and perceptual responses of office workers in the studied hot indoor environment.

2. Methodology

2.1. Human subjects

Eleven young male office workers (age: 21.9 ± 2.38 years, weight: 61.41 ± 2.54 kg, height: 1.74 ± 0.02 m, body surface area: 1.74 ± 0.04 m^2, body mass index: 20.46 ± 0.84 kg/m^2) volunteered for this study. They were physically healthy and had no history of heat illnesses, cardiovascular, metabolic or respiratory diseases. Prior to participation, all subjects were fully explained of the purpose, details and potential medical risks associated with this study. They were then asked to sign a written informed consent. They were also notified that they could quit this study at any time without penalty. This study was approved by the Ethics Committee of Soochow University.

2.2. Hybrid personal cooling garment (PCG)

A set of hybrid PCG consisting of a long-sleeve cotton/polyester jacket (a mesh linear sewn with a main fabric) and full-length cotton/polyester pants was selected (see Fig. 1). Both the jacket and pants were incorporated with PCM packs and air ventilation fans. Eighteen PCM packs were placed into the 18 separate pockets (made of polyester mesh fabrics) stitched on the mesh linear of the jacket (i.e., 4 packs at the upper arms region, 6 at the chest and 8 at the back). Two ventilation fans were embedded to the lower back region. For pants, six PCM packs were inserted into the pockets of the pants at the thighs region, and two air ventilation fans were installed at the lateral pelvis area.

The main ingredients of PCMs are a mixture of sodium sulphate and water ($Na_2SO_4 \cdot 10H_2O$ known as the Glauber's salt) and additives. Its melting temperature and latent heat of fusion are 21.0 °C and 144 kJ/kg, respectively [35]. The weight and covering area of each PCM pack are 86 g and 92.4 cm^2, respectively. Thus the total weight and total covering area of the 24 PCM packs (i.e., 18 in the jackets and 6 in the pants) are 2.064 kg and 2217.6 cm^2, respectively. Each fan has a maximum flow rate of 12 l/s and its diameter is 10 cm. The total weight of the PCG including the main fabric of the garment is 3.589 kg. To facilitate the best cooling performance, the PCG was made with the bottom hems of the jacket and the

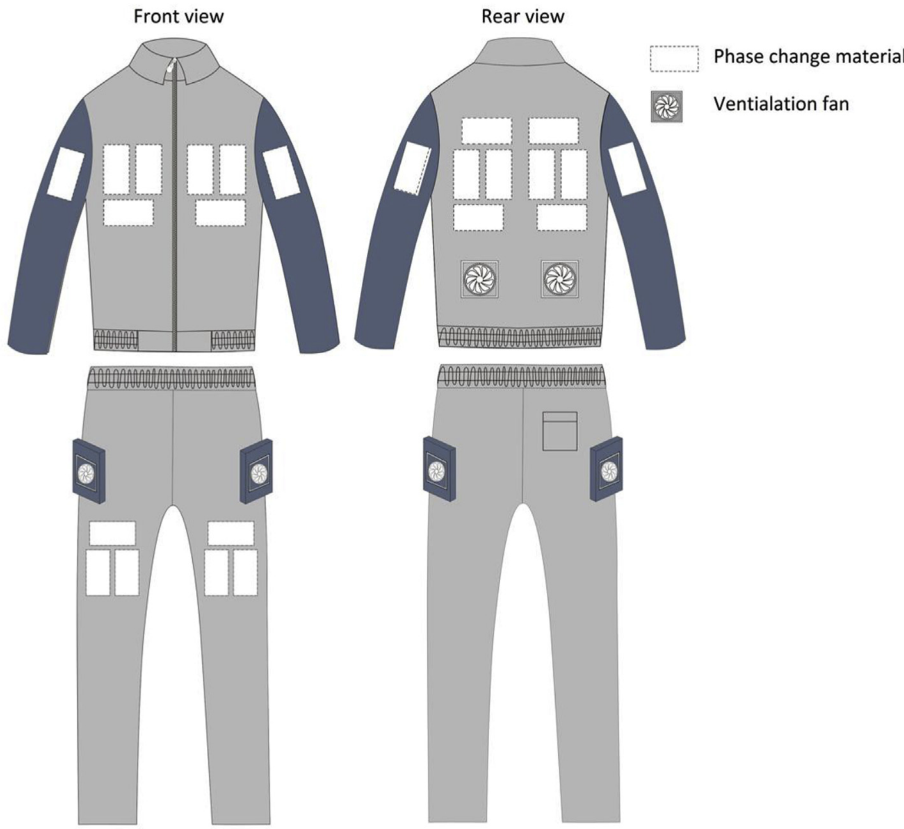

Fig. 1. The schematic diagram of the hybrid personal cooling garment.

waist of the pants tightly fitting to the body by elastic straps, and with two vertical ventilation channels at the chest and the back (channel width: 5 cm) as well as gaps between every two adjacent PCM packs (channel width: 2 cm).

Previous manikin tests showed that the PCG could supply an averaged cooling power of 76 W/m^2 and 213 W/m^2 in hot humid (i.e., 34.0 ± 0.5 °C, RH = 75 ± 5% and v_a = 0.4 ± 0.1 m/s) and hot dry (i.e., 34.0 ± 0.5 °C, RH = 75 ± 5% and v_a = 0.4 ± 0.1 m/s) environments, respectively [30]. The unit of W/m^2 denotes the cooling energy (in the unit of watts) absorbed per body surface area (in the unit of m^2).

2.3. Experimental design

All subjects received no heat acclimation. They were required not to drink coffee or tea at least 2 h before the trial, and also not to consume alcohol or do strenuous activities at least 24 h prior to each test. Each subject underwent two wear trials (two testing scenarios), one in PCG (i.e., with the hybrid cooling clothing ensemble) and another in CON (i.e., no cooling condition, PCMs were taken out from the PCG and four air ventilation fans were switched off). The intrinsic thermal insulation of the PCG ensemble (i.e., including PCG_{CON}, the underwear, socks and shoes) is 0.70 clo, which represents typical summer indoor workwear according to the study of McCullough and Wyon [35]. All trials were performed in a fully randomized and counter-balanced order. To eliminate the impact of the circadian variation [36], the trials were conducted at the same time of the day, spaced by at least 48 h. The subjects were assigned the same undergarment (i.e., a polyester T-shirt and cotton briefs).

The subjects were instructed to swallow an ingestible core temperature pill 3 h before each test. Upon arrival, they were asked to drink a cup of tepid water (the water temperature was about 37.0 °C and the total volume was 200 ml) [37]. They rested in a seated position for 30 min at the room temperature (i.e., 23 ± 1 °C, RH = 60 ± 5% and v_a = 0.15 ± 0.05 m/s) to assure their core temperatures felling into the range of 36.8–37.2 °C. Afterwards, they were dressed in the assigned clothing ensemble (i.e., underwear, socks, shoes and PCG or CON), had all instruments into place, and entered the climate chamber. They then sit on an office chair in an upright posture in front of the office desk and read a book for 90 min to simulate light office work (shown in Fig. 2). After the trials, they came out of the chamber, took off the equipment and changed their own clothing. The climatic chamber was kept at an air temperature of 34.0 ± 0.5 °C, the relative humidity was 65 ± 5% and an air velocity of 0.15 ± 0.05 m/s. The partial water vapour pressure inside the chamber was 3.5 kPa accordingly. The selection of such a hot and moderate humid condition was aimed to simulate the typical indoor environments with no access to air conditioning in many areas of China during the summer season [38].

2.4. Measurement variables

2.4.1. Physiological parameters

Metabolic rate was continuously sampled with a cardiopulmonary tester (MetaMax®3B, Cortex Biophysik GmbH, Leipzig, Germany). The tester was calibrated before each test for gas, volume and pressure. Heart rate (HR) was measured using a heart rate monitor (Polar Electro Oy, Kempele, Finland). The core temperature (T_c) was measured using a data recorder (CorTemp, HQI, America). Skin temperatures at ten sites of the left body, namely, the chest, scapula, upper arm, paravertebral, abdomen, thigh and the calf,

Fig. 2. A picture of a subject in PCG during an experiment.

were measured by thermocouples (MSR®145B4, MSR Electronic GmbH, Seuzach, Switzerland). All physiological parameters were sampled every 1 min throughout the 90 min trial. Mean skin temperature ($\overline{T}_{sk}$) was derived by: $\overline{T}_{sk} = 0.3 \times (T_{chest} + T_{upper\ arm}) + 0.2 \times (T_{thigh} + T_{calf})$ [39]. Mean body temperature (T_b) was calculated as: $T_b = 0.8 \times T_c + 0.2 \times \overline{T}_{sk}$ [40]. Heat storage (ΔS, in W/m^2) was computed as: $\Delta S = C_m \times W_m \times \Delta T_b/A_{du}$ (where, $C_m = 3480$ J kg^{-1} °C^{-1}, W_m is the pre-test body mass, kg, A_{du} is the body surface area, m^2, and ΔT_b is the change in T_b) [41]. Cooling energy (in the unit of W/m^2) of the PCG was calculated by subtracting the body heat storage in PCG from that in CON.

The nude body (i.e., just with briefs) and each piece of clothing and equipment were weighed before and after each trial using a balance with a precision of ±1.0 g (KCC150s, METTLER-TOLEDO AG, Zurich, Switzerland). As no drink intake or urine loss during the entire test, the total sweat production (in grams) was calculated by subtracting the post-trial nude body weight from that before the trial. The percentage of dehydration was obtained as: the mass of the produced sweat/the nude body mass. The percentage of the absorbed sweat was obtained by dividing the increased garment mass before and after the test from the total sweat production. As no sweat dripping was observed throughout the whole trials, the percentage of evaporated sweating was: (the mass of the total produced sweat minus the mass of the sweat absorbed by clothing)/the total sweat production.

2.4.2. Perceptual responses

The whole-, upper- and lower-body thermal sensation (TS), skin wetness sensation (WS) and comfort sensation (CS) were scaled by the subjects every 10 min throughout the whole trials. Ratings of TS, WS and CS ranged from −4 ('Very cold') to 4 ('Very hot') [42], 0 ('Neutral') to 3 ('Very wet') [43] and −3 ('Very uncomfortable') to 0 ('Comfortable') [44], respectively. The three rating scales are displayed in Table 1.

2.5. Statistical analysis

Data were expressed as mean ± standard deviation (SD) and they were analysed using the SPSS v.20.0 software (IBM Corp., Armonk, NY, USA). A two-way repeated-measures ANOVA (testing scenarios: PCG and CON vs. time: 5 min intervals or 10 min intervals) was conducted to compare both the thermophysiological (core, skin and body temperatures and heart rate) and perceptual parameters (thermal, wetness and comfort sensations). Significant main effect was further examined using a *post hoc* test with Bonferroni correction. A Paired Samples t-test was performed to compare the metabolic rate, the body dehydration percentage, the percentage of the absorbed and evaporated sweat between PCG and CON. Statistically significance was set as $p < 0.05$ (label * in the figures).

3. Results

3.1. Perceptual sensations

Comparison of changes in perceptual sensations, i.e., the whole-, upper-, and lower-body thermal sensations (TS), skin wetness sensations (WS) and comfort sensations (CS), between PCG and CON are shown in Fig. 3a, b and c, respectively. The whole-body TSs WSs and CSs were significantly lower in PCG compared with CON during most of time of the trials (from the 10th min to the 40th min and from the 70th min to the 80th min for TSs, from the 20th min to the end of the test for WSs and from the 10th min to the end of test for CSs). PCG was observed to lower both the upper-body and lower-body TSs, WSs and CSs than CON from the 10th min to the end of the test ($p < 0.05$), and a significant interaction effect between the two scenarios and time was found for these sensations ($p < 0.05$).

At the end of the trials, ratings of the whole-body TS, WS and CS in CON reached to 2.5 ± 0.6 (between 'Warm' and 'Hot'), 2.0 ± 0.4 (close to 'Wet') and −2.0 ± 0.4 (close to 'Uncomfortable'), respectively. In contrast, the whole-body TS, WS and CS in PCG were lowered to 1.5 ± 0.8 (between 'Slightly warm' and 'Warm'), 1.0 ± 0.5 ('Slightly wet') and −1.1 ± 0.7 (close to 'Slightly uncomfortable'), respectively. For the upper-body, the ratings of TS, CS and WS were concluded at 2.6 ± 0.5 (between 'Warm' and 'Hot'), 2.1 ± 0.3 (close to 'Wet') and −2.0 ± 0.4 ('Uncomfortable') in CON, whereas they were registered at 1.6 ± 0.8 (between 'Slightly warm' and

Table 1
Ratings of the perceptual sensations.

	Thermal sensation (TS)	Comfort sensation (CS)	Wetness sensation (WS)
−4	Very cold	–	–
−3	Cold	Very uncomfortable	–
−2	Cool	Uncomfortable	–
−1	Slightly cool	Slightly uncomfortable	–
0	Neutral	Comfortable	Neutral
1	Slightly warm	–	Slightly wet
2	Warm	–	Wet
3	Hot	–	Very wet
4	Very hot	–	–

Note: –, not applicable.

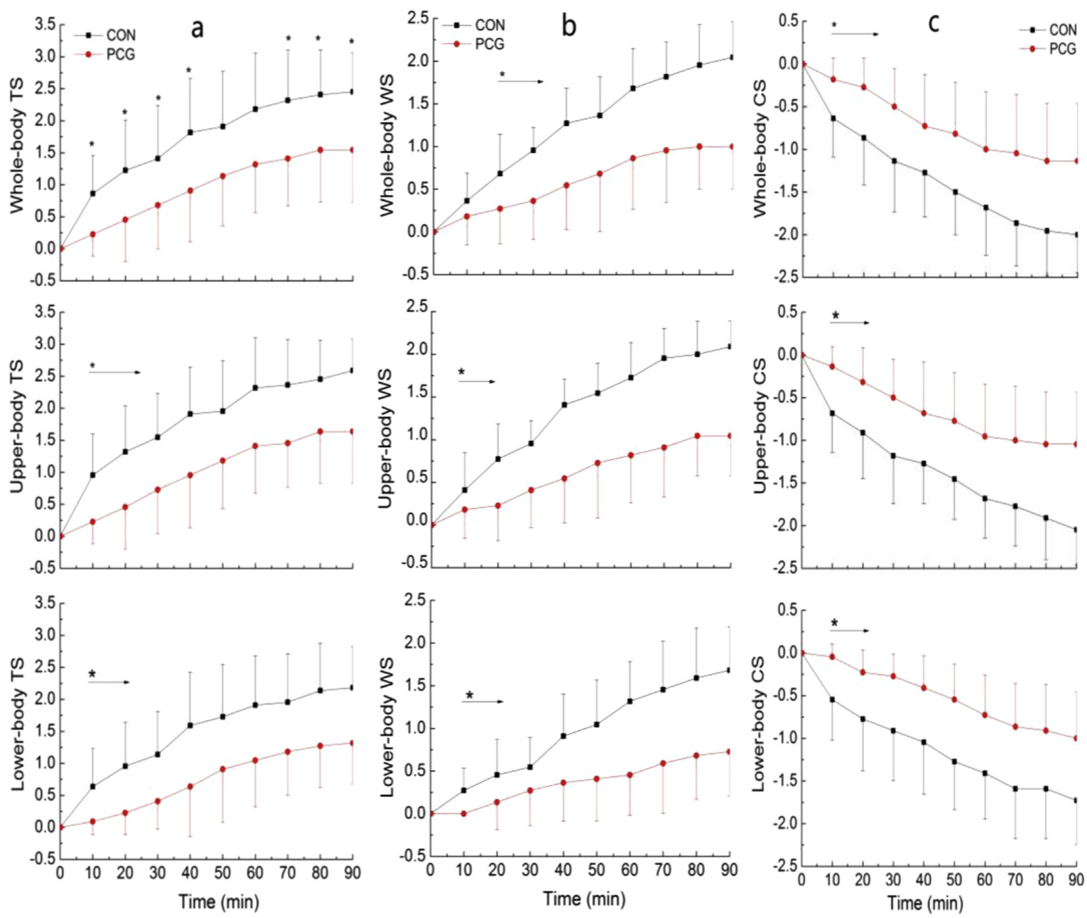

Fig. 3. Time changes in the whole-, upper- and lower-body thermal sensations (a), skin wetness sensation (b) and comfort sensations (c) in PCG and CON.

'Warm'), −1.0 ± 0.6 ('Slightly Uncomfortable') and 1.0 ± 0.50 ('Slightly wet') in PCG. As to the lower-body part, the ratings of TS, CS and WS ratings reached up to 2.2 ± 0.6 (close to 'Warm'), 1.7 ± 0.5 (close to 'Wet') and −1.7 ± 0.5 (close to 'Uncomfortable') in CON, and 1.3 ± 0.6 (close to 'Slightly warm'), 0.7 ± 0.5 (close to 'Slightly wet') and −1.0 ± 0.5 (i.e., 'Slightly uncomfortable') in PCG.

3.2. Physiological responses

The participants showed similar metabolic rates in both PCG (i.e., 78.3 ± 16.2 W/m^2) and CON (i.e., 75.2 ± 14.1 W/m^2). Body heat storage was significantly lower in PCG (i.e., 6.8 ± 2.1 W/m^2) compared with CON (i.e., 11.7 ± 2.1 W/m^2) ($p < 0.01$). Cooling energy of the PCG was 4.9 W/m^2. The comparison of the changes in core temperature (T_c) and heart rate (HR) between PCG and CON are shown in Fig. 4. Significantly higher T_c was observed in PCG compared with CON from the 15th min to the 45th min of the test ($p < 0.05$). It is also observed that T_c dropped significantly from the 40th min to the 55th min of the test (main time effect, $p < 0.05$). At the end of the test, T_c increased to 37.2 ± 0.2 °C and 37.3 ± 0.2 °C in PCG and CON, respectively. HR fluctuated and increased with time (time main effect, $p < 0.01$), and fell into ranges of 73.5–85.6 beats/min and 73.5–89.0 beats/min in PCG and CON, respectively. No significant difference in HR was observed between PCG and CON ($p < 0.05$).

The changes in the mean skin temperature ($\overline{T}_{sk}$) and local skin temperatures in PCG and CON are shown in Figs. 5 and 6, respectively. $\overline{T}_{sk}$ in CON kept rising and concluded at 35.3 ± 0.3 °C at the

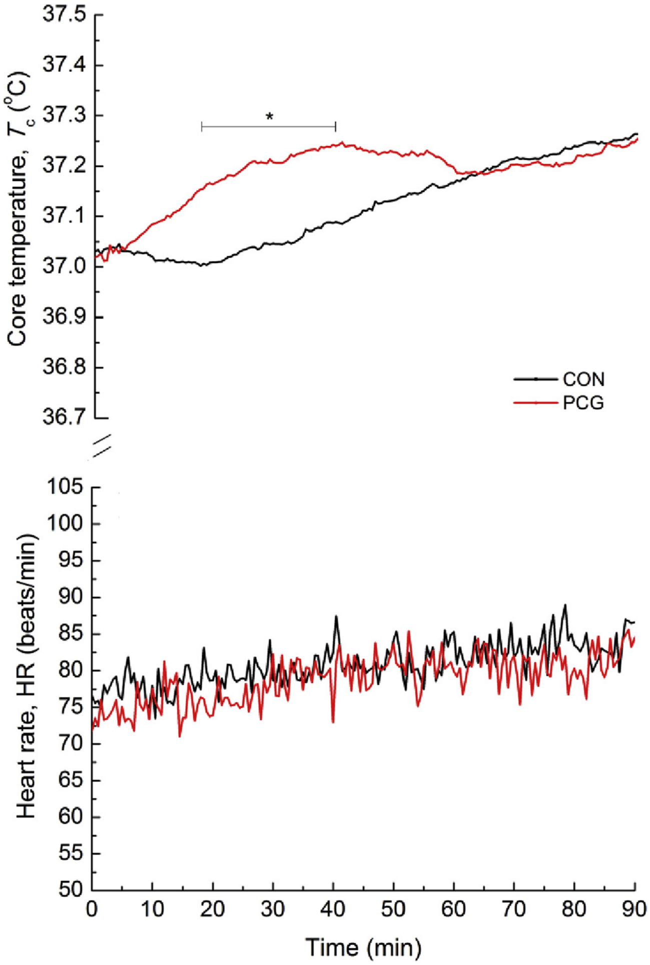

Fig. 4. Time changes in the whole-, upper- and lower-body thermal sensations (TSs), skin wetness sensations (WSs) and comfort sensations (CSs) in PCG and CON

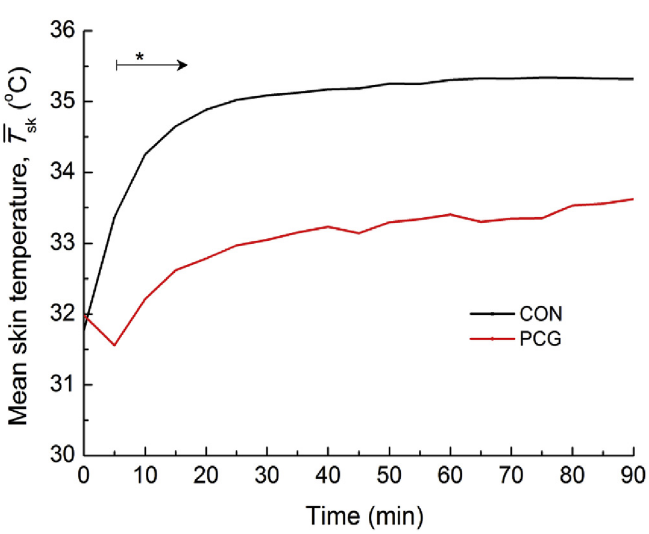

Fig. 5. Comparison of changes in the mean skin temperature between PCG and CON.

end of the test. In contrast, $\overline{T}_{sk}$ in PCG exhibited an obvious reduction (i.e., reduced from 32.0 ± 0.5 °C to 31.4 ± 1.0 °C) during the first 5 min of the test and then increased to 33.6 ± 0.9 °C at the

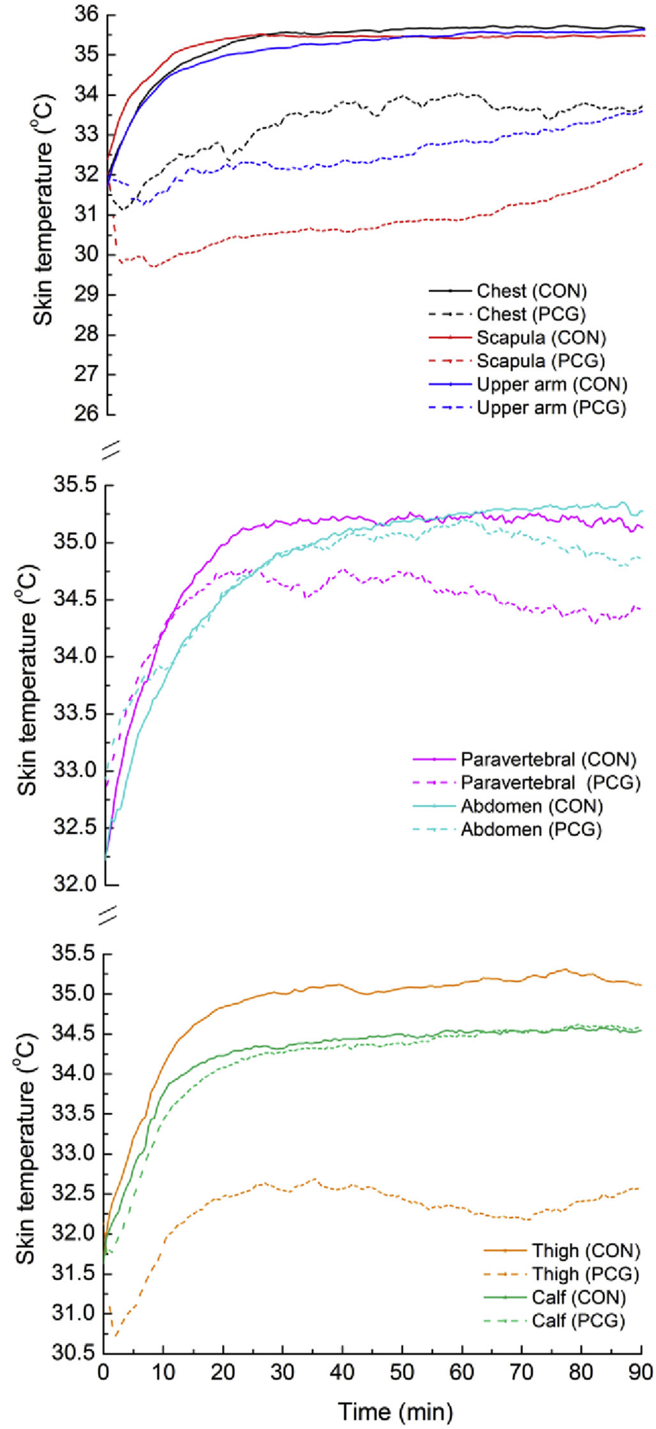

Fig. 6. Comparison of changes in the local skin temperatures at the chest, scapular, upper arm, paravertebral, abdomen, thigh and calf between PCG and CON.

end of the test. Moreover, $\overline{T}_{sk}$ displayed significantly higher values in PCG than in CON during the entire test, and the interaction effect between the two testing scenarios and the time was detected in $\overline{T}_{sk}$ ($p < 0.01$).

The changes of local skin temperatures at the chest, scapular, upper arm and thigh in PCG and CON are displayed in Fig. 6. Local skin temperatures at the chest, scapula, upper arm as well as the thigh region exhibited significantly lower values compared to those in CON ($p < 0.01$) throughout the whole trial. Local temperatures displayed pronounced reductions during the initial testing stage (reductions: 0.74–2.36 °C) at these body regions, and the scapula showed the most pronounced reduction (i.e., from 32.07 °C to 29.71 °C, a reduction of 2.36 °C). It was also noted that the local skin temperature at the thigh in PCG was dropping throughout the 35–70th min of the trials. Skin temperature at the paravertebral region was significantly lower in PCG from the 25th min to the end of the test. Skin temperatures at the abdomen and calf regions showed no difference between PCG and CON ($p > 0.1$).

The total sweat production was significantly lower in PCG (i.e., 132.5 ± 31.0 g) compared with CON (i.e., 194.4 ± 41.2 g) ($p < 0.05$). Similarly, the percentage of dehydration was significantly higher in PCG (i.e., 0.22 ± 0.06%) compared with CON (i.e., 0.32 ± 0.07%) ($p < 0.05$). The mass of the sweat absorbed was significantly lower in PCG (i.e., 33.2 ± 25.3 g in PCG vs. 43.9 ± 21.8 g in CON) ($p < 0.05$), but no difference was observed in the percentage of the sweat absorbed (i.e., 25.1 ± 6.5% in PCG vs. 22.5 ± 9.2% in CON) ($p > 0.1$). In addition, the mass of sweat evaporated was significantly higher in PCG (i.e., 150.6 ± 31.2 g) than in CON (i.e., 98.4 ± 23.2 g, $p < 0.05$), but no difference was detected in the percentage of the sweat evaporated (i.e., 74.9 ± 6.6% in PCG vs. 77.5 ± 9.1% in CON, $p > 0.1$).

4. Discussion

In this study, the highest T_c and HR captured were 37.3 ± 0.2 °C and 89.0 ± 11.8 beats/min in the two clothing scenarios, respectively, both falling into the normal data ranges (i.e., 36.5–37.5 °C for T_c and 60–100 beats/min for HR) [45]. The percentage of body dehydration was (i.e., 0.22 ± 0.07% in PCG and 0.32 ± 0.06% in CON) much lower than the thirst threshold at rest (i.e., 1.0 ± 0.7%) [45]. However, some heat storage inside the human body was observed (i.e., 6.8 ± 2.1 W/m^2 in PCG and 11.7 ± 2.1 W/m^2 in CON), indicating that the subjects experienced slightly heat strain in both PCG and CON during the 90 min test while doing office work in the hot and moderate humid environment (i.e., 34.0 ± 0.5 °C and 65 ± 5% RH). The insignificant difference in metabolic rates between PCG and CON has indicated that there was no body shivering while using the PCG.

4.1. The effect of PCG on local skin temperatures

The hybrid PCG was developed to take advantages of the PCM cooling (strong and quick conductive cooling) and natural air cooling (steady and prolonged convective and evaporative cooling) to provide the human body with a strong, steady and prolonged cooling effect [23]. PCM cooling utilizes the latent heat absorption of PCMs when they change from solid to liquid state [32]. Generally, the effectiveness of PCM cooling is positively correlated with the latent heat of fusion, total weight and body coverage of the PCMs [34]. To enlarge cooling effect, the melting temperature of the PCMs should be at least 6 °C lower than the mean skin temperature [46]. Also, PCMs must be tightly contacted with the human body. The PCMs used in this study had a melting temperature of 21.0 °C, a total weight of 2.064 kg, and they covered 12.7% of the whole body surface. They were placed at the regions (i.e., chest, scapula, upper arm and thigh) with smaller air gaps to ensure a close contact with the skin surface. The effectiveness of PCM cooling was obviously seen from local skin temperature drops in those local regions where PCMs were placed. The scapula region displayed the largest skin temperature drop than other body parts, which was different from our previous study with regard to the effectiveness of hybrid cooling garments in alleviating human heat strain while exercising in a hot environment [24]. Our previous study showed that the chest had a larger skin temperature drop. Such local body temperature differences may be induced by different body postures. In our previous study, subjects had a walking posture. The PCMs may have better contact with the scapular while sitting in this study, whereas the chest part had better contact with the PCMs while walking on the treadmill. The air cooling effect was largely decided by the flow rate and locations of the ventilation fans [47]. In our study, the PCGs had a flow rate of 12 l/s and those fans were placed to the lower back and lateral thigh regions where large air gaps were presented. The air cooling benefit might be evidenced by the significantly lowered local skin temperature in the paravertebral during the testing stage when air cooling played a mainly role in cooling the body (i.e., when PCMs were fully melted and no more PCM cooling could be provided). The evolution of the local skin temperature at the thigh (both PCMs and ventilation fans were located at this body part) was different from those of other local body parts, which were equipped with only PCMs (i.e., chest, scapula and upper arms) or ventilation fans (i.e., the paravertebral). The initial skin temperature dropping (within the first 5 min) at this region might be caused by the PCM cooling, while the second obvious dropping (i.e., the 35–70th min) might be induced by air cooling. The abdomen and calf gained minimal cooling benefits, as no difference in the local skin temperatures at these two parts were observed between PCG and CON. This might also be attributed to the sitting posture, which somehow inhibited the air ventilation at these two body parts.

4.2. The effect of PCG on physiological responses

Considering the local skin temperature drops, it could be understood that $\overline{T}_{sk}$ displayed significantly lower values in PCG than in CON during the entire test. Interaction effect between these two test scenarios and the time in $\overline{T}_{sk}$ revealed that the cooling benefit of PCG would continue if time proceeds. All the detected $\overline{T}_{sk}$ values (i.e., 32.1–33.6 °C) excluding one point in PCG were laid in the widely accepted thermoneutral range (i.e., 32.0–34.0 °C) [45]. However, $\overline{T}_{sk}$ in CON exceeded 34.0 °C shortly after the test and reached to 35.3 ± 0.3 °C at the 90 min of the trial. It was interesting to note that T_c showed significantly higher values in PCG compared to CON ($p = 0.15$) for almost 30 min from the 15th min of the trial. The same phenomenon was also observed by Huizenga et al. [48] who discovered that cooling the torso parts such as the pelvis in a warm environment was able to increase T_c immediately. Continuous cooling could give rise to reflexive cutaneous vasoconstriction, and restricted the convective/mass heat transfer via blood circulation, which may increase T_c in normothermic individuals [49]. T_c showed a significantly drop from the 40th min to the 55th min of the trial. As time proceeds, a larger temperature gradient was established between the body central core and skin, which greatly promotes the rate of heat transfer between these two parts, and induces a significant drop of the core temperature [45]. Further, the PCG also provided some benefits for the cardiovascular system, indicated by the significantly lowered HR in PCG. The significant lowered upper body temperatures in PCG might reduce the torso skin blood flow, and increase the central blood volume, resulting in lowered HR. The dehydration percentage was significantly lower in PCG (i.e., 0.22 ± 0.07%) compared in CON (i.e., 0.32 ± 0.06%) ($p < 0.05$), which might be associated with the significantly alleviated body thermal status in PCG: the body heat storage was significantly lower in PCG (i.e., 6.8 ± 2.1 W/m^2) compared with CON (i.e., 11.7 ± 2.1 W/m^2) ($p < 0.01$). No statistical difference was observed in the percentage of sweat evaporated between PCG (i.e., 74.9 ± 6.6%) and CON (i.e., 77.5 ± 9.1%) ($p > 0.1$). The PCM packs (covering 12% of the total body surface area) in PCG might inhibit the sweat evaporation [30], while evaporation of sweat could be promoted by ventilation fans. Hence, these two conflicting cooling effects on sweat evaporation might be counterbalanced.

4.3. The effect of PCG on perceptual responses

Previous studies have demonstrated that both whole-body TSs and local TSs were closely related to the mean skin temperature and local skin temperatures [50,51]. WS was strongly linked to moisture accumulated on the skin and inside the clothing [52]. In contrast, CS was influenced by multiple factors including the mean skin temperature, moisture, clothing pressure and mechanic properties [53]. In addition, the whole-body perceptual sensations were also affected by local sensations [54]. Given the significantly improved physiological responses in PCG (i.e., $\overline{T}_{sk}$ and local skin temperatures were lowered, the total sweat production and absorbed sweat were also reduced), the whole-, upper- and lower-body perceptual sensations were all greatly improved ($p < 0.24$).

Further, the PCG brought more benefit in improving WSs compared to TSs and CSs, observed by the significantly lowered whole-, upper- and lower- WSs during the entire test, and the benefit would probably continue (the detected interaction effect between the clothing conditions and time in WSs) if the trial continues. The effects of PCG in improving the whole-, upper- and lower-body TS and CS were more evident during the initial test stage (i.e., significantly lower TSs and CSs in PCG than those in CON). Similar results were also reported by Gao et al. [34] who discovered both the whole-body TS and the TS at the torso were remarkably reduced right after donning the PCM cooling vest. This might be resulted from the remarkably lowered $\overline{T}_{sk}$ and local skin temperatures in the upper- and lower-body which were most likely caused by the strong and quick cooling effect of the PCMs [23,30]. In our study, the lower-body TS was significantly lowered in PCG at the later testing stage, which might be interpreted by the remarkably reduced skin temperature at the thigh. Though not reported, the lowest temperature captured at the scapular was 29.71 °C, which might be likely to stir up some slightly cool sensation and discomfort [31].

Approaching the end of the trials, TS, WS and CS in the whole-body (TS: 1.5 ± 0.8, WS: 1.0 ± 0.5, and CS: −1.1 ± 0.7), upper-body (TS: 1.6 ± 0.8, WS: 1.0 ± 0.50, and CS: −1.0 ± 0.6) and lower-body (TS: 1.3 ± 0.6, WS: 0.7 ± 0.5, and CS: −1.0 ± 0.5) in PCG were rated as between 'Slightly warm' and 'Warm', 'Slightly wet', and close to 'Slightly uncomfortable', respectively. This indicated that the whole-body and local thermal discomfort was registered. In view of this, the three essential thermal comfort requirements (i.e., body heat balance was maintained; both the mean skin temperature and the sweat rate were kept within comfort limits; no local discomfort exists) defined by Fanger [2] were not satisfied. Thus, at the end of the trial, the PCG failed to provide enough body cooling because 'Slightly warm' to 'Warm' thermal sensations were reported. Future research should be conducted to improve the hybrid PCG by enlarging its cooling power without compromise of overcooling at the local body (e.g., the scapular).

4.4. Implications and limitations

Extremely hot weather emerged in high frequency and with prolonged duration recent years in many areas of China such as cities in the Yangtze River area [55]. According to the Meteorological Information Centre of China, air temperatures could often hit 40 °C, and the condition normally lasts for several days or even few weeks in these regions [55]. This would cause great energy consumptions for HVAC to keep an ideal indoor temperature, or it severely affects the thermal comfort and work performance of the workers with no access to HVAC. In fact, extremely hot weather was also crinose in other regions and countries in the past few decades [56–58]. For example, in 2006, California recorded air temperatures greater than 40 °C in many cities [56]. In 2010, Russia experienced air temperatures as high as 42 °C for a number of days [57]. More recently in 2015, air temperatures exceeded 40 °C and even reached 49 °C in India and Pakistan [58]. Not optimistically, it is anticipated that extremely hot weather would happen in high frequency accompanied with global warming in the future [3], which could further deteriorate indoor environments. Therefore, seeking effective personal cooling strategies for office workers is of particular importance to their health and performance.

The present results suggested that the hybrid PCG could significantly improve human thermal comfort while doing office work in a hot and moderate humid indoor environment. However, several issues must be addressed before the application of the PCG to field workers. The usability of a PCG was determined by two key factors, namely, cooling effect (such as cooling power) and ergonomic concerns (such as weight and movement restriction) [23]. Our previous study has demonstrated that the hybrid PCG could provide cooling power values of 76.0 and 212.7 W/m^2 under hot humid environment (i.e., 34.0 °C, 75% RH) and hot dry environment (i.e., 34.0 °C, 47% RH), respectively. The cooling power of the hybrid PCG was negatively related to the ambient relative humidity [30]. Thus, the estimated average cooling power of the hybrid PCG over the 90 min test in this study (i.e., 34 °C, 65% RH) was slightly higher than 76.0 W/m^2. This cooling power supplied by the PCG could bring significantly improved thermal comfort for the human subjects while doing office work (i.e., 69.8 ± 11.6 W/m^2) for 90 min. However, for office work with higher exercise intensities and/or longer work durations, the cooling benefits were unknown. Particularly, for those indoor settings with no access to air conditioning systems in hot summer or during a severe heat wave incident, the high indoor temperature combined with high humidity would depress the cooling benefits of the hybrid PCG [26,55]. More studies should be performed to ascertain the effectiveness of PCG in improving human thermal comfort while doing high-intensity or/and prolonged office work in hot and humid environments. Regarding the ergonomic problems brought by the hybrid PCG, they were not evident in this study due to the nature of the simulated work (i.e., light office work) [31]. However, for other office tasks such as packing and lifting with large ranges of motions, ergonomic problems must be taken into consideration. In view of this, wear trials should be performed to evaluate the ergonomic problems in PCGs for various types of office work.

Lastly, some limitations should be acknowledged. Only healthy young male university students were recruited in this study to represent the office workers, which may restrict the finding to other populations such as females, the elder, and the disabled. Females have different physiological and perceptual responses as well as clothing preference from men in hot environments [59]. They usually have greater body fat burden, less muscle mass and smaller circulating blood volumes that were benefit for storing body heat, and thus were more susceptible to a given imposed heat stress (i.e., higher heart rate and core temperature in the heat) [59]. Moreover, more dissatisfaction with high temperatures was discovered among females than males in field studies [60]. For the elder, they normally have fragile cardiovascular systems, vestigial temperature perception function, and worse sweating and body temperature regulation systems, and thus were more susceptible to heat stress, and experienced more severe body heat strain in hot conditions [61]. Viewing this, the aforementioned two groups were of more needing for the personal temperature control compared to young men in hot indoor environments [60]. These may indicate the usability of the PCG to the two groups in hot indoor conditions. However, besides the usability, aesthetic appeal serves as another factor affecting the wearability of clothing for both males and females, especially for females [61]. Considering this, improved pattern design of the PCG will be conducted to enhance its aesthetic appeal. Besides, the relative importance of the two factors (i.e., usability and aesthetic appeal) will be investigated for the two sex groups in hot indoor, and the wearability of the PCG could be assessed.

Combing together, in future studies, large-scale wear trials (involve both two genders, more subjects and populations with wide age distributions and fitness states) are required to examine the actual effectiveness of the PCG (involving usability and aesthetic assessment) while doing office field daily work in various hot indoor conditions.

5. Conclusions

In this paper, we examined the effectiveness of a new hybrid PCG (combined PCM cooling and air cooling) in improving indoor thermal comfort of office workers while doing light office work in a hot and moderate humid environment. It was found that the hybrid PCG could bring improved perceptual sensations for the whole-, upper-, and lower-body. Moreover, it also provided some benefits for the thermoregulatory system. The findings of this study might be important for office workers or the public who live indoors with no access to air conditioning systems during either hot summer or severe heat wave incidents, or help to save energy by elevating temperature set-points of HVAC systems. Future field studies should be conducted to fully evaluate the actual effectiveness of the PCG in improving thermal comfort of office workers before putting the hybrid PCG into use.

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