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Research Article

Novel Design of a Personal Liquid Cooling Vest for Improving the Thermal Comfort of Pilots Working in Hot Environments

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Wearing a liquid cooling garment (LCG) that offers near-zone cooling improves the thermal comfort of pilots working in hot environments. Four LCG samples with different arrangements of tubes for distributing liquid were developed. Based on the analysis of the overall and local cooling efficiency of the four LCG samples using manikin tests, another novel LCG with a horizontal-vertical combined tube was proposed to achieve optimal cooling performance. Human trials were conducted to check the novel LCG for improving the thermal comfort of pilots in a hot indoor environment (40°C, 40% RH). The mean skin temperature of the subjects wearing the novel LCG was reduced by 1.9°C in the 120-minute-duration flying simulation work compared to the no-cooling scenario, and the greatest decrease in skin temperature (i.e., 5.7°C) was exhibited at the back waist. The thermal sensation at the upper body was improved to nearly neutral, and the heat stress level was reduced from moderate to slightly. The findings provide a guideline for designing personal LCG, thus benefiting the comfort and safety of pilots in hot cockpits.

1. Introduction

Combat aircraft pilots need to work in hot environments either at high altitudes or on the ground [1]. They are very likely to suffer from heat strain during work. This will detract their attention, decrease their working efficiency, and even influence their health and safety [2]. Therefore, artificially creating a moderate thermal environment for them is of great importance. Normally, there is an environmental control system (ECS) on the combat aircraft to adjust the temperature in the cockpit. However, the performance of ECS is not satisfying in hot seasons and when flying at high speed, causing a lot of heat due to friction with the atmosphere. Therefore, a personal cooling system (PCS), which has a much lower energy cost and can effectively adjust the microenvironment around the human body, is a useful supplement [3–5].

PCS is always attached to clothing ensembles or chairs to have good contact with the human body. Depending on the cooling medium, the commonly used cooling technology includes air cooling, liquid cooling, and phase change material (PCM) cooling [6]. Air cooling, which forms air ventilation in the microenvironment underneath clothing, is great in taking away heat from the human body through thermal convection and evaporation [5, 7]. Liquid cooling, which normally uses water, overwhelms air cooling in terms of the greater heat conductivity and thermal capacity of water than air. Also, air cooling is affected by the surrounding environment a lot. It will accelerate the heat gain of the human body in hot environments by promoting convective heat exchange with the surroundings. Although liquid cooling has a pronounced cooling efficiency, it is always accompanied by a complex configuration of tubes used for distributing liquid, cooling machines and pumps.

PCM, such as paraffin and polyethylene glycol, would adjust the temperature of the microenvironment around human skin [8]. However, it suffers from a short cooling duration and a nonadjustable cooling temperature (common range of 20–40°C) [9]. The choice of the cooling medium for pilots is affected not only by cooling efficiency but also by the flexibility of attaching the technology to pilots. In addition, the PCS should not pose a negative influence on the daily work of pilots. Considering that pilots are always sitting in the cockpit, their position is generally fixed. Liquid cooling technology, which is not portable but has good cooling efficiency, is suitable for pilots sitting in the cockpit at a high temperature. Therefore, a liquid cooling garment (LCG) has been developed and used in the aerospace industry since the 1960s [10]. It has been proven to effectively reduce the heat stress of pilots [11–13].

The cooling efficiency of LCG is affected by many factors, including the liquid temperature, flow rate of the liquid, distribution of tubes, and dimension and loops of tubes [14]. Theoretically, a lower temperature of the liquid, which results in a greater temperature gradient between the human skin and the cooling liquid, will cause more conductive heat exchange and better cooling efficiency. However, cooling liquid may induce cold sensation and thermal discomfort for the wearer. Therefore, there should be a balance between cooling efficiency and thermal comfort in terms of the liquid temperature. Recently, an active liquid cooling system adjusting the temperature of the liquid automatically according to the temperature of the microclimate between the human body and the clothing was proposed [7]. This has alleviated possible thermal discomfort caused by cold liquid. Regarding the arrangement of tubes, Niu et al. [15] found that a horizontal distribution of tubes has better cooling power than a vertical distribution. Additionally, the style of the garment and the exact position for attaching the tubes are influential for the final cooling efficiency provided for the human body. The most appropriate body parts for attaching the tubes were not discussed yet. It is known that having the tubes covering the whole body would result in better overall cooling performance than having the tubes covering only the upper body [16]. However, this is inappropriate for pilots who want their legs to be flexible during driving. According to the studies by Zhang et al. [17, 18], the local thermal sensation at the chest, back, and pelvis has the main effect on the overall thermal sensation of the body in warm/hot environments. This may provide guidelines for the design of LCG for pilots. Till now, there is still a lack of systematic studies on the factors affecting the cooling efficiency of LCG. The optimized design with prominent cooling efficiency still requires further investigation.

This study is aimed at proposing a prototype of LCG with prominent cooling efficiency for pilots. Factors influencing the cooling efficiency, including the liquid temperature, arrangement of tubes, and dimension of tubes, were systematically explored based on manikin tests. Human trials were also conducted to examine the effect of the proposed LCG on improving the thermal comfort of pilots working in hot environments.

2. Materials and Methods

2.1. Samples. Five tight-fit vests were designed and produced according to the dimensions of the Chinese male pilot population. They were originally the same size (170/92Y). Tubes made of silica were then fixed on the inner side of the five vests separately. They are different in the dimension and arrangement mode, resulting in five prototypes of LCG (S1–S5). The details of each LCG sample are listed in Table 1, and the pictures of the LCG samples (view of the inner side) are presented in Figure 1. The liquid (water in the current study) was cooled and distributed at a constant flow rate of 2 L/min for all the samples. The tubes were vertically distributed over the inner surface of S4 but horizontally distributed over S1–S3. The tube of S3 has a smaller diameter than that of S1, S2, and S4. Each single loop of the tube is parallel to each other for S1 but not for S2–S4. S5 is a combination between S4 and S3. Such a design of S5 was based on the good cooling efficiency of S4 for the front and that of S3 for the back of the torso. This will be presented later according to the results of manikin tests.

The properties of the fabric used for making the vests are given in Table 2. The fabric is weft-knitted jersey stitched and has good elasticity. This allows close contact between the samples and the human body, thus providing good cooling efficiency.

2.2. Manikin Tests. Manikin tests were performed to compare the cooling efficiency between S1 and S4 and determine the optimal arrangement of tubes. A 34-zone sweating thermal manikin Newton (Figure 2(a)) was applied. The tests were conducted in a climatic chamber according to ASTM F2371-2016. The air temperature was controlled at 35 ± 0.5 °C, the air velocity was 0.2 ± 0.1 m/s, and the relative humidity was 40% ± 5%. The sweat rate was set at 800 mL/(hr·m^2) to have the surface of the manikin fully wet during the whole test. The surface temperature of the manikin was 35 ± 0.1°C. The temperature of the liquid distributed into the tubes was 12°C, 16°C, and 20°C, respectively.

Two groups of tests were conducted for each LCG sample. A baseline test was conducted with the liquid cooling function off. The power input of the manikin was recorded every minute during the test till it was stabilized for at least 30 minutes. Then, the other cooling performance test was conducted with the liquid cooling function on. The power input of the manikin was recorded every minute until it was stabilized for at least 30 minutes. Each LCG sample was tested at least three times to have any of the tests vary within 10% from the average of the three.

2.3. Human Trial Tests

2.3.1. Subjects and Clothing Ensembles. Eight active and healthy male volunteers participated in the human trial tests. The detailed information was as follows: age: 22–24; height: 1.70 ± 0.03 m; body mass: 65.4 ± 4.2 kg; body mass index: 22.4 ± 1.2 kg/m^2; chest girth: 88.4 ± 3.6 cm; and waist girth: 79.5 ± 2.1 cm. Each volunteer participated in the test twice. For the no-cooling case, a standard summer pilot clothing ensemble was used, including a short-sleeved shirt and a coverall outfit (Figure 2(c)). For the cooling case, a liquid cooling vest (S5) was dressed between the short-sleeved shirt and the coverall outfit. The volunteers participated in the two tests in a random sequence. All the participants were

Table 1: Details of five liquid cooling vest samples.

Sample no.	Direction of the tube	Inner × outer diameter of the tube (mm)	Relation between adjacent loops	Maximum interval between adjacent loops (mm)	Length of the tube (mm)
S1	H	4 × 6	Parallel	45	9000
S2	H	4 × 6	Not parallel	45	13000
S3	H	3 × 5	Not parallel	40	15000
S4	V	4 × 6	Not parallel	45	13000
S5	V/H (front/ back)	4 × 6 (front) 3 × 5 (back)	Not parallel (front) Not parallel (back)	45 (front) 40 (back)	14000

Note: "H" means horizontal, and "V" means vertical.

accepted for this experiment, and informed consent was obtained from all individual participants included in the study.

2.3.2. Measurements. The local skin temperatures at twelve sites (forehead, upper arm, lower arm, abdomen, hand, thigh, calf, chest, back waist, back, neck, and foot; Figure 3), core temperature, body mass, and heart rate were recorded during the whole test. The sensors and devices used for measurements are listed in Table 3. The thermocouples were attached to the skin surface tightly using micropore medical tape. In addition, local thermal sensation, thermal comfort, and wet sensation were asked every 10 min during the test. The rating scales (Table 4) were designed according to ISO 10551.

2.3.3. Test Procedure. The subjects were required to take the core temperature pill at least three hours before the test. Devices and sensors listed in Table 3 were attached to the subjects by the same operator. The operator helped the subjects put on the clothing ensemble. Then, the subjects walked into the climatic chamber and sat there for two hours, simulating the driving work of the pilot in the cockpit. Once the subjects entered the chamber and sat down, the LCG (S5) (if there is one) was connected to the chiller placed next to the chair. The temperature of the liquid was set to 12°C. The climatic chamber was set to 40 ± 0.5°C, 40 ± 5% RH, and 0.2 ± 0.1 m/s to simulate the environmental conditions in the cockpit. All the tests were conducted at the same time of day. The operators could stop the experiment at any point if the volunteers felt terrible or their heart rate was found to be beyond 160 bpm.

2.4. Data and Statistics. The cooling efficiency (q_c) of the LCG samples based on the manikin tests is calculated according to Equation (1). A greater q_c indicates better cooling efficiency.

$$q_c = \sum_{i=1}^{n} \Delta q_i * \alpha_i, \quad (1)$$

$$\Delta q_i = \frac{(H_{c,i} - H_{b,i})}{S_i}, \quad (2)$$

where q_c is the cooling efficiency of a LCG, W/m^2; Δq_i is the local cooling efficiency of segment i, W/m^2; α_i is the weight ratio of the surface area of segment i of the manikin; n is the number of covered body segments of the manikin (i.e., upper chest, shoulder, chest, middle back, waist, and lower back), equaling 6; $H_{c,i}$ is the power input of segment i of the manikin as the liquid cooling function is turned on, W; $H_{b,i}$ is the power input of segment i of the manikin as the liquid cooling function is turned off, W; and S_i is the surface area of segment i, m^2.

The mean skin temperature (Equation (3)) of the subjects from the human tests was calculated according to the seven-point method proposed by Hardy and DuBois. Body temperature (Equation (4)) was calculated based on core temperature and mean skin temperature.

$$\begin{aligned} T_{\mathrm{m,sk}} = {} & 0.07 * T_{\mathrm{forehead}} + 0.14 * T_{\mathrm{lower\,arm}} + 0.05 * T_{\mathrm{hand}} \\ & + 0.07 * T_{\mathrm{foot}} + 0.13 * T_{\mathrm{calf}} + 0.19 * T_{\mathrm{thigh}} \\ & + 0.35 * T_{\mathrm{abdomen}}, \end{aligned} \quad (3)$$

$$T_b = 0.8 * T_{re} + 0.2 * T_{\mathrm{m,sk}}, \quad (4)$$

where $T_{\mathrm{m,sk}}$ is the mean skin temperature, °C; T_{forehead}, $T_{\mathrm{lower\,arm}}$, T_{hand}, T_{foot}, T_{calf}, T_{thigh}, and T_{abdomen} are the skin temperature of the forehead, lower arm, hand, foot, calf, thigh, and abdomen, respectively, °C; T_b is the body temperature, °C; and T_{re} is the core temperature, °C.

The comprehensive heat stress index (CHSI, Equation (5)) [19] was calculated based on heat storage, the increase in body temperature, the sweat rate, and the increase in the heart rate.

$$\mathrm{CHSI} = 0.01 * \Delta P + \Delta T_b + 0.1 \Delta W + S, \quad (5)$$

$$\triangle W = W_{nb} - W_{na}, \quad (6)$$

$$S = 3.486 * T_b, \quad (7)$$

where $\triangle P$ is the increase in the heart rate, beat/min; ΔW is the sweat rate of the human body, g/min; W_{nb} is the weight of the nude body before the test and W_{na} is the weight of the nude body after the test, kg; S is the heat storage of the human body, kJ/kg; and 3.486 is the heat capacity of the body tissue, kJ/(kg°C).

One-way ANOVA was performed using IBM SPSS Statistics version 17.0 to check the significance of the difference (significance level is 0.05) in cooling efficiency, local skin temperature, mean skin temperature, core temperature, and CHSI between the cooling and no-cooling cases. Besides, a paired sample t-test was used to check the significance of the difference in the sweat rate between the two cases.

(a) S1

(b) S2

(c) S3

(d) S4

(e) S5

Figure 1: Five samples of the liquid cooling vest different in the dimension and arrangement of tubes (view of the inner side).

Table 2: Properties of the fabric for the vest.

Structure	Special processing	Moisture permeability ($L/m^2 \cdot d$)	Mass ($g \cdot m^{-2}$)	Thickness (mm)	Elastic recovery rate
Weft-knitted jersey stitch	One-sided sanding	2211.95	220	0.8	92%

Figure 2: (a) Thermal manikin Newton. (b) Tested LCG on Newton (only segments 13, 14, 15, 16, 17, and 18 are covered by the LCG). (c) Coverall outfit for pilots.

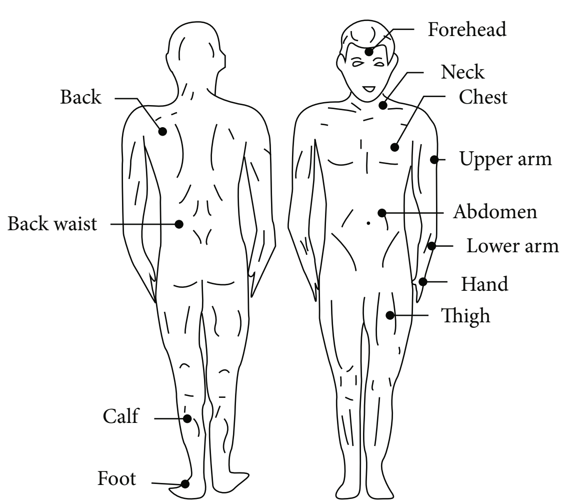

Figure 3: Measurement sites for local skin temperatures.

3. Results

3.1. Cooling Efficiency of the LCG Samples

3.1.1. Overall Cooling Efficiency. Figure 4 presents the overall cooling efficiency of the five LCG samples for the manikin (average cooling efficiency for all the body segments). The significance of the difference was checked within S1–S4 and S3–S5 separately. There is a significant ($p < 0.05$) difference between S1 and S2 at the three liquid temperatures. S3 and S5 present greater cooling power at each temperature than S4, and S5 shows a significant difference from S4 at temperatures of 20°C and 16°C.

3.1.2. Local Cooling Efficiency. Figure 5 gives the cooling efficiency of the samples for individual body segments at a liquid temperature of 12°C. By comparing the local cooling efficiency between S1 and S4, there is a significant difference between S1 and S2 at the chest, shoulder, abdomen, and back waist segments and between S2 and S4 at the back

Table 3: Sensors and devices used for collecting objective data.

Objective data	Sensor/device	Brand and type	Accuracy	Acquisition frequency
Core temperature	Core temperature pill	e-pill HT150001	0.01°C	30 s
Skin temperature	Thermocouple	MSR 325	0.01°C	60 s
Heart rate	Heart rate belt	Polar H10	0.1 bpm	30 s
Body mass	Weighing scale	Mettler Toledo® ICS439	0.0001 kg	Before and after the test

Table 4: Subjective rating scales.

Rating	Thermal sensation	Thermal comfort	Wettedness
-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	—	—

and back waist segments. Significant differences were also found between S3 and S5 at the chest and between S4 and S5 at the back and back waist.

3.2. Thermal Responses of Human Subjects

3.2.1. Mean Skin Temperature and Core Temperature. The transient mean skin temperature and core temperature of the subjects are shown in Figure 6. For the mean skin temperature, it is almost the same between the cooling and no-cooling cases in the first five minutes. Then, there appears to be a significant ($p < 0.05$) difference during 30–45 min, and the difference becomes even more significant ($p < 0.01$) since the 45th min. For the core temperature, it shows a very small change, and there is no significant ($p > 0.05$) difference between the cooling and no-cooling cases during the whole test.

3.2.2. Local Skin Temperature. Figure 7 presents the transient local skin temperature of the torso segments, including the chest, abdomen, back, and back waist, during the whole test. The local skin temperatures were lower when equipped with a cooling vest compared with a no-cooling vest. Generally, the difference in the local skin temperature between the two cases becomes significant since the 10th~15th minute.

Local skin temperatures of the other segments are presented in Figure 8. No significant difference was found between the cooling and no-cooling cases, except at the neck, exhibiting a significant ($p < 0.01$) difference since the 10th minute.

3.2.3. Heart Rate and Comprehensive Heat Stress Index (CHSI). Figure 9 shows the heart rate of the subjects during the whole test. It slowly increased, and that in the no-cooling scenario was higher since the 30th min, but no significant difference was found between the two cases.

The CHSI of the subjects in the cooling case was 1.3 ± 0.3, and it was significantly ($p < 0.05$) lower than that in the no-cooling case, i.e., 2.6 ± 0.1.

3.2.4. Subjective Sensation. Subjective thermal sensation ratings during the test are given in Figure 10. A significant ($p < 0.05$) difference in the thermal sensation at the upper body was detected since the 10th minute. This difference became even more significant ($p < 0.01$) during 40–120 minutes. With regard to the lower body, the difference between the cooling and no-cooling cases is not obvious. However, the thermal sensation rating of the whole body was significantly ($p < 0.05$) lower for the cooling case when compared to the no-cooling case since the 30th min.

Figure 11 gives the subjective thermal comfort ratings during the test. The thermal comfort ratings at the upper body with cooling vests were significantly ($p < 0.05$) greater than those without cooling vests during 30–80 minutes. The difference between the lower body and the whole body is insignificant.

Figure 12 presents the wet sensation ratings of the subjects during the test. A significant ($p < 0.05$) difference in the wet sensation at the upper body between the cooling and no-cooling cases was detected since the 20th minute. However, there was no significant difference in the wet sensation at the lower body between the two cases during the whole test. As for the whole body, a significant difference was observed at the 10th minute and between 30 and 50 minutes.

4. Discussion

4.1. Effect of Tube Arrangement on LCG Cooling Efficiency

4.1.1. Overall Cooling Efficiency. The cooling efficiency of samples 1–4 follows the sequence of S1<S4<S2<S3. By comparing S4 with S2, it reveals that a horizontal layout of tubes would take away more heat from the whole human body than a vertical layout. This is consistent with the finding from the study by Niu et al. [15]. However, due to a different way of presenting cooling efficiency (a drop in the temperature at the manikin surface in the study by Niu et al.), a direct comparison between Niu et al.'s and the current study is not possible here. As for S1, S2, and S3, they all have a horizontal layout of tubes. The differences among them include the relation between adjacent tube loops and the diameter of the tube, which finally result in the difference in the coverage area of the human body by the tubes. The greater cooling

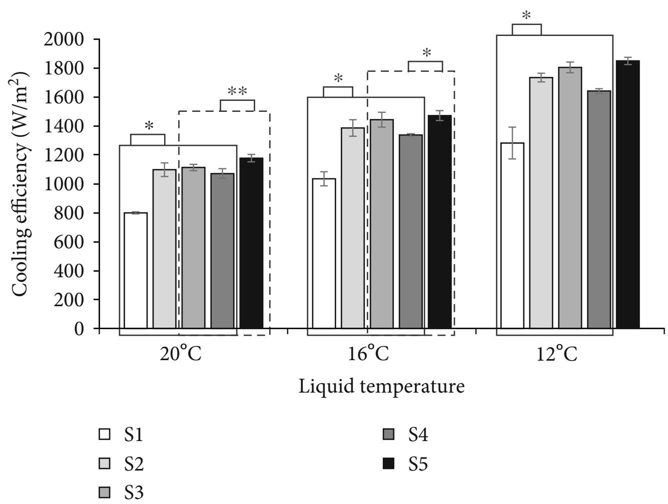

FIGURE 4: Overall cooling efficiency of LCG samples 1–5 with different liquid temperatures (∗ indicates $p < 0.05$, and ∗∗ indicates $p < 0.01$).

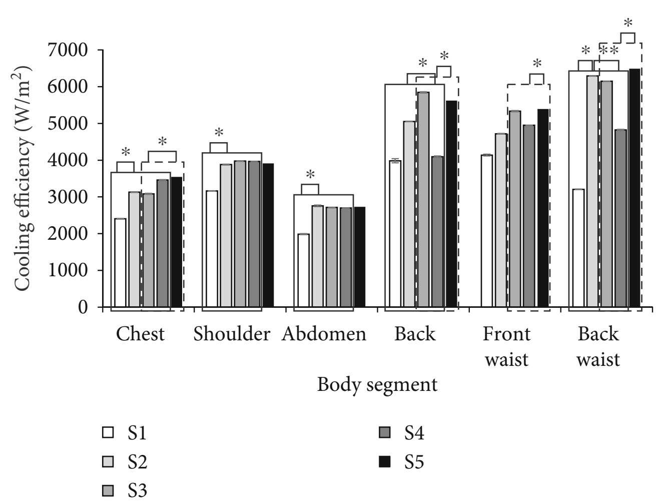

FIGURE 5: Local cooling efficiency of LCG samples 1–5 at a liquid temperature of 12°C (∗ indicates $p < 0.05$, and ∗∗ indicates $p < 0.01$).

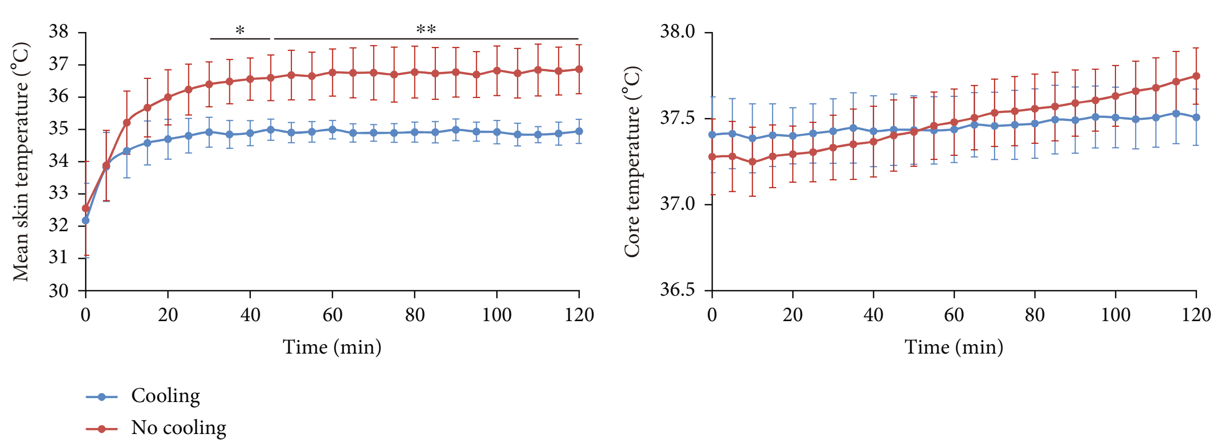

FIGURE 6: Mean skin temperature and core temperature of the subjects during the human test (∗ indicates $p < 0.05$, and ∗∗ indicates $p < 0.01$).

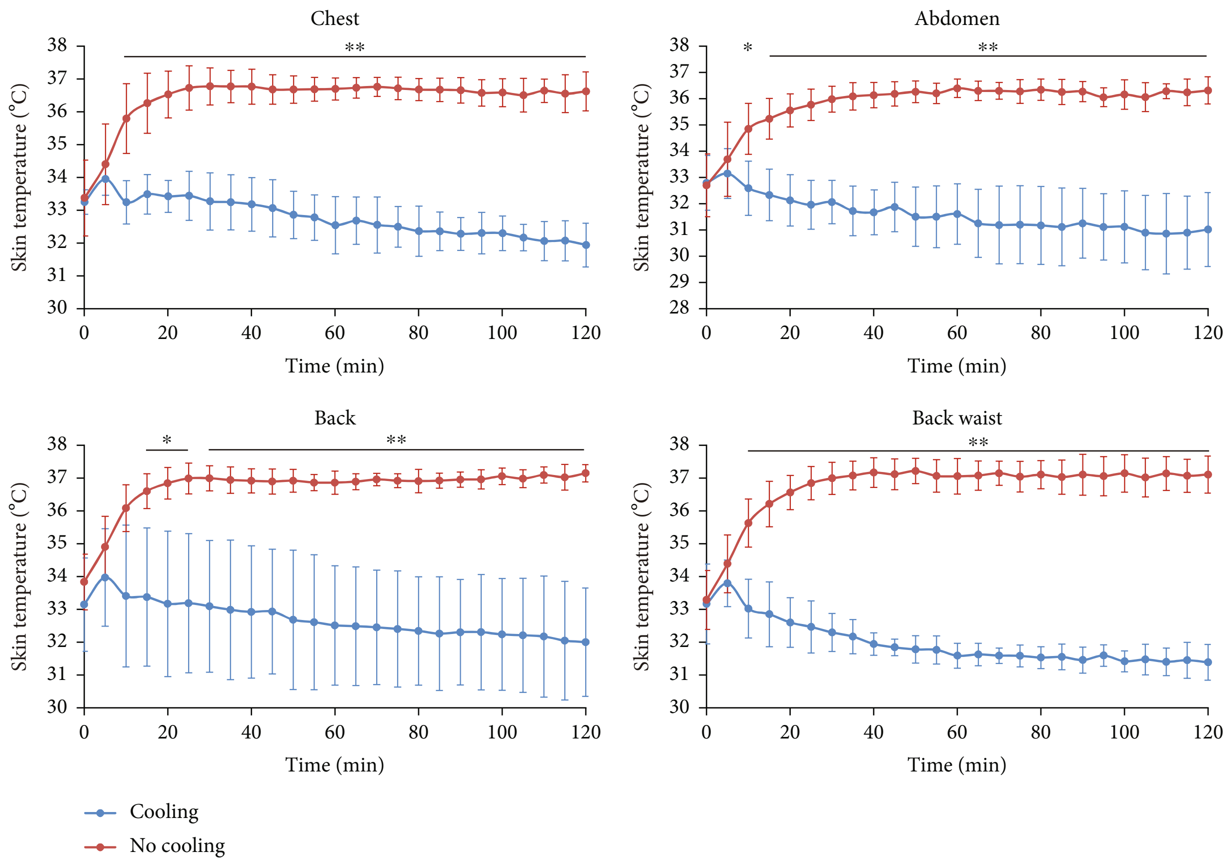

Figure 7: Local skin temperature of the torso segments during the human test (∗ indicates $p < 0.05$, and ∗∗ indicates $p < 0.01$).

efficiency of S3 than S2 and S1 is due to the longer tube and greater coverage area of the tube of S3.

A lower temperature of the liquid indicates a greater temperature gradient between the human body and the liquid. Thus, it is shown in Figure 4 that more heat is taken away with the decrease in the temperature of the liquid. This is also the reason for applying a liquid temperature of 12°C in the human tests. According to previous studies, the low temperature of the liquid would bring a cold sensation for the wearer. Also, a great temperature gradient between the liquid and the human skin (more than 20°C if the liquid temperature is 12°C) would result in a sudden drop in the skin temperature. It is likely to lead to cold stress for the wearer and thus may induce health problems [20, 21]. Therefore, whether the liquid temperature of 12°C is appropriate for real human subjects still needs investigation.

4.1.2. Local Cooling Efficiency. The influence of the tube arrangement mode on the local cooling efficiency varies between body segments. Generally, S3 shows better cooling efficiency than the other samples at most body segments, including the front waist, shoulder, and back. This is due to the denser arrangement of tubes for S3 than for S1 and S2, where the tubes are also arranged in a horizontal direction. For the rest of the body segments, S4 with a vertical arrangement direction of the tubes has shown better performance at the chest, where a neutral temperature is important for the health of a person since it is close to the heart. S2 performed better at the abdomen and back waist segments. However, the difference in the cooling efficiency between S2 and S4 at the abdomen, between S2 and S3 at the back waist, and between S3 and S4 at the front waist is insignificant. Therefore, a novel combination of the tube arrangement mode between S3 and S4, i.e., S5, was further proposed in the current study.

According to Figure 5, S5 presents better cooling performance than S4 at the front of the torso. Also, there is a significantly greater cooling efficiency at the chest for S5 than for S3. Although a horizontal layout of tubes was found to have better cooling performance than a vertical layout in the previous study [15], the vertical layout seems to show advantages at the chest area in the current study. This would be related with the interval between adjacent loops. The area of the chest is greater than that of any other body segment. Tubes at the chest area of S3 may be too dense (maximum interval is 40 mm) that the temperature of the water can be heated quickly as heat is gained from the chest area. However, with regard to S5, the tubes at the chest area are less dense (maximum interval is 40 mm). The increase in the temperature of the water can be slower to keep good cooling performance over the entire chest area for S5. Besides, different from the previous study [15], it can be told from Figure 1 that the specific vertical layout of tubes at the chest in this study fits with the curvature of the surface of the chest as well as the horizontal layout. With regard to the back of the torso, S5 significantly ($p < 0.05$) overwhelms S3 at the

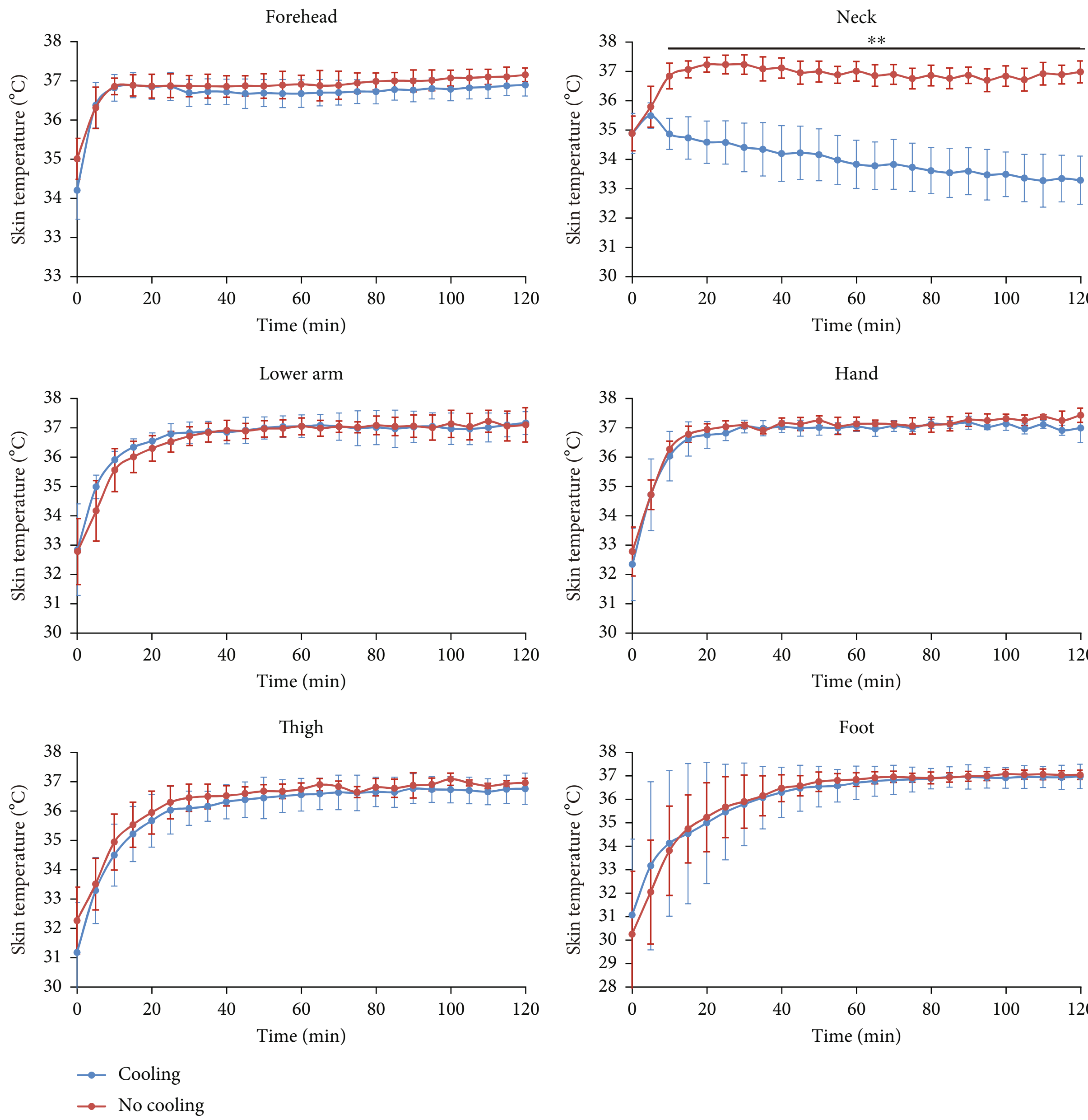

Figure 8: Local skin temperature of the limbs and extremities during the human test (** indicates $p < 0.01$).

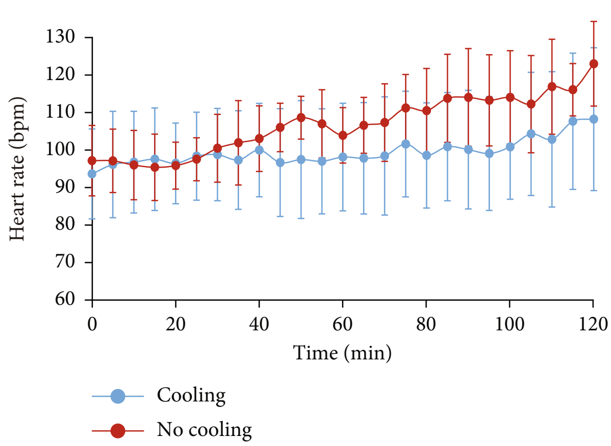

Figure 9: Heart rate of the subjects during the test.

back waist. For the shoulder and back segments, although the cooling efficiency of S5 is lower than that of S3, the difference between them is minor and statistically insignificant ($p > 0.05$). Thus, it could be concluded that S5 provides the best cooling performance among the five samples and it was selected for the real human tests to check its performance for people working in hot environments.

4.2. Effect of LCG on Human Thermal Responses

4.2.1. Overall Thermal Responses. As soon as the subjects shifted from a thermally neutral environment to the climatic chamber of 40°C, they started to gain heat from the environment instead of releasing heat to the environment. Therefore, there is a similar rapid growth of the mean skin

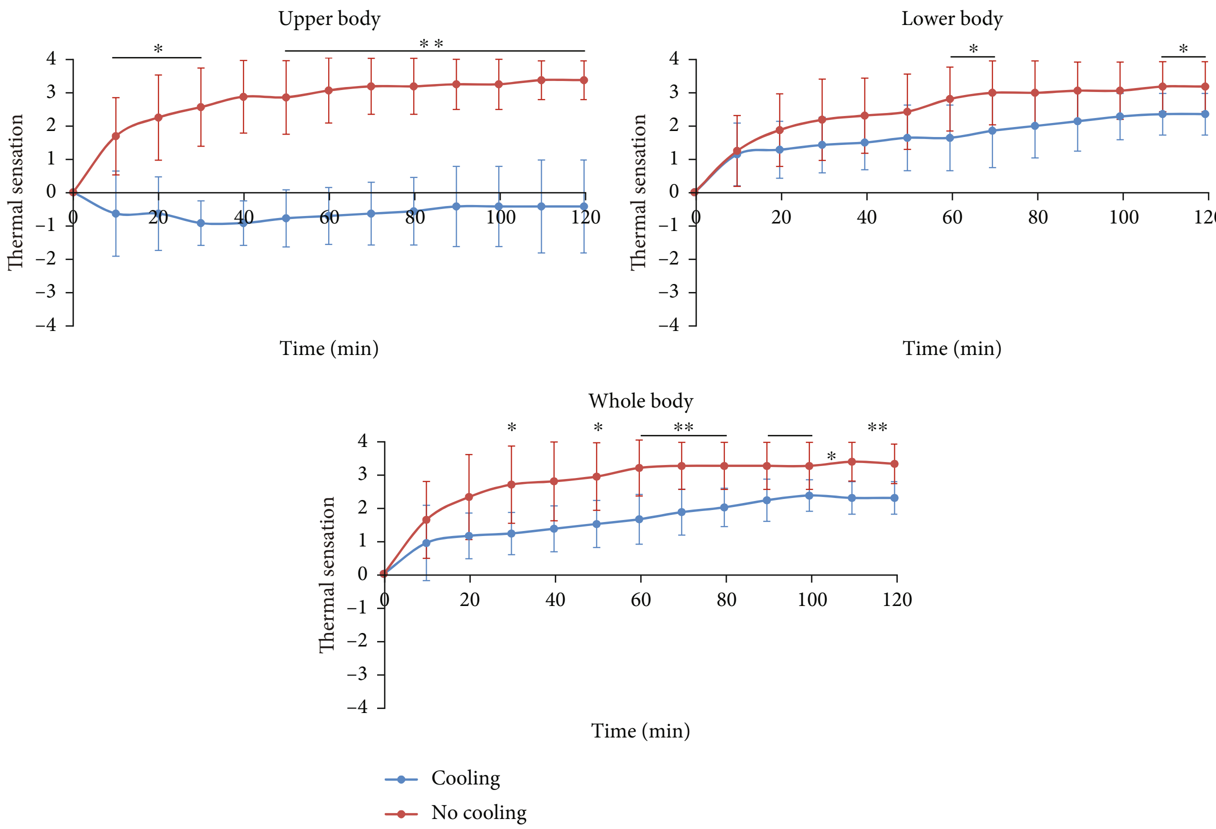

FIGURE 10: Subjective thermal sensation ratings during the test ($*$ indicates $p < 0.05$, and $**$ indicates $p < 0.01$).

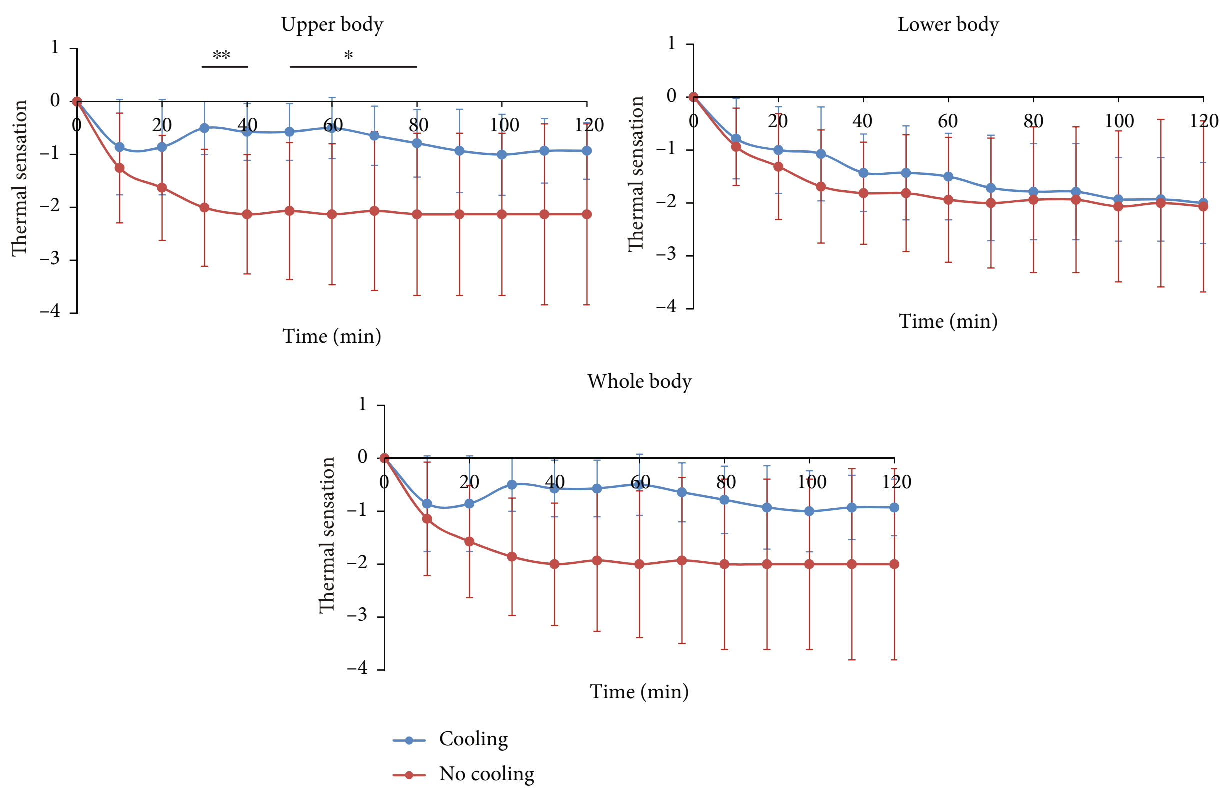

FIGURE 11: Subjective thermal comfort ratings during the test ($*$ indicates $p < 0.05$, and $**$ indicates $p < 0.01$).

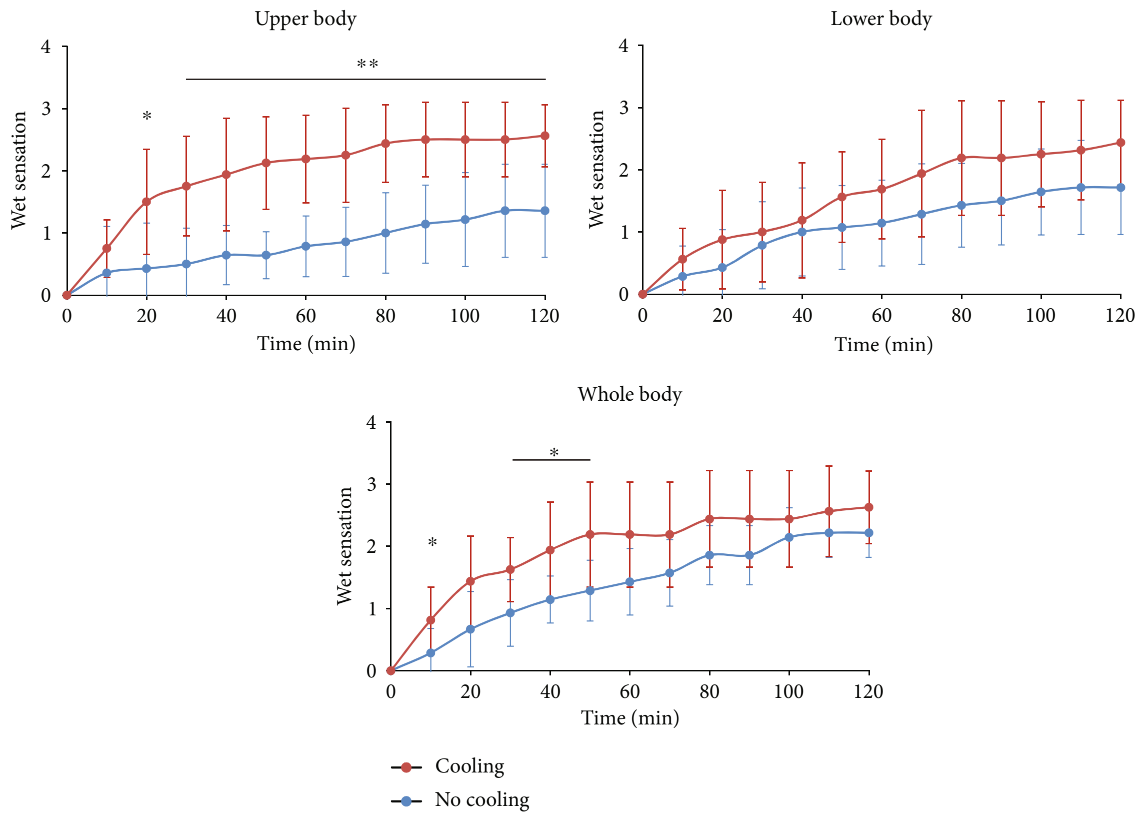

Figure 12: Subjective wet sensation ratings during the test ($*$ indicates $p < 0.05$, and $**$ indicates $p < 0.01$).

temperature (Figure 6) during the first 5 minutes for both the cooling and no-cooling cases. At this initial period, the function of the liquid cooling vest was not obvious since the influence of the sudden increase in the air temperature on human thermoregulation was stronger. Then, as the human body adapted to the environment, the function of the liquid cooling vest started to appear. The difference in the mean skin temperature between the two cases became significant ($p < 0.05$) after 10 minutes. After about 60 minutes of exposure, the mean skin temperature remained at a steady level and it was lower by 1.9°C for the cooling case compared with the no-cooling case. As it was previously reported by Koelblen et al. [22], a deviation of every 1.0°C in the mean skin temperature would cause a variation of 3 units and 1.1 units in the predicted vote for thermal sensation by the TS model by Zhang et al. [17, 18] and the DTS model by Fiala et al. [23], respectively. According to the subjective votes in the current study, the overall thermal sensation rating did decrease from 3.3 (hot) to 2.3 (warm). Besides, the vote for thermal comfort changed from -2 (uncomfortable) to -0.9 (slightly uncomfortable). This has proven an efficient function of the developed cooling vest S5 in improving overall thermal comfort for pilots.

Although there is no significant decrease in the final core temperature (Figure 6) of the human body for the cooling case compared with the no-cooling case, it was noted that the increase in the core temperature during the 120 min exposure was only 0.1°C for the cooling case while it was 0.5°C for the no-cooling case. This means that the application of cooling vests would help the core temperature remain at a relatively steady level. The heat taken away by the cooling liquid from the human body would almost balance the heat gained by the human body from the environment. Besides, the core temperature of the subjects wearing cooling vests was steady during the whole test, while it still had a tendency to go up at the end of the test without cooling vests. This means that the subjects are likely to suffer from a higher core temperature if they are exposed to the hot environment for a longer time without cooling vests. In addition, the increase in the heart rate (Figure 9) during the 120-minute exposure was 27% without cooling, while it was reduced to 16% with the application of cooling vests. As a result, the value of CHSI was reduced from 2.6 (moderate heat stress) to 1.3 (mild heat stress). This has proven an efficient function of the developed cooling vest S5 in reducing the possible heat stress of pilots working in hot environments.

4.2.2. Local Thermal Responses. Locally, an increase in the skin temperature was observed at all the body segments as soon as the subjects got inside the chamber for both the cooling and no-cooling cases as a result of the sudden growth of the environmental air temperature. For the cooling case, the skin temperature started to decrease at the neck, chest, back, abdomen, and back waist after 5 minutes till the end of the test. However, for the rest of the body segments (forehead, lower arm, hand, thigh, and foot), the skin temperature kept increasing and reached a steady level after the 60-minute exposure. In contrast, with regard to the no-cooling case, the local skin temperatures increased all the way and were maintained around a steady level after 60 minutes. According to the measurements, the function of the liquid cooling vest could be found at the torso (which was covered by the cooling vest) and neck segments, where an opposite variation trend of the skin temperature was obviously shown between the cooling and no-cooling cases. The flowing cooling liquid (12°C), as a medium between the environment and the human body, absorbed heat from both the environment (40°C) and the human skin (over 30°C). Therefore, the final skin temperature at the torso was lower by 4.7–5.7°C compared with the no-cooling case. For the final skin temperature at the neck, it was lower by 3.7°C with the application of cooling vests. Although there was no cooling liquid flowing over the surface of the neck, it is close to the covered areas of the body trunk, which would have an influence on the skin temperature at the neck. Besides, the neck arteries are close to the heart. The temperature regulation at the neck through blood circulation would be affected by that at the chest. Thus, the cooling function of the vest was also revealed at the neck besides at the body torso.

As a result of the lower local skin temperatures at the torso and neck, the thermal sensation at the upper body was close to "neutral" (rating of -0.4) by wearing the liquid cooling vest, while it was "hot" (rating of 3.4) without the vest. Besides, the wet sensation at the upper body also changed from wet (rating of 2.6) to slightly wet (rating of 1.4) by adding the liquid cooling vest, indicating that the subjects sweated less at the upper body with the cooling vest. Basically, with the addition of the cooling vest, the thermal comfort at the upper body was improved from uncomfortable (rating of -2.0) to slightly uncomfortable (rating of -0.9). However, as no cooling function was applied to the limbs, no significant difference in the skin temperature at the limbs was found between the cooling and no-cooling cases, and the subjective thermal sensation and thermal comfort were not improved at the lower body.

5. Conclusions

A denser arrangement of cooling liquid tubes would expect greater near-zone cooling efficiency for the human body. A vertical arrangement of tubes has better cooling efficiency than a horizontal arrangement for the front of the human torso, whereas it is the opposite for the back of the human torso. Therefore, a combination of the horizontal layout and vertical layout of tubes was proposed to have optimal cooling efficiency. The proposed combined cooling vest would significantly decrease the mean skin temperature of the wearers by 1.9°C while working in hot environments. The comprehensive heat stress level was reduced from moderate to slightly. Subjective thermal perceptions were all improved at the upper body, which was covered by the cooling vest. The lower the liquid temperature, the greater the cooling efficiency. The temperature of 12°C used in the current study is proper and suggested. The proposed novel prototype of LCG in the current study will work to improve the thermal comfort as well as the working performance of pilots in hot environments.

Data Availability

Data are available from the corresponding authors upon request of the readers.

Additional Points

Practical Implications. Personal cooling equipment providing a comfortable microenvironment around the human body is vastly applied in indoor environments. The designed LCG in the current study offers optimal cooling efficiency locally and globally for pilots. It would reduce the mean skin temperature of the wearer by 1.9°C. Also, the subjective thermal perception was significantly improved. Therefore, it is implied that the proposed design of LCG has the potential to be applied in cockpits for pilots with a much lower energy cost and better cooling performance than the macroenvironment control system.

Ethical Approval

Human tests conducted in the current study have been approved by the Ethics Committee of Soochow University.

Conflicts of Interest

The authors have no conflicts of interest to declare.

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