Use of a novel smart heating sleeping bag to improve wearers’ local thermal comfort in the feet

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Previous studies have revealed that wearers had low skin temperatures and cold and pain sensations in the feet, when using sleeping bags under defined comfort and limit temperatures. To improve wearers’ local thermal comfort in the feet, a novel heating sleeping bag (i.e., MARHT) was developed by embedding two heating pads into the traditional sleeping bag (i.e., MARCON) in this region. Seven female and seven male volunteers underwent two tests on different days. Each test lasted for three hours and was performed in a climate chamber with a setting temperature deduced from EN 13537 (2012) (for females: comfort temperature of $-0.4 \, ^\circ C$, and for males: the limit temperature of $-6.4 \, ^\circ C$). MARHT was found to be effective in maintaining the toe and feet temperatures within the thermoneutral range for both sex groups compared to the linearly decreased temperatures in MARCON during the 3-hour exposure. In addition, wearing MARHT elevated the toe blood flow significantly for most females and all males. Thermal and comfort sensations showed a large improvement in feet and a small to moderate improvement in the whole body for both sex groups in MARHT. It was concluded that MARHT is effective in improving local thermal comfort in the feet.

A sleeping bag is an essential textile product that is aimed at protecting people in cool or cold outdoor environments. They are widely used in field training, rescue and relief work and are also becoming common equipment in travelling and recreation for ordinary people1. Traditional sleeping bags are generally composed of an outer layer, an inner layer and the filling. Sleeping bags are often required to be marked with four labelled temperatures according to the EN 13537 (2012) standard2: maximum temperature, comfort temperature, limit temperature, and the extreme temperature. Of all these four labelled temperatures, comfort temperature and limit temperature are the two most important temperatures for users. Comfort temperature indicates the lower threshold temperature at which a standard woman could sleep for eight hours without cold feeling in a relaxed posture (i.e., lying on their back) under the standard condition. The limit temperature refers to the lower threshold temperature for a standard man sleeping in a curled up body posture for eight hours without feeling cold under the standard condition. Previous studies have shown that the comfort temperature and limit temperature were sometimes questioned by users and scientists3. This is because some manufacturers defined these two temperatures based on qualitative methods, such as customers’ feedback and assessments from bag’s thickness, weight and loftiness4.

Many models have been developed to compute the operating temperatures of the sleeping bag. For example, the EN 13537 (2012) model5, the KSU model6, Belding’s model7, Goldman’s model8, Holand’s model9, den Hartog’s model10, and the IREQ (Required Clothing Insulation) model10. However, all these models calculate the global comfort and limit temperatures, i.e., these models only considered the whole body thermal comfort. It seems that both the comfort temperature and the limit temperature defined by the models failed to take care of local thermal comfort in the feet. Lin et al.3 investigated the physiological and psychological responses of females and males in different sleeping bags under both the EN 13537 (2012) and the IREQ model defined temperatures. Although the mean skin temperature was within its thermal neutral range, almost all subjects had continuously dropping toe temperatures throughout the two-hour exposure. The temperature dropping in the toes has already caused a great sensation of cold and pain. It was thus concluded that such defined temperatures were unable to allow users to have an eight-hour comfortable sleep. Huang11 also observed continuously decreasing
was hypothesized that local thermal comfort could be improved by using the smart heating sleeping bag in cold outdoor environments.

Methods

Subjects. Seven female and seven male subjects voluntarily participated in this study. They were physically healthy and had no smoking habit. They also had limited experience in using sleeping bags. The average age, height, weight, body surface area and the body mass index of the females are 24.0 ± 1.4 yr., 160.9 ± 2.8 cm, 52.1 ± 4.9 kg, 1.53 ± 0.07 m² and 20.1 ± 1.6 kg/m², respectively, and those of males are 24.9 ± 1.7 yr., 172.8 ± 2.6 cm, 62.0 ± 3.5 kg, 1.74 ± 0.06 m² and 20.8 ± 0.9 kg/m², respectively. They were asked not to drink alcohol and do intensive exercises at least twenty-four hours before the test. Also, they were not allowed to drink tea or coffee at least two hours before each trial. This study was approved by the ethical committee of Soochow University and was strictly performed in agreement with legal requirements and international norms (Declaration of Helsinki, 1964). The research methods are in accordance with the approved guidelines. Subjects were informed about the purpose, the procedure and potential risks associated with the experiment. Each participant signed a written consent form prior to participation.

Sleeping bag. A mummy-shaped sleeping bag (code: MAR) was randomly selected from the market. Based on this sleeping bag, a novel smart sleeping bag was developed by embedding two electrical heating pads into MAR at the feet region. The heating pad was engineered by sandwiching a 2.25 m winding carbon heating wire (total electric resistance: 322 Ω) between two high-density polyester fabric layers (length × width × thickness: 38 cm × 38 cm × 0.159 cm). The total weight of two heating pads was 464 g. The heating pads were connected to a power supply and the heating power could be adjusted from 0 to 45 W. In this study, two levels of heating power was selected, 0 W (i.e., heating was turned off) and 20 W (i.e., close to medium heating power), corresponding to two testing scenarios written as MARCON and MARHT, respectively. MARCON represents the non-heating traditional sleeping bag, and MARHT is the smart heating sleeping bag to be examined in this study. The selection of a constant heating power (i.e., 20 W) was based on previous findings of our pilot study27, in which the heating power was stepwise adjusted from 0 to 45 W with 5 W increments. Both male and female subjects (i.e., 4 males and 4 females) rated thermoneutral when the power was set to 20 W during three-hour sleep time under the same environmental conditions as those used in this study.

The extremities of human body are more sensitive to cold exposure compared to other body regions because of the large specific surface area and the low local metabolic heat production in these regions. Skin temperature dropping normally appears in those regions initially, and results in the first sign of cold and pain sensations in those local regions. Besides the induced local thermal discomfort, the whole body thermal comfort was also found to be strongly related with the extremity temperatures. It is reasonable to speculate that heating the extremity, e.g., the feet region, could prevent the local skin temperature dropping, and thereby improve local thermal comfort of the human body.

In this study, a novel smart heating sleeping bag was developed by embedding two electrical heating pads into traditional sleeping bags at the feet region. It is anticipated that the smart heating sleeping bag is useful in such outdoor settings as camping sites and recreational facilities. The physiological responses and perceptual responses when using the traditional sleeping bag and newly developed smart heating bag were examined and compared. It was hypothesized that local thermal comfort could be improved by using the smart heating sleeping bag in cold outdoor environments.

Table 1. Characteristics of the sleeping bag tested. – not applicable.
Test conditions. For the manikin tests, the ambient temperature was set to $-2 \pm 0.5 \, ^\circ\text{C}$, the relative humidity was set to $80 \pm 5\%$ and the air velocity was controlled at $0.5 \pm 0.1 \, \text{m/s}$. All human trial tests were conducted in a climate chamber with different setting temperatures for females and males. For females, they were exposed to the air temperature of $-0.4 \, ^\circ\text{C}$ (i.e., the comfort temperature of MARCON) in both MARCON and MARHT, and for males, they were exposed to $-6.4 \, ^\circ\text{C}$ (i.e., the limit temperature) in the two sleeping bags (i.e., MARCON and MARHT). The air temperature fluctuations were controlled within $\pm 0.5 \, ^\circ\text{C}$ for both genders. The relative humidity and air velocity in the chamber were set as $80 \pm 5\%$ and $0.5 \pm 0.1 \, \text{m/s}$, respectively.

Test protocol. Each participant was asked to sleep in the smart heating bag (MARHT) and the traditional sleeping bag (MARCON) in a randomized and counter-balanced order. A total of 28 tests were performed (i.e., 14 participants times 2 tests). Each test was conducted at the night time and the same time of a night with an interval of at least 48 hours in between to eliminate the circadian variation impact. The participants were blinded to the sleeping bags to avoid prejudice. They were dressed with the same underwear and knee-length socks that were used in the manikin tests.

Upon arrival for the tests of the sleeping bag, the participants were asked to rest on a chair for 15–30 min at a room temperature of 20.0 $^\circ\text{C}$, and then instrumented. After the preparation, the participants entered the climatic chamber (where the test condition was set based on the assigned test scenario) and laid into the bag randomly assigned in a flat lying posture. This transition period (from the outside room to the chamber) normally took about 5 min. The sleeping bag was placed on an inflated mattress supported by a wooden table. The participants were asked to stay in the sleeping bags for a maximum of 3 hours. The test was terminated when any of the following criteria were met: i) the toe temperature dropped to 12.0 $^\circ\text{C}$; ii) the participant refused to continue; and iii) the 180 min testing was achieved. After the test, the participants came out of the chamber and they were asked to take off the clothing and the equipment.

Metabolic rate was measured continuously for 5 min with a cardiopulmonary tester at the 20th min of the test (MetaMax® 3B, Cortex Biophysik GmbH, Leipzig, Germany). Skin temperatures on eleven sites, namely, forehead, upper arm, forearm, chest, scalp, hand, finger, thigh, calf, left foot and the 4th toe, were measured by temperature sensors (MSR® 145B4, MSR Electronic GmbH, Seuzach, Switzerland). Blood flow of the 4th toe was measured using a Doppler-type laser flow meter (ALF 21R, Advance Co., Ltd, Tokyo, Japan). Heart rate was obtained via a Polar® chest strap and a heart rate watch (Polar Electro Oy, Kempele, Finland). The skin temperatures, the skin blood flow and the heart rate were logged at an interval of 30 s throughout the test.

Perceptual sensations of the participants in the hands and feet as well as the whole body were rated 15 min before the test, in the beginning of the test, at the 20th and the 180th min of the test (Fig. 1). Each rating of the perceptual sensations was explained to the participants in detail prior to the trial. Thermal sensation (TS) of “−4” corresponds to very cold, “−3” cold, “−2” cool, “−1” slightly cool, “0” neutral, “1” slightly warm, “2” warm, “3” hot, and “4” very hot. Comfort sensation (CS) of “−3” corresponds to very uncomfortable, “−2” uncomfortable, “−1” slightly uncomfortable, and “0” neutral. Skin wetness sensation (WS) of “−3” corresponds to very dry, “−2” dry, “−1” slightly dry, “0” neutral, “1” slightly wet, “2” wet and “3” very wet. The perceptual ratings were verbally reported by the participants at the time points mentioned above.

Calculations. The thermal insulation ($I_t$ in clo) of the sleeping bag was computed by the serial method defined by EN 13537, expressed as equation (1).

$$I_t = \frac{1}{0.155} \sum_{i=1}^{n} a_i \left( T_{sk,i} - T_a \right)$$

(1)

where, $A$ is the manikin surface area (i.e., 1.697 m$^2$); $n$ is the segment number, $n = 32$; $a_i$ is the surface area of the segment $i$, m$^2$; $H_{si}$ is the heat flux of the $i$ segment, W/m$^2$; $T_{sk,i}$ is the skin temperature of the segment $i$, °C; $T_a$ is the ambient air temperature, °C.

The mean skin temperature ($T_{sk}$) was calculated using the Gagge and Nishi’s equation (Gagge and Gonzalez, 2011), expressed as equation (2).

$$T_{sk} = 0.07 \left( T_{\text{forehead}} + T_{\text{upper arm}} + T_{\text{forearm}} \right) + 0.175 \left( T_{\text{chest}} + T_{\text{specula}} \right)$$

$$+ 0.057 T_{\text{hand}} + 0.19 T_{\text{thumb}} + 0.207 T_{\text{calf}}$$

(2)

Statistical analysis. Data were presented as mean ± standard deviation (SD). A two-way repeated measures ANOVA [Test scenarios (MARHT vs. MARCON)] × Time ([i.e., the 0th, 10th, 20th, 40th, 60th, 80th, 100th, 120th, 140th, 160th, and the 180th min]) was performed using SPSSv20 (IBM Inc., Armonk, NY) to assess the differences in the physiological responses between the two test conditions, time effect and the interaction effect between conditions and the time. When the Mauchly’s Test of Sphericity was violated, the Greenhouse-Geisser correction was employed as statistical significance. When the repeated measures showed a significant effect, a paired sample t-test for was conducted at each time point. The significance levels were $p < 0.05$ (marked * on the graphs) and $< 0.01$ (**) in all tests. The bias-corrected hedge’s effect sizes (standardized mean difference) were calculated for evaluating the differences in perceptual responses at the two time points (the 20th min and the 180th min) between the two conditions and also between the two points (Hedges et al., 1985). The effect sizes (EFSs) were obtained using the Review Manager V.5.2.0 software, involving the input parameters of mean outcome, the standard deviation and the sample size. The magnitude of EFS was interpreted as: $0–0.19 =$ negligible effect, $0.20–0.49 =$ small effect, $0.50–0.79 =$ moderate effect and $>0.8 =$ large effect. Negative effects of MARHT, and time were displayed with a minus sign.
Results

Metabolic rate. All subjects finished the 180 min test. Metabolic rate was not significantly different between MAR\textsubscript{CON} and MAR\textsubscript{HT} for both females (i.e., 1.1 ± 0.1 METs in MAR\textsubscript{CON} and 1.2 ± 0.2 METs in MAR\textsubscript{HT}, p > 0.05) and males (i.e., 1.1 ± 0.2 METs in MAR\textsubscript{CON} and 1.1 ± 0.2 METs in MAR\textsubscript{HT}, p > 0.05).

The 4th toe and foot temperatures. Figure 1 presented the evolution curves of the $T_{\text{toe}}$ and $T_{\text{ft}}$ curves for females and males in MAR\textsubscript{CON} and MAR\textsubscript{HT}. Significantly higher $T_{\text{toe}}$ and $T_{\text{ft}}$ were detected for both females and males in MAR\textsubscript{HT} compared to MAR\textsubscript{CON} from the 5th min to the end of the test (p < 0.01). Linearly dropping $T_{\text{toe}}$ and $T_{\text{ft}}$ were detected for both females and males in MAR\textsubscript{CON} (main time effect, p < 0.01), while $T_{\text{toe}}$ and $T_{\text{ft}}$ significantly increased during the initial 20 min (main time effect, p < 0.01) and then remained stable in MAR\textsubscript{HT} throughout the remaining test duration. At the end of the test, $T_{\text{toe}}$ and $T_{\text{ft}}$ of females in MAR\textsubscript{CON} sank to 15.1 °C and 22.7 °C, respectively, and for males to 13.2 °C and 23.5 °C, respectively. Comparing the average $T_{\text{toe}}$ and $T_{\text{ft}}$ values in the stable stage (time range from the 20th min to the 180th min) for the two sex groups in MAR\textsubscript{HT}, $T_{\text{toe}}$ was higher for males (i.e., 30.7 ± 2.8 °C) than that for females (i.e., 28.9 ± 2.7 °C), though not significant (p > 0.1), while $T_{\text{ft}}$ was significantly higher on females (33.9 ± 1.0 °C) than that on males (i.e., 32.8 ± 1.4 °C) (p < 0.05).

The 4th toe blood flow. The evolution curves of the 4th toe blood flow (SkBF) for all the fourteen subjects in MAR\textsubscript{CON} and MAR\textsubscript{HT} were listed in Fig. 2. The average values of SkBF from the 20th min to the end of test were calculated for all the subjects (SkBF). SkBF decreased to near zero values with the exposure time for all the subjects in MAR\textsubscript{CON}. While SkBF values fluctuated at relatively higher values at different levels for the subjects (except for F1) in MAR\textsubscript{HT} (SkBF ranging from 1.2 to 4.6 ml/100g/min and 1.2 to 18.8 ml/100g/min for females and males, respectively) compared to those in MAR\textsubscript{CON} (SkBF ranging from 0.5 to 1.3 ml/100g/min and 0.6 to 2.1 ml/100g/min for females and males, respectively). It was also noted that the SkBF on five out of seven males (4.8 to 18.8 ml/100g/min) in MAR\textsubscript{HT} exhibited higher values compared to all females (1.2 to 4.6 ml/100g/min) in MAR\textsubscript{HT}.

Mean skin temperature and mean heart rate. The mean skin temperature ($T_{\text{sk}}$) in MAR\textsubscript{CON} and MAR\textsubscript{HT} significantly increased during the first 20 min (time main effect, p < 0.01) and then were kept stable throughout the whole test (Fig. 3). No significant difference was observed in $T_{\text{sk}}$ between MAR\textsubscript{CON} and MAR\textsubscript{HT} for both females and males (p > 0.1). The average $T_{\text{sk}}$ data in the stable stage for females (i.e., 33.0 ± 0.8 °C in MAR\textsubscript{CON} and 33.2 ± 0.9 °C in MAR\textsubscript{HT}) were close to those of males (i.e., 33.2 ± 0.6 °C in MAR\textsubscript{CON} and 33.3 ± 0.8 °C in MAR\textsubscript{HT}) (see Fig. 3, p > 0.1).
Figure 2. The evolution curves of the 4th toe blood flow for females and males. F1 to F7 means females numbered from 1 to 7, M1 to M7 means males numbered from 1 to 7.
Heart rate fluctuated with the testing time and no time main effect was observed ($p > 0.05$). No significant difference in heart rate was detected for females in MARHT compared to MARCON ($p > 0.1$). Heart rate was with similar average values for females in MARCON (i.e., 60.5 ± 7.8 beats/min) and MARHT (i.e., 63.1 ± 7.2 beats/min). However, significantly lower heart rate was observed on males in MARHT compared to those on males in MARCON at the 25th min, the 95th min and the 150th min of the test ($p < 0.05$) (Fig. 3). Besides, the average heart rate on males in MARHT (i.e., 59.0 ± 7.3 beats/min) was higher compared to that on male subjects in MARCON (i.e., 63.0 ± 7.6 beats/min) ($p = 0.052$) and the difference was approaching statistical significance. The average heart rate values between the two genders showed no significant difference in neither MARCON ($p > 0.1$) or MARHT ($p > 0.1$).

Perceptual responses. As listed in Table 2 and Table 3, all subjects stayed in a thermal neutral state (TS, CS and WS = 0) before and at the start of the cold exposure, as well as at the 20th min of the exposure except for TS of females in MARCON. Perceptual responses deviated from zero in different levels at the end of cold exposure. Comparing the perceptual data at the end of the test with those at the start, TS and CS in the feet are subjected to the most obvious declines for both females and males in MARCON (negative large EFSs). The evolution of the TS and CS in the hand for the two sex groups in MARCON was not apparent (negative small EFSs). TS alterations in the whole body are moderate for females (negative moderate EFSs) and small for males in MARCON (negative small EFSs). CS alterations in the whole body are small for both genders in MARCON (negative small EFSs). Wetness sensation showed no change in the feet or in the whole body, and was small in the hand for the two genders in MARCON.

Concerning the perceptual data in the feet between MARCON and MARHT at the 180th min of the exposure, cool to cold sensations were detected for both females and males in MARCON, while slightly cool and slightly warm sensations were observed for them in MARHT respectively (MARHT vs. MARCON: large EFSs). Slightly uncomfortable to uncomfortable ratings were nominated by both genders in MARHT, while neutral comfort sensation was rated by them in MARHT (MARHT vs. MARCON: large EFSs). No skin wetness sensation was perceived by the participants for all the test conditions.

With respect to perceptual data in the hand, slightly cool sensations were detected for both females and males in MARCON, while slightly warm and neutral sensations were observed for females and males in MARHT, respectively (MARHT vs. MARCON: moderate EFSs). Slightly uncomfortable to uncomfortable ratings were nominated by both genders in MARCON, while neutral comfort sensation was rated by them in MARHT (MARHT vs. MARCON: large EFSs). Skin wetness sensations of slightly wet were perceived by the two sex groups in both MARCON and MARHT (MARHT vs. MARCON: negligible EFSs).

Figure 3. The evolution curves of the mean skin temperature and heart rate for females and males in MARCON and MARHT.
Table 2. Perceptual sensations of the seven female subjects in the two sleeping bag test scenarios.

| Time  | Perceptual responses | Feet | Hand | Whole body |
|-------|---------------------|------|------|------------|
|       |                     | −15 min | 0 min | 20 min | 180 min |
| TS    |                     | 0 ± 0 | 0 ± 0 | −0.21 ± 0.27 | −2.0 ± 1.04 d |
| MARCON | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| MARHT | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| CS    |                     | 0 ± 0 | 0 ± 0 | −0.07 ± 0.19 | −1.36 ± 1.03 d |
| MARCON | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| MARHT | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| WS    |                     | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| MARCON | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| MARHT | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |

As for the whole body, slightly cool sensation was perceived by both sex groups in MARCON, while slightly warm sensation and the neutral sensation were detected in MARHT (MARHT vs. MARCON: moderate EFSs for females and small EFSs for males), respectively. Slightly uncomfortable to uncomfortable ratings were nominated by both genders in MARCON, whereas neutral comfort sensations were rated in MARHT (MARHT vs. MARCON: moderate and small EFSs for females and males, respectively). No wetness sensation was detected.

Discussion

Sleeping bags serve as an important protective textile product for human body while sleeping under cool or cold outdoor environments. A sleeping bag should allow the wearers to sleep for four to eight hours without feeling cold under the bags’ operating temperatures. Even though the total duration of each trial in this study was 3 hours, the linearly decreasing toe (T toe) and foot temperatures (T b) (see Fig. 1) could cause pronounced cold sensations in the feet for both genders. Thus, our results have reconfirmed that the local region of the human body was inadequately protected while using the studied sleeping bag under the environmental temperatures defined by EN 13537 (2012). Lin et al. detected that T toe of females in a traditional sleeping bag decreased to 21.1 °C at the 20th min while exposed to EN 13537 defined comfort temperature (i.e., 3.8 °C). In this study, T toe of females decreased to 21.3 °C at the 120th min. However, Lin et al. observed no declination of T toe for males in MARCON under EN 13537 defined limit temperature (i.e., 11.2 °C and 2.1 °C). The discrepancy might be due to the lower...
in the cold microenvironment between foot and MAR CON, while the promoted SkBF values for the subjects in MARHT was attribute to vasodilatation of AV As in the warm microenvironment created by the MARHT. Individual on the ambient temperature of the extremities 18,19, which expressed vasoconstriction (to reduce heat loss) and heated socks was much greater than that in non-heated socks. In this study, greater skin blood flow at the 4th toe the effects of the heated and non-heated socks on the feet and discovered that the skin blood flow at the toes in action modes of AV As relied (i.e., small blood vessels that interconnect small veins with small arteries), which controlled 90% of the blood flow in MARHT than that in MARCON, was also observed on most subjects. The mechanism behind the toe blood flow Table 3. Perceptual sensations of the male subjects in the two sleeping bag test scenarios. 

| Time  | Perceptual responses | −15 min | 0 min | 20 min | 180 min |
|-------|----------------------|---------|-------|--------|---------|
| Feet  | TS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | −2.40 ± 0.48 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0.07 ± 0.19  | 0.71 ± 0.49 |adro |
|       | CS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | −1.50 ± 0.5  |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       | WS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
| Hand  | TS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0.19| −0.43 ± 0.87 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       | CS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | −0.43 ± 0.35 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       | WS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0.07 ± 0.19 | 0.43 ± 0.45 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
| Whole body | TS       | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | −0.43 ± 0.45 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       | CS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | −0.43 ± 0.35 |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       | WS                   | MARCON  | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |
|       |                     | MARHT   | 0 ± 0 | 0 ± 0  | 0 ± 0   | 0 ± 0        |adro |

exposure temperature (i.e., −6.8 °C) adopted in this study, reconfirming that the human body extremity was more affected by environmental temperatures compared to other body parts.

Further, it is evident that the MARHT could well maintain \( T_{feet} \) and \( T_b \) of both females (i.e., \( T_{feet}: 28.9 \pm 2.7 °C \) and \( T_b: 33.9 \pm 1.0 °C \)) and males (i.e., \( T_{feet}: 30.7 \pm 2.8 °C \) and \( T_b: 32.8 \pm 1.4 °C \)) in a thermoneutral range (i.e., 25.0–34.0 °C)13. The heating pads had two positive effects in preventing the toe and foot temperature dropping, i.e., creating a warm microclimate and raising the local apparent thermal insulation at the feet region due to the added heating layer. As no investigation was conducted on smart heating sleeping bags, we could only retrieve literature regarding the effect of heated footwear on the local skin temperature. van Someren et al.15 narrated that heating the feet would keep the feet temperature the same as the rest of the body and suggested that the feet play a significant role in the whole body thermoregulatory response to cold. Isik16 also found heating the feet could provide stable skin temperature in the region, but it exerted no effect on the other parts of the body.

Supplying heat to the feet region could promote the local skin blood flow (i.e., SkBF). House et al.17 compared the effects of the heated and non-heated socks on the feet and discovered that the skin blood flow at the toes in heated socks was much greater than that in non-heated socks. In this study, greater skin blood flow at the 4th toe in MARHT than that in MARCON, was also observed on most subjects. The mechanism behind the toe blood flow was consistently pinpointed by researchers to depend on the action modes of arteriovenous anastomoses (AVAs) (i.e., small blood vessels that interconnect small veins with small arteries), which controlled 90% of the blood flow in the local regions18, and was abundantly presented in the extremities18,19,20. The action modes of AVAs relied on the ambient temperature of the extremeties18,19, which expressed vasoconstriction (to reduce heat loss) and vasodilatation (to increase heat loss) modes under low and high temperatures, respectively. It is thus reasonable to speculate that the close to zero SkBF values for subjects in MARCON was induced by the vasoconstriction of AVAs in the cold microenvironment between foot and MARCON, while the promoted SkBF values for the subjects in MARHT was attribute to vasodilatation of AVAs in the warm microenvironment created by the MARHT. Individual difference exists expressed by the unaffected SkBF evolutions of one female and different levels of SkBF promotions for the rest subjects in the two sleeping bags.
The relationship between SkBF and $T_{in}$, when supplying feet with exogenous heat was investigated by some researchers. Song conducted a study by having subjects touching heating floor with different surface temperatures, and discovered that the blood flow rate in the toe at the dorsal part increased with the increasing toe temperature ranging from 20.0 to 34.0°C (sharp increment occurs at from 30.0 to 34.0°C). Allwood et al. applied increased local temperatures at feet and discovered that SkBF increased gradually from temperature of 15 to 29°C and then remarkably from 29 to 32°C. The SkBF of most males in MARHT, was higher compared to that of all females, which might be obtained from the higher toe temperatures (i.e., 30.7 ± 2.5°C) on males than on females (28.9 ± 2.7°C) or from the AVAs difference between the two genders.

Heating the feet region exerted no effect on the whole body temperature. Similar findings were also observed by Isik, who detected that heating the feet played no effect on the body temperature at other regions. All the observed $T_a$ values were laid in the thermal neutral range of 32.0–34.0 °C. Heart rate fluctuated with the testing time in the range of 60 to 80 beats/min (bpm). Our results confirmed that the EN 13537 (2012) defined temperatures only considered the whole body thermal balance rather than sleeping thermal comfort. Significantly lower heart rate was detected on males in MARHT compared to MARCON, at some points during the 3-hour exposure. In addition, MARHT showed a much lower average heart rate during the 3-hour exposure compared to MARCON and approached the statistical significance indicated by $p = 0.052$. Some researchers pointed out that there exists a connection between blood flow fluctuations through AVAs in the fingers and toes, and spontaneous heart rate as well as the blood pressure variability. In this study, the significant heart rate difference observed on males might be caused by the high toe blood flow in MARHT. Future studies should be conducted to ascertain the relationship between these two variables; however.

Given the physiological responses in the feet, it is not surprising to find that the perceptual responses (TS and CS) of participants in MARCON deteriorated with the exposure time. Local perceptual responses play an important role in affecting the whole body sensations. Arens et al. opined that cold feet would disrupt the whole body thermal comfort even if the rest of the body was properly dressed. Huang detected that TS in the feet is highly correlated to that in the whole body (the Spearman correlation coefficient of 0.8). Though no aggravated global physiological responses (i.e., the mean skin temperature and the heart rate), it is still inevitably to observe the disruption of the whole body perceptual responses (TS and CS) in MARCON, which might be aroused by the worsened local thermal responses in the feet. Our findings further demonstrate that the EN 13537 (2012) failed to protect the local body region. Therefore, it is highly necessary to revise the EN 13537 (2012) to address the issue on the protection of local body areas, e.g. feet.

In MARHT, a large improvement of perceptual responses (TS and CS) in the feet was observed, and the resultant small to moderate improvement in the whole body sensation was thus detected. Slight wetness sensation was detected in the hands regardless of the sleeping bag types, which might be explained from the aspect of the hand warming due to the close contact between hands and the torso. The perceptual responses (TS, CS and WS) in MARHT have demonstrated the advantage of the newly developed smart heating sleeping bag over traditional sleeping bags.

Perceptual responses of females and males in MARHT and MARCON were consistent except for TS in the feet (slightly warm and cool sensations for males and females, respectively). This was in accordance with and also might be explained from the difference of physiological responses in feet for the two sex groups. Females exhibited significantly lower foot temperatures and blood flow than males.

Finally, there are generally two potential approaches to protect the human extremities such as the feet when sleeping outdoors: selecting a high insulation bag and using it at higher temperatures than the EN 13537 (2012) defined operating temperatures or supplying heating to the feet regions. Although the first method seems effective, high insulation sleeping bags are bulky and costly. Hence, supplying heat to the feet regions using such as heating pads is a promising way to protect human feet. Compared to traditional thick and bulky sleeping bags, smart heating sleeping bags are slimmer and cheaper. Research findings presented in this study have evidently demonstrated that a smart heating sleeping bag is effective in improving wearers’ thermal comfort during sleeping under cold outdoor environments. Particularly in the camping sites and other outdoor recreation facilities where electricity can be easily accessed, using heating sleeping bags could be served as one of the best choices to provide wearers a better sleeping environment. For the outdoor settings where electric power is not available, a light and portable high capacity lithium-ion battery could be used to supply power to smart heating sleeping bags. However, it should be noted that such a high capacity battery, depends on its actual capacity, may only provide users a limited heating period (ranging from several hours to a number of days). Finally, the application of such smart heating sleeping bags to those settings as long-period hiking in the wilderness is greatly restricted due to the battery capacity and load concerns.

Limitations should be acknowledged that the weight increment in the smart sleeping bag is 464 g, accounting for about 45% in comparison to the weight of the traditional sleeping bag. This added load may lower the users’ enthusiasm to use the smart sleeping bags. The durations of the tests were three hours, somewhat shorter to mimic the normally use of the sleeping bags. In future studies, lighter smart sleeping bags would be designed and prolonged testing duration will be adopted to investigate their effectiveness in improving the wears’ local thermal comfort in the feet.

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