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Performance evaluation of an active heating garment in a cold environment

: Influence of heated body regions

한랭 환경에 노출된 작업자 체온 유지를 위한 발열의류의 성능 평가: 인체 가온부위의 영향

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Abstract

Performance evaluation of an active heating garment in a cold environment
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The purpose of this study was (1) to investigate the physiological and psychological responses in accordance with the quantified amount of heat insertion on the varied upper body regions using a liquid-perfused shirt with its inner surface temperature of 42°C, and (2) to propose the optimal combination of heating regions in terms of supporting the thermoregulatory responses for the workers in cold environments. A total of 10 healthy males (24.9 ± 2.8 y, 177.3 ± 5.0 kg, 76.1 ± 15.9 kg) participated in three experimental conditions: (1) Control (non-heating), (2) ChestBack (heating the chest and back), and (3) BackArm (heating the back and upper arms). A trial consisted of 80 min including the phases of 10-min rest, 60-min exercise, and 10-min recovery. All experiments were conducted in the climatic chamber with a temperature of -9.1 ± 0.6°C. For the two shirt-wearing conditions of ChestBack and BackArm, an average of 398 $kcal \cdot h^{-1}$ of heat was injected respectively without any significant difference. No significant difference in rectal temperature between the three conditions was found, but the increase in rectal temperature during 80 min exposure was significantly greater in the two conditions with a heating shirt compared to the control ($P = 0.012$). Mean skin temperature was significantly higher in the two conditions wearing a shirt compared to the control, but no difference was found between the two heating conditions. In particular, forearm skin temperature was significantly higher in the back and upper arm heating condition than in the chest and back heating condition ($P = 0.042$), being maintained without a large degradation during 80 minutes of exposure. Hand skin temperature was also found to be significantly higher in the second half of cold exposure under the two conditions of wearing a shirt compared to the control ($P < 0.005$). The average oxygen intake under the two heating conditions was significantly reduced compared to the control ($P < 0.005$). Perceived thermal sensation was significantly different between the three experimental conditions ($P < 0.01$), and about 2 to 3 points higher in the heating conditions than the control at the end of exercise and the subjects felt 'a little warm' in the heating conditions. For thermal comfort, the difference between the two heating conditions was found. Less frequency of shivering was reported in heating the back and upper arms compared to the chest and back. To conclude, when developing an active heating garment for workers using their extremities frequently, both the combination of 'Chest/Back' and 'Back/Upper arm' will be effective, but it is believed that applying heating to the combination of the back and upper arms will not only improve manual efficiency but reduce the sense of shivering. The findings of the present study can be used as basic data for developing an active heating garment for workers exposed to cold environments.

Keywords: Cold stress, Upper arms, Rectal temperature, Peripheral skin temperature, Thermal sensation, Oxygen consumption, Shivering sensation

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List of Abbreviations

ChestBack	The condition of heating the chest and upper back
BackArm	The condition of heating the upper back and upper arms
$\boldsymbol{T}_{\mathbf{re}}$	Rectal temperature
$\overline{\boldsymbol{T}}_{\mathbf{sk}}$	Skin temperature
$\boldsymbol{f}_{\mathbf{w}}$	Water flow rate of the shirt
$\boldsymbol{C}_{\mathbf{w}}$	Water specific heat
$\boldsymbol{T}_{\mathbf{wi}}$	Water inflow temperature
$\boldsymbol{T}_{\mathbf{wo}}$	Water outflow temperature
BSA	Body surface area
BMI	Body mass index
RCV	The phase of recovery
$\dot{\boldsymbol{V}}\mathbf{O}_{\boldsymbol{2}\mathbf{max}}$	Maximal oxygen consumption

Chapter 1. Introduction

There is no agreed international definition of 'cold stress', but ISO 12894 (2001) considers temperatures below 0℃ as the beginning of cold. The average winter temperature in South Korea over the past five years is 1℃. However, in the case of Taebaek, Gangwon-do which is the coldest region in South Korea, the average minimum temperature in January is about -9.6℃, and the lowest temperature in history is -21.7℃, which was observed in 2013. To protect workers exposed to cold environments, it is important to effectively wear winter clothes (padding jackets, multiple overlapping, hats, gloves, boots, etc.) as the weight or overlapping of the winter garments hinders workers' mobility.

Recently, active heating garments have been widely worn in industrial fields to prevent cold-related diseases such as hypothermia, frostbite, or non-freezing cold injury. At the same time, those heating garments are expected to minimise the load of a battery that might affect the mobility of workers. In order to reduce total mass of garments, selective body heating is efficient. In this regard, physiological evaluation on regional body heating strategies has been continuously conducted. Research has been continuously conducted on which part of the human body to be heated, especially comparing the chest and back area, is effective in maintaining body temperature during cold exposure. Park et al. (2016) compared the chest and upper back heating and observed the increase in skin temperature not only of the upper body but also the lower body. Likewise, it was reported that there was no significant difference in sustaining the body temperature between warming the whole body and only the upper body during the abdominal opening surgery (Janicki et al., 2001). Additionally, Shin et al. (2017) found that it was more effective to help the mean skin temperature remain when heating the back than the chest. Recently, further studies have been examining the effective heating regions including subdivide upper body areas as well as the chest and back. Kim & Hong (2014) compared the physiological responses by heating the waist, abdomen, shoulders, and feet to verify where to heat is advantageous using hot packs, and found that shoulder was the most effective region for increasing peripheral temperature. In the previous study comparing the effect of removing fillers by compartment of a long-padded jumper on body temperature maintenance when exposed to cold, the thermoregulatory response worsened significantly under the condition of removing fillers in the upper back or upper arms (Kwon et al., 2017). These results are coupled with the previous study that blood flow in the coronary artery and superficial vein of the upper arm during systemic heating increased linearly with the increase in core temperature (Ooue et al., 2007). However, there are rare studies reporting which part of the upper body is quantitatively more effective to warm in an extremely cold environment where workers are actually exposed in South Korea.

In the current study, two possible combinations of body regions to be heated were designated: (1) the chest and upper back, and (2) upper back and upper arms. The present study aimed to verify the impact of the heating strategy using a liquid-perfused shirt in accordance with the varied body regions and to suggest the effective combination of the upper body regions to be heated in terms of empirical usage of an active heating garment.

In order to identify the thermoregulatory impact of a liquid-perfused shirt, physiological and subjective responses were quantitively collected. The present study hypothesised that (1) the active heating strategy will have a positive effect on skin temperature consistency during the exposure to a cold environment, (2) differentiating the body regions to be heated will affect the degree of the uniformity in peripheral skin temperature, and (3) the degree of psychological perception including thermal sensation, thermal comfort, and shivering sensation will be proportionally elevated with heating the upper body during the cold exposure.

Chapter 2. Methods

2.1. Subjects

A total of 10 healthy young males in their 20s who have lived in Seoul/Gyeonggi for at least five years (24.9 ± 2.8 y, 177.3 ± 5.0 kg, 76.1 ± 15.9 kg) participated in the experiments (Table 1). The number of subjects was decided by using the sample size calculation program G*Power. Based on the repeated measurement variance analysis, the statistical power was calculated at 0.95, the medium effect size of 0.25, and the significance level of 0.05, turning out to be 9 persons. For this study, it was determined to be 10 in consideration of the dropout rate. All subjects went through health pre-screening interview such as diabetes, high blood pressure, and heart disease. Excessive smokers and habitual drinkers were excluded from the experiment, but the subjects with past experience in smoking and drinking could be included. All subjects refrained from strenuous exercise, alcohol, and caffeine intake for 24 hours before visiting the laboratory, and remained fasted for at least 3 hours in advance. The subjects recruited in the present study participated in a total of three experimental trials, each experimental condition with. The sequence of the trials was randomly determined to reduce the effect of the experimental order and each trial was conducted at least 48 hours apart one another. All subjects were provided with information on the purpose, experimental process, any possible discomfort or potential risk in advance, and agreed in written consent before participation. All procedures of the present study were approved by the Institute Review Board of Seoul National University (IRB No. 2212/001-013).

Table 1 Anthropometric characteristics of subjects

Subject No.	Age (y)	Height (cm)	Weight (kg)	Body fat mass (kg)	BSA[1)] (m^2)	BMI[2)] (kg/m^2)
S1	27	185.0	83.2	13.8	2.11	24.3
S2	26	176.0	76.2	13.5	1.96	24.6
S3	27	173.7	72.2	12.3	1.90	23.9
S4	21	177.3	88.2	17.9	2.10	28.1
S5	25	178.0	58.1	10.2	1.76	18.3
S6	23	179.5	72.1	13.9	1.95	22.4
S7	26	172.2	70.9	13.4	1.87	23.9
S8	20	171.1	56.6	8.9	1.70	19.4
S9	29	174.5	71.8	17.6	1.90	24.1
S10	25	185.8	112.1	33.0	2.41	32.8
Mean	24.9	177.3	76.1	15.5	1.97	24.2
SD	2.8	5.0	15.9	6.8	0.20	4.2

[1)]BSA (Body Surface Area) = 73.31 * (Height)0.725 * (Weight)0.42 (Lee et al., 2008)

[2)]BMI (Body Mass Index) = Weight (kg) / $Height^2$ (m^2)

2.2. Newly developed liquid-perfused shirt

To find out the thermoregulatory impact in accordance with the combinations of upper body regions and to quantify heat flow on each region, the liquid-perfused shirt was newly developed in the present study (Fig. 1). The newly developed liquid-perfused shirt did not rely solely on the textile's warmth, but rather helped maintain body temperature by connecting constant temperature water baths to allow hot water to flow through the connected tube (Fig. 2). Considering the general fabric usage for the winter jumpers, nylon-polyester fabric was chosen and for the lining nylon-spandex mixed mesh fabric was adopted on which the tube was placed (85% nylon; 15% polyurethane). To minimise the deviation of the surface area on which the thermal insulation influences, 8 m PVC tubes were placed by dividing the shirt into 6 compartments: both upper arms, left upper back, right upper back, left chest, and right chest. Based on the previous study (Ko et al., 2020), tubes were arranged in a spiral structure for a uniform water injection rate without interfering with water circulation. The temperature for water injected (T_{wi}) was set at 45.4 ± 0.6°C; water flow rate at 617 ± 12 ml · h^{-1}) (RW-0525G, Jeiotech, Korea). The surface temperature of PVC tubes inside the shirt was 41.2 ± 0.4°C. Regarding the difference in anthropometric information for each subject, Velcro was attached to the seams of the arms and side lines to adjust the fit individually and lessen the influence of the air gap in the garment.

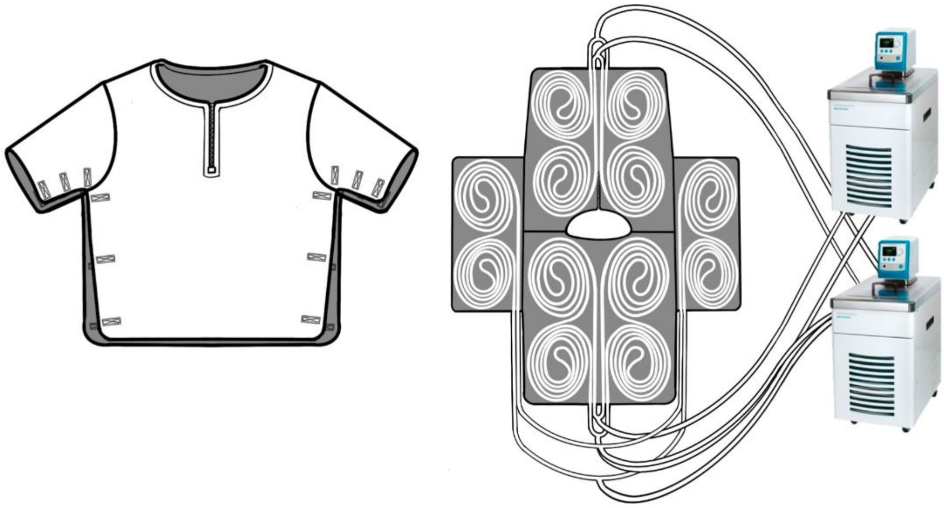


Fig. 1 A schematisation of liquid-perfused heating shirt and tube placement with water baths.

Fig. 2 A prototype of a liquid-perfused shirt.

2.3. Experimental conditions

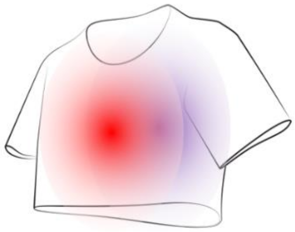
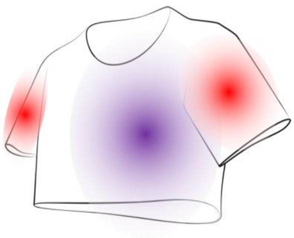
Every trial was conducted in a climatic chamber (FLC-5000S, Fuji Medical science, Japan) with a temperature of -9.1 ± 0.6°C, which was designed based on the yearly average of minimum air temperature for 10 years from 2011 to 2021 (Korea Meteorological Administration Weather Nuri, 2021). During all experiments, the measured airflow was at the level of insensible airflow, $0.2 \pm 0.01\ m \cdot s^{-1}$ (Table 2).

All subjects wore training set-ups, goose down padded jumper, underwear, socks, and sneakers in common. Clothing sizes provided were different based on anthropometric information for each subject. Whether to wear a liquid-perfused shirt was decided depending on clothing conditions of (1) non-heating (Control), (2) chest and back heating (ChestBack), and (3) back and upper arms heating (BackArm) (Table 3). In Control, the subjects did not wear a liquid-perfused shirt, whereas in ChestBack and BackArm they wore a liquid-perfused shirt of 1.8 kg including the weight of water injected.

Table 2 Environmental condition of the present study

Items	Environment	
	Mean	SD
Air temperature (ºC)	-9.1	0.6
Air velocity ($m \cdot s^{-1}$)	0.2	0.01
Injected water temperature (ºC)	45.4	0.6

Table 3 Three clothing conditions of the present study

Condition	Condition 1	Condition 2	Condition 3
Name	"Control"	"ChestBack"	"BackArm"
	No shirt		
Heating region	-	Chest and back	Back and upper arms
Weight (kg)	-	1.77	1.77

2.4. Experimental protocol and measurement

Each subject participated in a total of three trials and was calculated body mass index. The subjects took enough rest more than 30 min upon arrival and drank 330 ml of water. Every visit right before and after participating in the experiment, the body weight was measured while wearing only underwear and a gown (F150S, Sartorius, Germany, resolution 1 g), as well as the blood pressure (JPN610T, OMRON, Japan). All the measurement sensors including a rectal temperature senor, skin temperature sensors in nine areas (forehead, chest, back, abdomen, forearm, hand, thigh, calf, and foot) (LT-8A, Gram Corporation, Japan), a heart rate sensor band on the chest, a watch-type data logger on the wrist (H10, Polar Electro, Finland), and clothing microclimate sensors on the chest and back were attached. Each trial consisted of three phases: 10-min rest, 60-min exercise, and 10-min recovery (Fig. 3). During a total of 80-min trial, rectal temperature, skin temperature, and clothing microclimate were recorded with a 5-s interval, and heart rate data was collected every second successively. Oxygen consumption was also measured breath by breath (Quark CPET, COSMED, Italy). Every 10 min of during the experiment, subjective responses of 9-point scale thermal sensation, 7-point thermal comfort and shivering sensation were asked. For the subjects' answering shivering sensation, a picture of a body with 21 compartments was presented (Table 4). The subjects were allowed to indicate the allocated number of each body area where they perceived to have shivers. In order to evenly control the amount of heat flow of heated body regions in every trial, the injected water temperature during all experiments was monitored every 5 s. To quantify the heat insertion on each body region, the following equation was used:

[Eq. 1]

$$\text{Heat insertion (kcal} \cdot \text{h}^{-1}) = f_w \cdot C_w \cdot (T_{wi} - T_{wo})$$

where f_w: water flow rate of the shirt (L · h^{-1}); C_w: water specific heat = 1 kcal · kg^{-1} · $°C^{-1}$; T_{wi}: water inflow temperature (°C); T_{wo}: water outflow temperature (°C).

After entering the chamber, the subjects took a rest for 10 min sitting in a chair with their back against the wall. Then, they walked for 60 min on a treadmill at a speed of 4 km·h^{-1}. After exercise, they took a 10-min recovery in a chair.

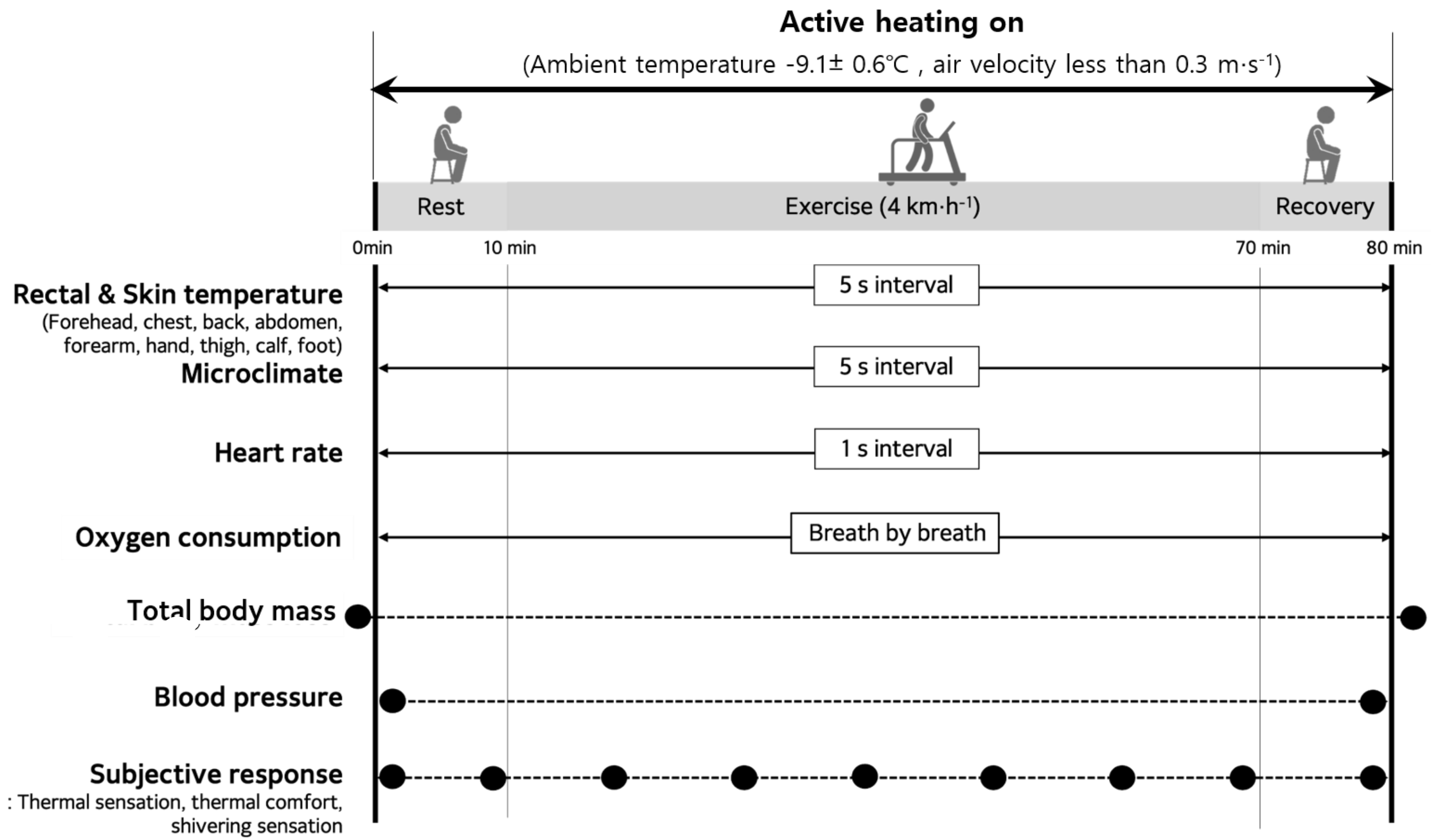
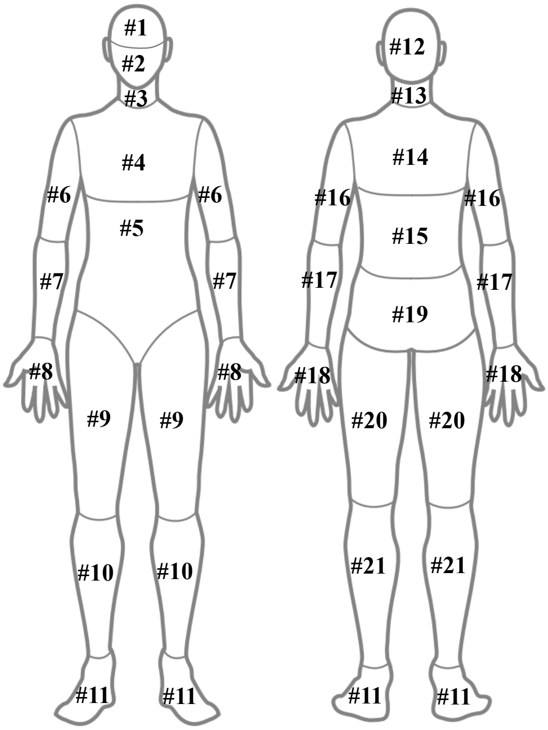


Fig. 3 Experimental protocol and measurements.

Table 4 21 compartments for answering shivering sensation



Num.	Body region	Num.	Body region
#1	Forehead	#11	Foot
#2	Face	#12	Back head
#3	Frontal neck	#13	Rear neck
#4	Chest	#14	Upper back
#5	Abdomen	#15	Lower back
#6	Frontal upper arm	#16	Rear upper arm
#7	Frontal forearm	#17	Rear forearm
#8	Palm	#18	Back of the hand
#9	Frontal thigh	#19	Hip
#10	Frontal calf	#20	Frontal thigh
		#21	Rear calf

2.5. Data analysis

Mean skin temperatures were calculated using a Hardy & Dubois 7-point scale formula (Hardy et al., 1938) (Eq. 2). For the present study, considering the heating area by condition, the proportional weight of the chest area of the existing formula was divided with the back so that the total of 8 body areas were adopted to calculate the mean skin temperature (Eq. 3).

[Eq. 2]

$$\bar{T}_{sk} = 0.07T_{forehead} + 0.35T_{trunk} + 0.14T_{arm} + 0.05T_{hand} + 0.19T_{thigh} + 0.13T_{calf} + 0.07T_{foot}$$

[Eq. 3]

$$\bar{T}_{sk} = 0.07T_{forehead} + 0.175T_{chest} + 0.175T_{back} + 0.14T_{forearm} + 0.05T_{hand} + 0.19T_{thigh} + 0.13T_{calf} + 0.07T_{foot}$$

An average of 10 min was used to analyse all measurement items. To examine the change in rectal temperature over the time courses, average values of 10 min of rest, initial 3 min of exercise, last 3 min of exercise, and 10 min of recovery were calculated. All the experimental results were presented as mean and standard deviation (Mean ± SD) and analysed using SPSS 25.0. A one-way repeated measures ANOVA was used to find the difference between the three conditions. For the analysis of blood pressure, paired sample *t*-test was used. Tukey HSD's post-hoc test was conducted on items showing a significant difference. For nonparametric items using the categorical scale, Friedman test was conducted to compare the three experimental conditions. The statistically significant level was set to $P < 0.1$.

Chapter 3. Results

3.1. Heat insertion

Throughout the time courses, the heat insertion was calculated using Eq. 1. The amount of heat inserted into the chest, back and upper arms was 192.0 ± 26.3, 198.3 ± 31.4, and 207.4 ± 33.7 $kcal \cdot h^{-1}$, respectively. There was no significant difference between the two shirt-wearing conditions, which indicated the amount of heat was uniformly inserted into each body region (Table 5).

Table 5 Heat flow on the heated body regions

Region	Heat insertion	*P*-value
Chest	192.0 ± 26.3	
Back	198.3 ± 31.4	N.S.
Upper arms	207.4 ± 33.7	

(Unit: $kcal \cdot h^{-1}$)

3.2. Rectal temperature

The rectal temperature in the baseline had no statistically significant difference was found throughout the phases (Fig. 4). Nevertheless, the relatively greater increase in rectal temperature under the heating conditions of along with the time courses (Table 6). At the end of the exercise, the rectal temperature under the condition of BackArm went higher by 0.54 ± 0.14℃ from the baseline, and by 0.50 ± 0.25℃ under ChestBack (P = 0.012). However, no statistical difference between the two heating conditions was found. In Control, the rectal temperature showed the least increase in Control of 0.35 ± 0.18°C. After recovery, the rectal temperature remained at a similar level to that at the end of the exercise in the heating conditions, while it slightly decreased in Control.

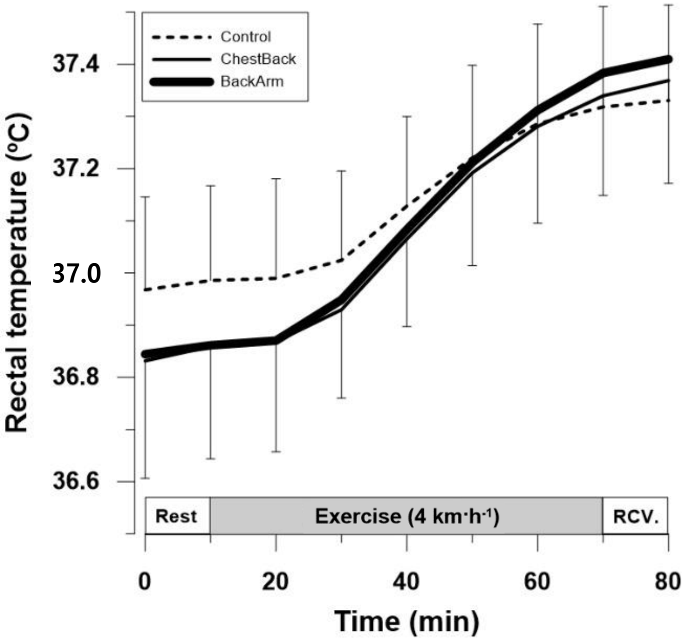


Fig. 4 Time courses of rectal temperature for the 80-min exposure.

Table 6 Changes in rectal temperature for the three conditions

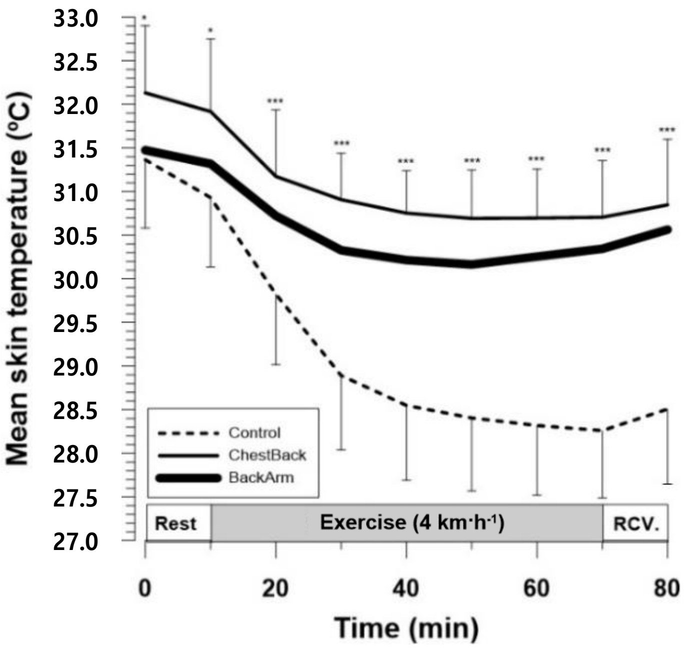
	Control	ChestBack	BackArm	*P*-value
① Rest	36.9 ± 0.2	36.9 ± 0.2	36.9 ± 0.2	0.172
② Exercise (Initial 3min)	37.0 ± 0.2	36.9 ± 0.2	36.9 ± 0.2	0.120
③ Exercise (Last 3min)	37.8 ± 0.2	37.4 ± 0.2	37.4 ± 0.2	0.442
④ Recovery	37.3 ± 0.2	37.4 ± 0.2	37.4 ± 0.1	0.492
Δ Exercise (③ - ①)	0.4 ± 0.2	0.5 ± 0.3	0.5 ± 0.2	0.012
Δ Recovery (④ - ①)	0.4 ± 0.2	0.5 ± 0.3	0.6 ± 0.2	0.078

(Unit: ℃)

3.3. Skin temperature

3.3.1 Mean skin temperature

As shown in Fig. 5, a statistical difference was observed in the baseline ($P = 0.09$). The highest mean skin temperature was found under the condition of ChestBack. However, just after 10- min rest being exposed to cold, the mean skin temperature dropped rapidly in Control, whereas the reduction in it under the two conditions of wearing the liquid-perfused shirt was eased especially in BackArm. The average decline under Control, ChestBack, and BackArm was 2.85℃, 1.28℃, and 0.91℃, respectively. Noticeably, although the mean skin temperature in BackArm was significantly lower in the beginning of the time courses than in ChestBack ($P < 0.001$), the consistent increasing



$^{*}P < 0.1$, $^{***}P < 0.001$

Fig. 5 Time courses of mean skin temperature for the 80-min exposure.

slope was observed after 40 min of the exercise in BackArm, resulting in little difference between the two conditions at the end of the protocol. The gap between the two heating conditions and Control appeared much widened from starting the exercise until the end of the protocol ($P < 0.001$).

3.3.2 Regional skin temperature

The changes in the regional skin temperature of nine body areas is presented on Table 7. The regional skin temperature showed a significant difference for most of body parts except of forehead and foot. Fig. 6 illustrates the time courses of the chest and the upper back skin temperature. As there was a direct heating on those body areas, each condition had a significant difference ($P < 0.001$). While heated, the chest skin temperature in ChestBack gradually rose and was maintained at the level of 37.5℃. The back skin temperature under the conditions of ChestBack and BackArm was about 38.5℃ while the back was heated and showed a significant difference with Control ($P < 0.001$). Even though the similar level of heat was inserted, it showed relatively higher values of than the chest skin temperature.

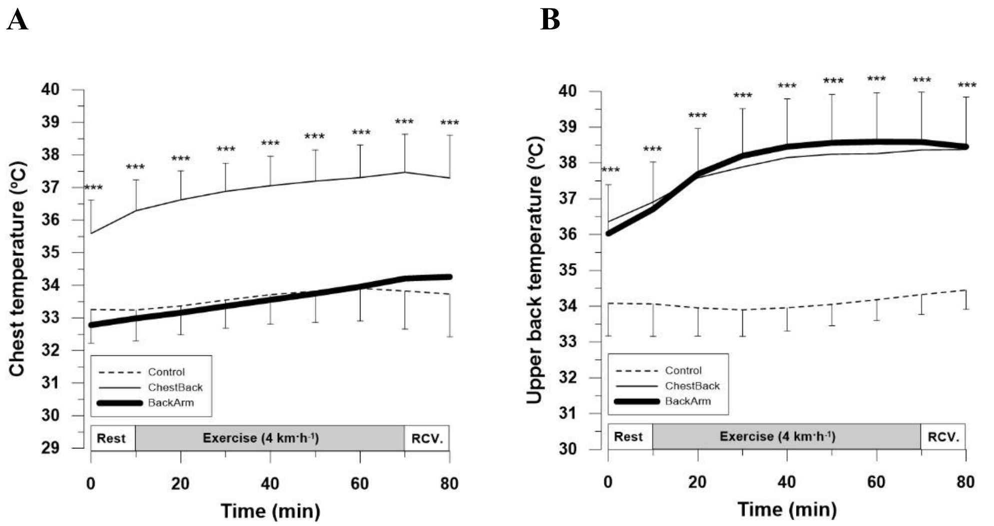
Among the nine body regions measured, Fig. 7 represents the time courses of peripheral temperature in upper body regions which showed a noticeable tendency over the time courses. In the baseline, the forearm temperature started from an average of 32.3℃ without any significant difference between the three conditions (Fig. 7A). However, a statistical difference started to be shown after 45 min of exercise ($P < 0.1$). For the 80-min time courses, the forearm temperature remained uniform in BackArm, while in Control and ChestBack decreased relatively greater by 4.2℃ and 2.1℃, respectively ($P = 0.025$). Although the hands were directly exposed to the cold air as the gloves were not worn, it was presented that the hand temperature in ChestBack and BackArm dropped relatively gently compared to Control. After 32 min of exercise, there was a significant difference found between the three conditions (Fig. 7B, $P < 0.1$). At the end of exercise, the mean hand temperature in ChestBack (19.8 ± 4.7°C) and BackArm (19.1 ± 5.1°C) was significantly higher, while in Control was 15.0 ± 4.4°C ($P = 0.002$). This shows the effect of the heating shirt regardless of differentiating the body regions to be warmed.

Fig. 8 shows the changes in lower body skin temperature. For the thigh temperature, a significant difference between the three conditions was shown up after 25 min of exercise (Fig. 8A, $P = 0.068$). The decline was more relatively moderate along with the wearing the liquid-perfused shirt, which infers to the effect of the shirt on maintaining the thigh temperature was similar under both conditions of ChestBack and BackArm. Unlike the observed changes in the thigh temperature, there was no significant difference found in the foot temperature between the three conditions (Fig. 8B). It can be assumed that wearing the heating shirt had little effect on maintenance of the foot temperature.

Table 7 Changes in regional temperatures for the three conditions

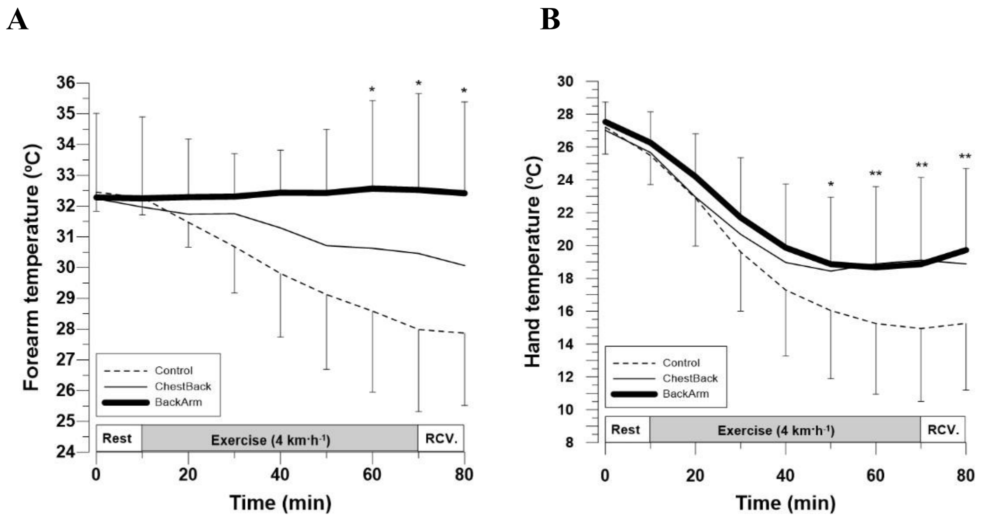
Region	Phase	Control	ChestBack	BackArm	*P*-value
Forehead	Rest	29.5 ± 1.1	29.2 ± 1.4	29.4 ± 1.1	0.581
	Exercise (Last 3min)	28.2 ± 2.1	28.2 ± 1.9	29.1 ± 1.5	0.309
	Recovery	28.3 ± 2.0	28.5 ± 1.7	29.0 ± 1.3	0.480
Chest	Rest	33.3 ± 1.^{a}	35.6 ± 0.7^{b}	32.8 ± 1.4^{a}	< 0.001
	Exercise (Last 3min)	33.9 ± 1.0^{a}	37.3 ± 0.6^{b}	34.0 ± 1.4^{a}	< 0.001
	Recovery	33.8 ± 1.2^{a}	37.5 ± 0.6^{b}	34.2 ± 1.4^{a}	< 0.001
Back	Rest	34.1 ± 1.3^{a}	37.0 ± 0.9^{b}	36.8 ± 0.7^{b}	< 0.001
	Exercise (Last 3min)	34.4 ± 1.4^{a}	38.4 ± 0.6^{b}	38.6 ± 0.2^{b}	< 0.001
	Recovery	34.5 ± 1.4^{a}	38.4 ± 0.5^{b}	38.5 ± 0.4^{b}	< 0.001
Abdomen	Rest	33.2 ± 1.8^{a}	34.6 ± 1.7^{b}	33.0 ± 1.4^{a}	0.073
	Exercise (Last 3min)	32.8 ± 1.1^{a}	35.1 ± 2.8^{b}	33.5 ± 2.7^{a}	0.040
	Recovery	33.0 ± 1.2^{a}	35.6 ± 3.0^{b}	33.7 ± 3.0^{a}	0.044
Forearm	Rest	32.2 ± 0.5	32.2 ± 0.9	32.3 ± 2.6	0.428
	Exercise (Last 3min)	28.1 ± 2.6^{a}	30.5 ± 1.9^{ab}	32.5 ± 3.0^{b}	0.041
	Recovery	28.0 ± 2.4^{a}	30.1 ± 1.9^{ab}	32.4 ± 3.0^{b}	0.031
Hand	Rest	25.4 ± 1.7	25.5 ± 1.3	26.1 ± 1.8	0.498
	Exercise (Last 3min)	15.0 ± 4.4^{a}	19.8 ± 4.7^{b}	19.1 ± 5.1^{b}	0.002
	Recovery	15.3 ± 4.0^{a}	19.4 ± 4.3^{b}	19.7 ± 4.9^{b}	0.002
Thigh	Rest	28.2 ± 1.5	28.4 ± 2.0	28.8 ± 1.2	0.535
	Exercise (Last 3min)	23.5 ± 1.6^{a}	24.3 ± 1.9^{b}	24.5 ± 1.8^{b}	0.053
	Recovery	24.4 ± 1.8^{a}	25.1 ± 1.9^{b}	25.3 ± 1.9^{b}	0.099
Calf	Rest	27.5 ± 1.0	27.9 ± 2.2	27.7 ± 2.3	0.596
	Exercise (Last 3min)	24.4 ± 2.3^{a}	27.5 ± 2.5^{b}	28.0 ± 0.9^{b}	0.005
	Recovery	24.8 ± 3.0^{a}	27.7 ± 2.3^{b}	27.4 ± 2.1^{b}	0.012
Foot	Rest	29.3 ± 1.6	29.3 ± 1.6	29.5 ± 1.3	0.430
	Exercise (Last 3min)	25.3 ± 4.4	25.3 ± 4.8	25.8 ± 4.7	0.624
	Recovery	25.3 ± 4.5	25.6 ± 4.6	26.1 ± 4.6	0.445

(Unit: ℃)



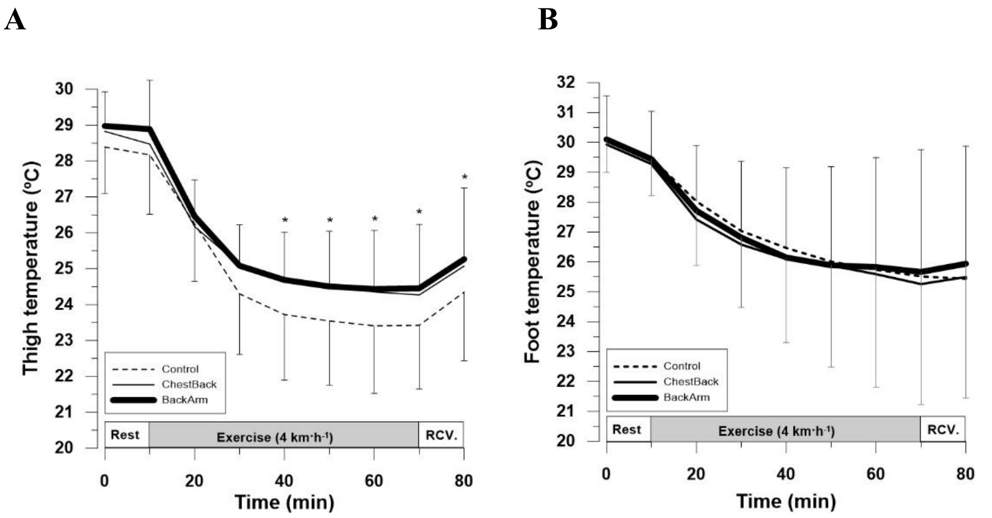
*** $P < 0.001$

Fig. 6 Time courses of chest (A) and upper back temperature (B) for 80-min exposure.



* $P < 0.1$, ** $P < 0.005$

Fig. 7 Time courses of forearm (A) and hand temperature (B) for 80-min exposure.

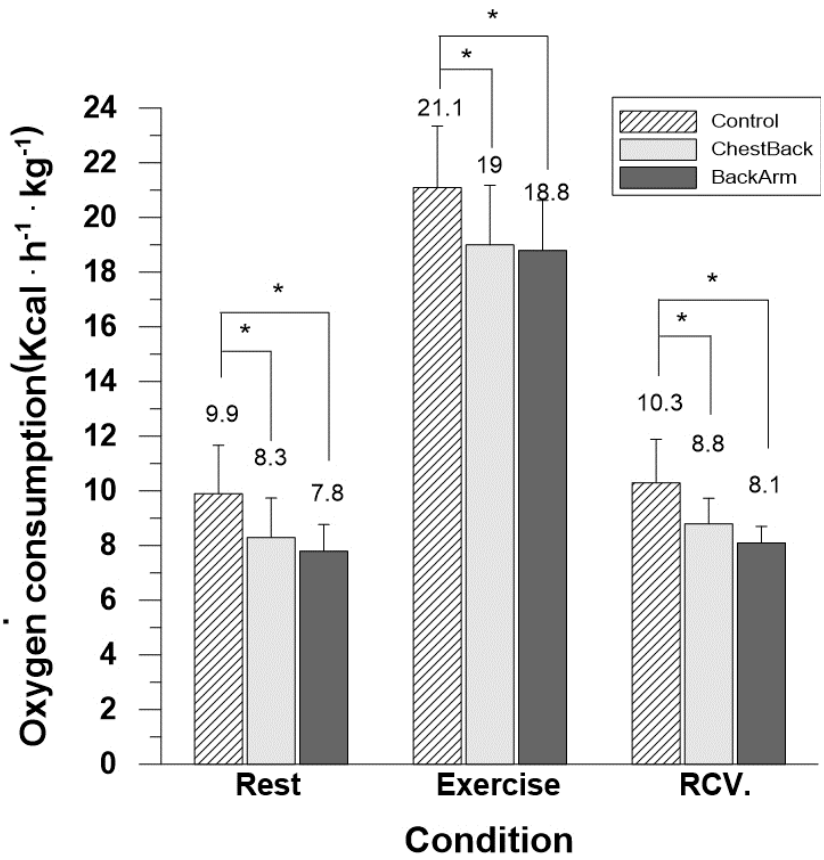


* P < 0.1, ** P < 0.005

Fig. 8 Time courses of thigh (A) and foot temperature (B) for 80-min exposure.

3.4. Oxygen consumption

Fig. 9 shows the changes in oxygen consumption during the rest, exercise and recovery. Throughout the overall time courses, the difference between the three conditions was found (Rest: $P < 0.001$; Exercise: $P = 0.002$; Recovery: $P = 0.003$). It was observed that the average amount of oxygen consumed under the two conditions of wearing a shirt lessened in all phases compared to Control. The average amount of oxygen consumed in the two shirt-wearing conditions were significantly lower than that in Control during the rest (Control: 9.9 ± 1.8; ChestBack: 8.3 ± 1.4; BackArm: 7.8 ± 1.0 kcal $\cdot$ h^{-1} $\cdot$ kg^{-1}, $P < 0.001$). However, there was no statistical difference between the two heating conditions. During the exercise, the amount of oxygen consumption in ChestBack and BackArm was shown to be smaller than in Control (Control: 21.1 ± 2.2; ChestBack: 19.0 ± 2.2; BackArm: 18.8 ± 1.8 kcal $\cdot$ h^{-1} $\cdot$ kg^{-1}, $P = 0.002$). No statistical difference between the two heating conditions appeared. Likewise, the average oxygen consumption lessened under the two heating conditions compared to Control in the phase of recovery (Control: 10.3 ± 1.6; ChestBack: 8.8 ± 0.9; BackArm: 8.1 ± 0.6 kcal · h^{-1} · kg^{-1}, $P = 0.003$). There was no statistical difference found between those two heating conditions.



* $P < 0.1$

Fig. 9 Changes in oxygen consumption.

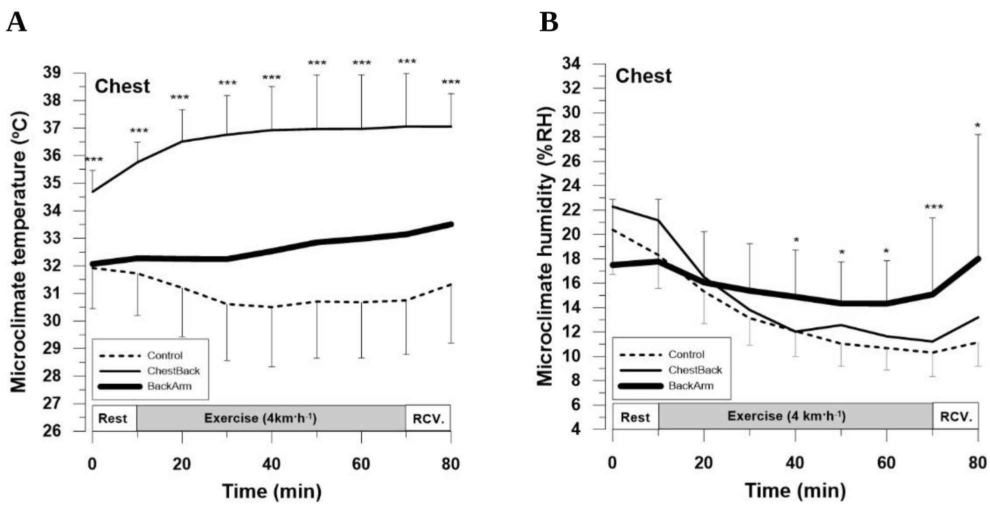
(Rest: $P < 0.001$; Exercise: $P = 0.002$; Recovery: $P = 0.003$)

3.5. Clothing microclimate temperature and humidity

3.5.1 Clothing microclimate on the chest

From the baseline, the mean microclimate temperature for the chest area was 34.7 ± 0.8℃ under the condition of ChestBack under which the chest was directly warmed by the shirt, showing a statistically large difference (Fig. 10A, $P < 0.001$). That in Control and BackArm was 31.9 ± 1.5℃ and 32.1 ± 1.6℃, respectively, without any significant difference. However, the microclimate temperature in the chest increased during the 10-min rest in the two conditions of wearing an active heating shirt, while that in Control tended to decrease. At the end of the protocol, the microclimate temperature in the chest under the BackArm condition steadily rose by 1.4 ± 1.1°C from the baseline despite the absence of direct heating to the chest and increased. In ChestBack, where the chest was directly heated, the microclimate temperature in the chest area increased by 2.4 ± 1.6°C. In the Control condition, it decreased by 0.7 ± 1.3°C.

The clothing microclimate humidity in the chest began to show a significant difference between the three conditions after 30 min of exercise (Fig. 10B, $P = 0.049$). While Control and ChestBack showed a steep decline during the exercise, humidity in BackArm tended to decrease relatively slowly. During the recovery, the chest microclimate humidity was found to increase in all three conditions, as well as a significant difference was found ($P = 0.079$). The increasing slope was also observed to be the steepest in BackArm.



$^{*}P < 0.1$, $^{***}P < 0.001$

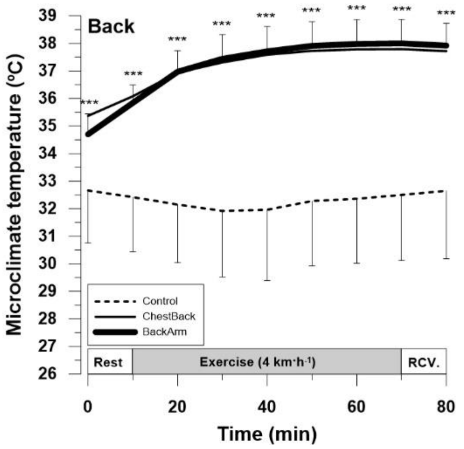
Fig. 10 Time courses of clothing microclimate temperature (A) and humidity (B) on the chest.

3.5.2 Clothing microclimate on the back

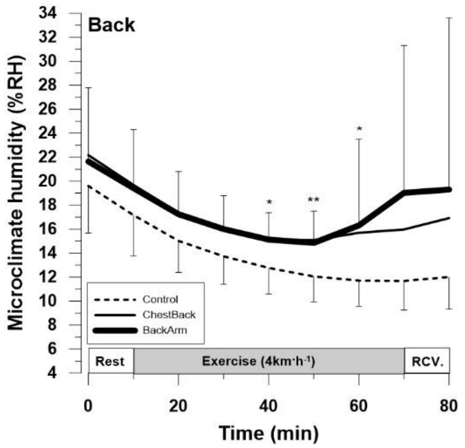
For the back area, the clothing microclimate temperature showed a significant difference between the three conditions over the time courses (Fig. 11A, $P < 0.001$). As both ChestBack and BackArm were the conditions with direct heating to the back area, it seemed similar during the 80-min protocol, not showing any significant difference. For both heating conditions, it steadily increased until 10 min after starting exercise and remained at the level of 37.5℃, while that in Control was below 33℃ for 80 min of the trials.

In the case of the microclimate humidity, there was no significant difference between the three conditions until 30 min of exposure, but after 30 min of exercise was a significant difference found ($P = 0.046$). Referring to Fig. 11B, the humidity under the BackArm condition tended to increase rapidly from 40 min after exercise, and the standard deviation was also large.

A



B



$^{*}P < 0.1$, $^{**}P < 0.05$, $^{***}P < 0.001$

Fig. 11 Time courses of clothing microclimate temperature (A) and humidity (B) on the back.

Table 8 Changes in clothing microclimate for the three conditions

			Control	ChestBack	BackArm	*P*-value
Chest	Temperature (℃)	Rest	31.8 ± 1.5	35.5 ± 0.7	32.1 ± 1.8	< 0.001
		Exercise (Last 3min)	30.9 ± 2.1	37.1 ± 1.9	33.1 ± 1.1	< 0.001
		Recovery	31.3 ± 2.1	37.1 ± 1.3	33.4 ± 1.1	< 0.001
	Humidity (%RH)	Rest	18.9 ± 2.8	22.1 ± 4.6	17.9 ± 5.2	0.104
		Exercise (Last 3min)	10.3 ± 2.2	11.1 ± 2.7	14.6 ± 4.1	< 0.001
		Recovery	10.8 ± 1.9	13.3 ± 5.4	18.3 ± 11.4	0.078
Back	Temperature (℃)	Rest	32.4 ± 2.0	36.1 ± 1.2	35.8 ± 0.6	< 0.001
		Exercise (Last 3min)	32.5 ± 2.4	37.8 ± 0.8	38.0 ± 0.9	< 0.001
		Recovery	32.7 ± 2.5	37.7 ± 0.7	37.9 ± 0.8	< 0.001
	Humidity (%RH)	Rest	17.8 ± 3.5	20.9 ± 4.3	20.6 ± 5.2	0.229
		Exercise (Last 3min)	11.7 ± 2.6	15.1 ± 2.7	19.1 ± 16.0	0.186
		Recovery	11.9 ± 3.0	17.5 ± 9.5	19.7 ± 17.5	0.306

3.6. Blood pressure

After the trials, a significant difference of average systolic pressure was found in ChestBack (P = 0.007) and BackArm (P = 0.064) compared to that in the pre-exercise phase (Table 9). In Control, 80 min of exposure to the cold air rarely affected the systolic blood pressure unlike those two heating conditions. In ChestBack, the systolic pressure increased by 6.1 ± 5.5 mmHg after the exercise compared to the baseline, and that in BackArm showed an increase of 3.7 ± 5.6 mmHg.

For the diastolic pressure, the declined values at the end of the exercise were observed in Control, ChestBack, and BackArm by 1.7, 0.4, and 0.8 mmHg, respectively. However, there was no significant difference found in the three conditions.

Table 9 Blood pressure at pre-exercise and post-exercise for the three experimental conditions

Variable	Condition	Phase	Mean ± SD	t	*P*-value
Systolic blood pressure (N = 10)	Control	Pre-EXE	124.1 ± 8.0	-0.587	0.572
		Post-EXE	125.2 ± 7.3		
	ChestBack	Pre-EXE	119.8 ± 6.5	-3.510^{**}	0.007
		Post-EXE	125.9 ± 8.3		
	BackArm	Pre-EXE	120.4 ± 7.5	-2.108^{*}	0.064
		Post-EXE	124.1 ± 8.7		
Diastolic blood pressure (N = 10)	Control	Pre-EXE	77.7 ± 4.3	1.494	0.169
		Post-EXE	76.1 ± 4.7		
	ChestBack	Pre- EXE	77.9 ± 7.0	0.206	0.841
		Post-EXE	77.5 ± 8.0		
	BackArm	Pre- EXE	77.6 ± 6.0	0.346	0.737
		Post-EXE	76.8 ± 6.8		

(Unit: mmHg)

3.7. Heart rate and total body mass loss

For the measured heart rate, there was no statistical difference found between the three experimental conditions throughout the time courses (Fig. 12). During the rest, the heart rate for Control, ChestBack, and BackArm was 69.5 ± 7.1, 88.6 ± 8.1, and 74.9 ± 8.4 bpm, respectively (Table 10). The maximum heart rate observed during the exercise was 95.5 ± 7.5 bpm in Control, 101.0 ± 11.0 bpm in ChestBack, and 96.0 ± 5.2 bpm in BackArm, showing no significant difference.

The total body mass did not show any significant difference between the three conditions. It decreased by 160 ± 120 g/trial in Control, 150 ± 30 g/trial in ChestBack, and 210 ± 130 g/trial in BackArm for 80 min of exposure without any significant difference (Table 11).

Table 10 Changes in heart rate for the three conditions

	Control	ChestBack	BackArm	*P*-value
Rest	69.5 ± 7.1	72.1 ± 10.2	72.0 ± 6.3	0.764
Exercise (Last 3min)	88.6 ± 8.1	92.6 ± 9.8	88.5 ± 5.4	0.413
Recovery	74.9 ± 8.4	79.3 ± 9.4	72.8 ± 7.5	0.290

(Unit: bpm)

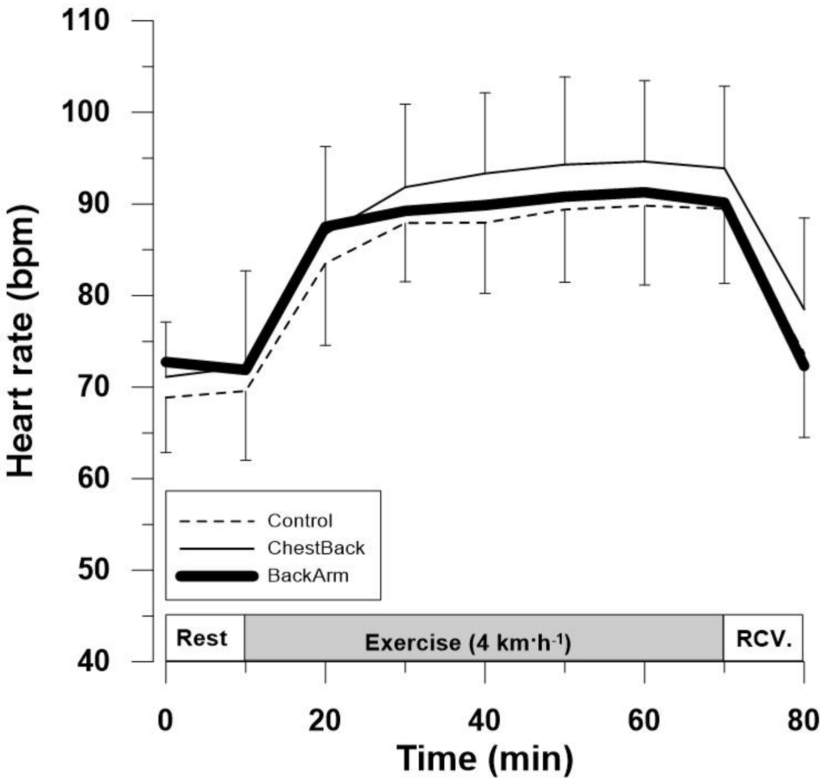


Fig. 12 Time courses of heart rate for 80-min exposure.

Table 11 Changes in body mass for the three conditions

	Control	ChestBack	BackArm	*P*-value
Pre-EXE	76.6 ± 15.9	76.6 ± 15.9	76.8 ± 16.1	0.720
Post-EXE	76.5 ± 15.9	76.5 ± 15.9	76.6 ± 16.1	0.844
Δ EXE (g/trial)	-160 ± 120	-150 ± 30	-210 ± 130	0.496

(Unit: kg)

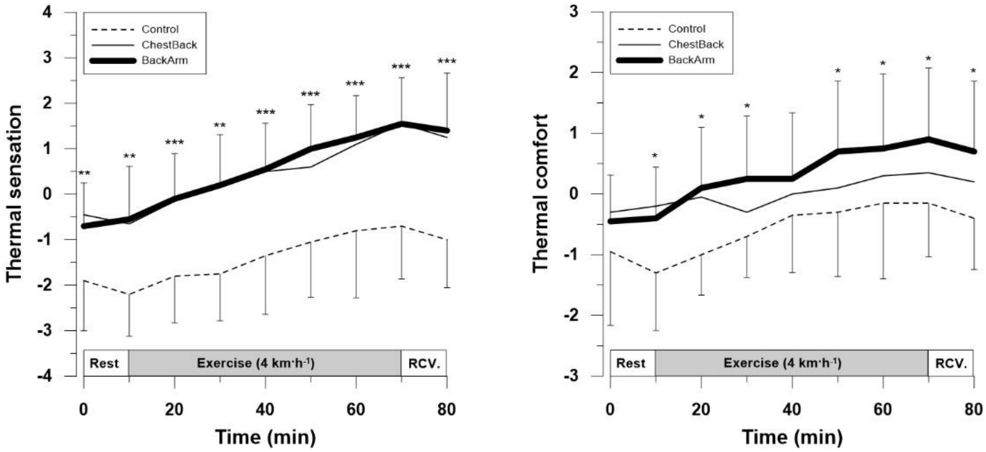
3.8. Subjective responses

3.8.1 Thermal sensation and thermal comfort

The average scores of thermal sensation showed a significant difference from the subjects' resting (Table 12). A significantly lower score was found in Control, and that in ChestBack and BackArm was -0.5 ± 1.3, and -0.7 ± 0.9, respectively (P = 0.003). During the rest, the subjects answered they felt cool in Control, and a little cool in ChestBack and BackArm (Fig. 13). Throughout the time courses, the thermal sensation showed the similar tendency of improvement within the two heating conditions with no statistical difference. At the end of the exercise, the difference between Control and the two conditions with the shirt got widened ($P < 0.001$), and the score of thermal sensation increased significantly to the extent that the most of subjects answered the sense of warmth in the two heating conditions. In Control, the subjects still felt a little cool even after completion of the treadmill walk. After 10 min of recovery, the score fell by 0.3 points under all three conditions, and a large statistical difference was also found between them ($P < 0.001$).

In terms of thermal comfort, there was no significant difference observed at the beginning of the protocol (P = 0.228). However, after 10-min rest, the subjects felt thermal discomfort with the intensified cold perceived in Control, while the score went up in the two heating conditions ($P < 0.01$). After the exercise, in Control the subjects responded they were still feeling a little uncomfortable with a bit freezing, whereas in ChestBack and BackArm they answered a little comfortable (Control: -0.2 ± 0.9; ChestBack: 0.4 ± 1.1; BackArm: 0.9 ± 1.2, P = 0.022). After 10-min recovery, in all three conditions the score fell by an average of 0.2 points and that in Control was the lowest (P = 0.034). Over the time courses, the responses were obtained that thermal comfort improved the most under the BackArm condition ($P < 0.05$).

A **B**



$^{*}P < 0.1$, $^{**}P < 0.05$, $^{***}P < 0.001$

Fig. 13 Time courses of thermal sensation (A) and thermal comfort (B) for 80-min exposure.

Table 12 Subjective responses at pre-exercise and post-exercise for the three experimental conditions

Subjective responses	Phase	Condition			*P*-value
		Control	ChestBack	BackArm	
Thermal sensation : Score -4 (very cold), -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), 1 (slightly warm), 2 (warm), 3 (hot), 4 (very hot)	Initial at rest	-1.9 ± 1.1[a]	-0.5 ± 1.3[b]	-0.7 ± 0.9[b]	0.003
	Last at rest	-2.2 ± 0.9[a]	-0.7 ± 1.8[b]	-0.6 ± 1.2[b]	0.005
	Last at exercise	- 0.7 ± 1.2[a]	1.6 ± 1.1[b]	1.6 ± 1.0[b]	< 0.001
	Last at recovery	-1.0 ± 1.1[a]	1.3 ± 1.3[b]	1.4 ± 1.3[b]	< 0.001
Thermal comfort : Score -3 (very uncomfortable), -2 (uncomfortable), -1 (a little uncomfortable), 0 (neutral), 1 (a little comfortable), 2 (comfortable), 3 (very comfortable)	Initial at rest	-1.0 ± 1.2	-0.3 ± 0.9	-0.5 ± 0.8	0.200
	Last at rest	-1.3 ± 0.9[a]	-0.2 ± 1.3[ab]	-0.4 ± 0.8[b]	0.058
	Last at exercise	-0.2 ± 0.9[a]	0.4 ± 1.1[ab]	0.9 ± 1.2[b]	0.012
	Last at recovery	-0.4 ± 0.8[a]	0.2 ± 0.9[ab]	0.7 ± 1.2[b]	0.017

3.8.2 Shivering sensation

Fig. 14 shows a total of the frequency obtained by all subjects for 80 min of cold exposure. Most of the responses of shivering were acquired in the phases of rest and recovery regardless of whether the subjects wore the shirt. However, it was confirmed that the frequency of shivers decreased noticeably during exercise especially for the two shirt-wearing conditions. In Control, it was found that the experimental subjects felt shivering throughout the body particularly on their arms and legs during the movements, including the back and chest areas (Fig. 15). They responded that they felt more shivers in the upper body than in the lower body. In ChestBack, despite heating to the chest and the back directly, the shivers on those areas were reported three times from the most of subjects. Compared to Control, the frequency of perceived shivering for the upper body periphery decreased, but no distinct effect of a shirt was found in the lower body. In BackArm, most of the subjects responded that they experienced a relaxed shiver throughout the body. In the case of unheated chest, more frequency of shivers was responded than in the ChestBack condition in the rest phase. Still, all subjects responded that the symptoms of shivering were alleviated during their exercising, including the periphery of the upper extremity and the entire lower extremity except the foot.

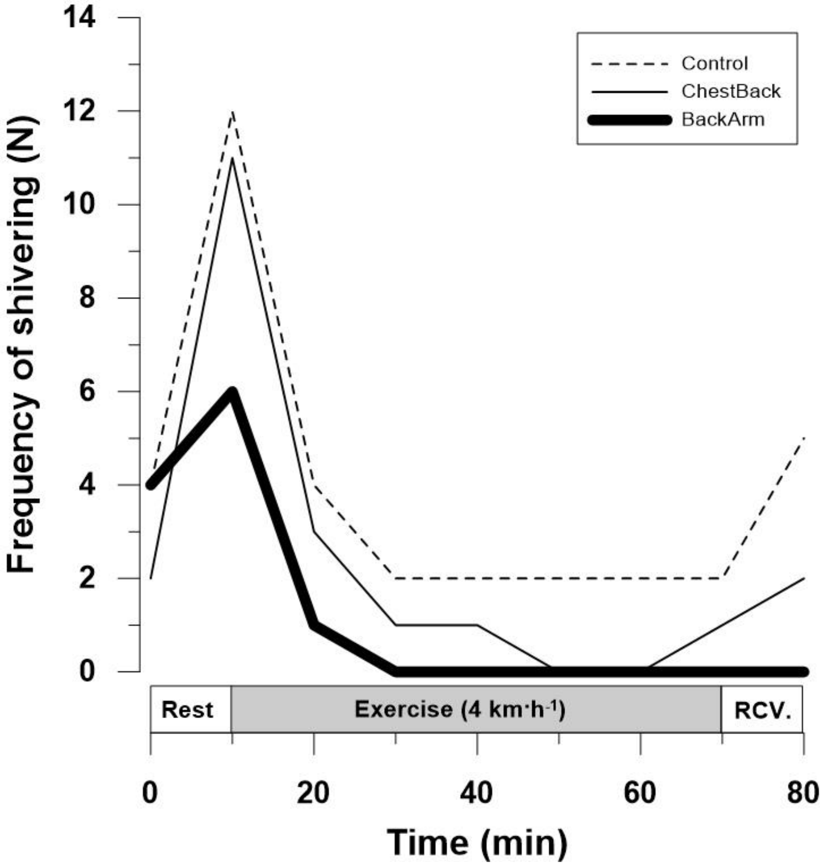
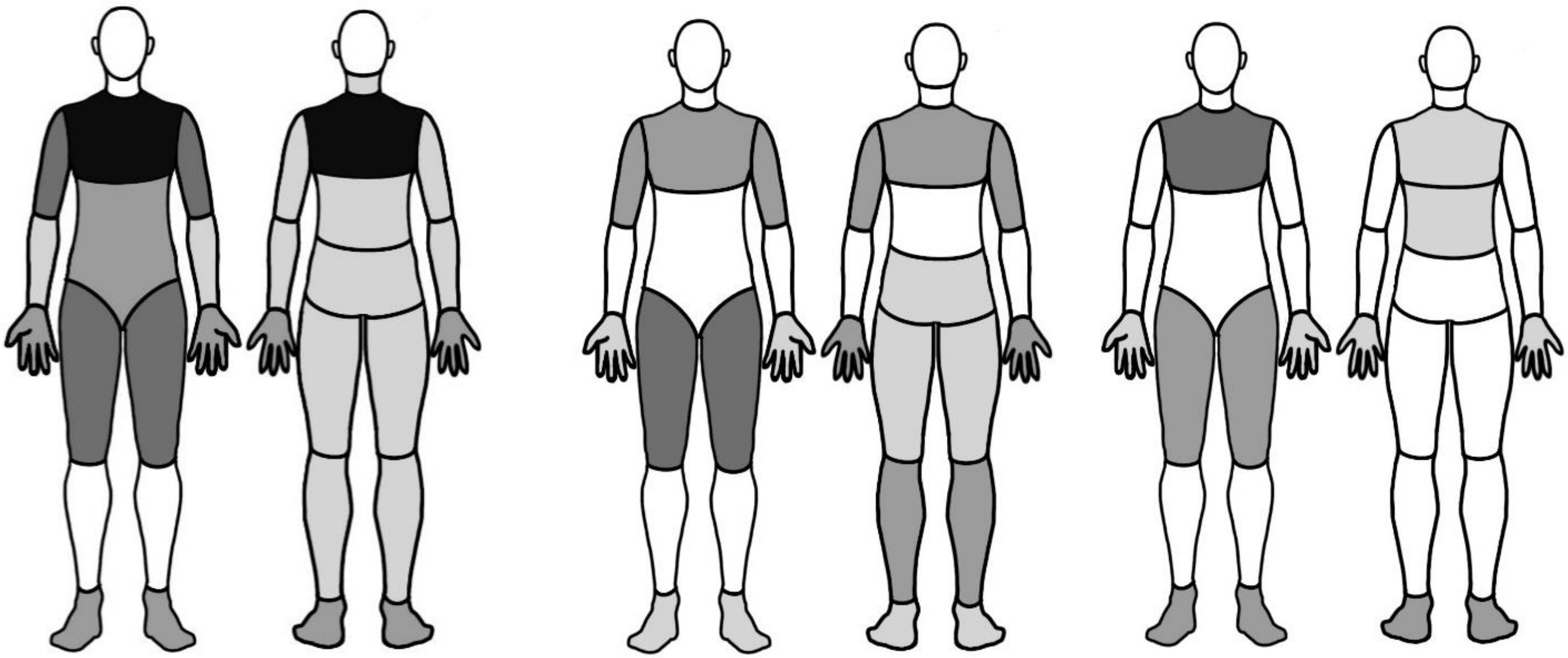


Fig. 14 Time courses of the frequency of the perceived shivers for 80-min exposure.

Fig. 15 The frequency of perceived shivering sensation of all subjects.

Control	ChestBack	BackArm



□: not mentioned, ■: once mentioned, ■: twice mentioned, ■: three times mentioned, ■: more than four times mention

Table 13 The frequency of regional shivering perception for the three conditions

Body region	Control	ChestBack	BackArm
#1	0	0	0
#2	0	0	0
#3	0	0	0
#4	6	2	3
#5	2	0	0
#6	3	2	0
#7	1	0	0
#8	2	1	1
#9	3	3	2
#10	0	0	0
#11	2	1	2
#12	0	2	0
#13	1	0	0
#14	7	2	1
#15	1	0	1
#16	1	2	0
#17	1	0	0
#18	2	2	1
#19	1	1	0
#20	1	1	0
#21	1	2	0
Total sum (N)	35	21	11

Chapter 4. Discussion

The present study was to figure out whether selective upper body heating could be an effective strategy for maintaining the mean skin temperature of the workers who are exposed to the cold. A sharp drop in the skin temperature not only during working hours but also during rest after work can cause cold-related diseases due the workers' sudden cessation of exercise. There are several previous studies showing that heating the upper body is much beneficial for body temperature control compared to heating the lower body as mentioned earlier (Janicki et al., 2001; Park et al, 2016). However, it is important to determine the optimal area that can increase thermoregulatory efficiency without hindering the movement of workers in the actual cold environments. The present study is a practical application of assessing the effectiveness of different body regions heated using an active heating garment in accordance with the consistent heat insertion. Those following three key findings are notable. Firstly, wearing an active heating shirt was effective to relieve the cold stress in terms of reducing oxygen consumption, keeping the skin temperature constant, and mitigating discomfort perception such as shivers. Secondly, the selective heating strategy that differentiated the body areas resulted in a difference in peripheral skin temperature maintenance responses. Lastly, the effect of wearing a heating shirt remained steady even after the exercise.

4.1. Advantages of wearing an active heating shirt

The most outstanding finding in the present study is that the frequency of perceived shivering was significantly reduced. Shivering thermogenesis is caused by involuntary contraction of skeletal muscle that occurs during exposure to cold. In a cold environment, shivering is an effective process to sustain the core temperature as it can induce body heat approximately trifold (Inoue & Kondo, 2013). But at the same time, it induces a muscle tremor resulting in body heat dissipation. In the present study, under conditions of wearing an active heating shirt the lower amount of oxygen consumption was measured in line with the symptom of shivering. Moreover, as mentioned in the previous study (Taguchi et al., 2004), the heating garment can be especially effective in transferring heat in the very beginning of warming. Regarding the heat transfer into the thermal core depends on skin temperature, it is noteworthy in the present study that the subjective responses of shivering were mostly acquired in the beginning of the trials and without any active exercise. Also, unlike the condition of control, in both heating garment conditions there were rare perceived shivers reported in the phase of recovery. If so, the impact of wearing a heating shirt before the exercise would have continued as the experiments progressed and it would have helped minimising the energy consumption consistently. Regarding the heat transfer into the thermal core depends on skin temperature, it is noteworthy in the present study that the subjective responses of shivering were mostly acquired in the beginning of the trials and without any active exercise.

Two conditions of wearing an active heating shirt during 80 min of exposure in cold environment induced different thermoregulatory responses compared to the control. In an environment of -9°C, wearing a heating shirt significantly affected ΔT_{re}, $\bar{T}_{k}$, and subjective responses and there was little difference between the two heating conditions. In particular, wearing a shirt can have extra benefits of maintaining the mean skin temperature, not just the upper body. The observation in the present study showed that regional skin temperature of the thigh, where the heat was not inserted directly, was remarkably well maintained while the subjects' wearing the shirt. Although the deviation between the two conditions, where the upper body regions being heated vary, was rare, it can be agreed that heating the upper body influences maintaining the thermal effect on the lower extremity. The results of the present study suggest that inserting the same amount of heat on the upper body will lead to the consistent maintenance of lower body skin temperature, no matter which combination of the upper body areas is heated.

The other key observation in the present study is that the upper body skin temperature especially of forearm was well maintained during the recovery phase. It can be a meaningful finding as a practical application for developing a worker-assistant garment. Physiologically, working out in a cold environment amplifies the heat loss by convection and conduction, so the body temperature tends to drop more rapidly. Viecsteinas (1982) found that the superficial shell insulation can lessen due the increased blood flow during the exercise. In this regard, suspending workers' exercise in a cold environment can cause the drastic decline in skin temperature. It is evident that the both shirt-wearing conditions prevent skin temperature from decreasing. Considering that workers are easily exposed to cold-related diseases due to a sharp drop in the skin temperature after work, the results of the present study suggest that wearing an active heating garment can alleviate the peripheral temperature decline.

4.2. Impact of different body regions heated

The tubes through which hot water flows were placed on the chest, back, and upper arms, respectively, according to each condition. During 80 min of exposure, the heat flow rate was consistently maintained at a similar level without any significant difference in both shirt-wearing conditions, which was an average of 199 $kcal \cdot h^{-1}$

on each compartment. This fact is well illustrated in the degree of maintenance of the mean skin temperature. In the control condition, where there was no extra heating during exposure to the cold environment, the clothing microclimate temperature continued to drop, which means that even if multiple layers of winter clothing are worn with a padded jumper, the warmth of the clothing weakens with exposure time. However, the clothing microclimate temperature in the back area within the two shirt-wearing conditions rose continuously, and the mean skin temperature was also maintained well during 80 min of exposure to the cold environment. In other words, active heating garments can help maintain mean skin temperature by providing constant warmth during and after workers' 60 min of exercise.

To maintain core temperature in a cold environment, the body displays skin vessel contraction to prevent heat dissipation, and therefore results in a decrease in peripheral temperature (Smolander et al., 1992). The current study affirmed that wearing an active heating shirt has a betterment in maintaining the peripheral skin temperature except of the foot especially when heating the back and upper arms. For example, as aforementioned, the forearm temperature was likely to remain uniform under the condition of heating the upper back and upper arms, while the other two conditions showed slight decrease from the very beginning of the trials and this gap widened as the exercise continued. This tendency appeared similar to the response of thermal comfort. Choi & Loftness (2012) reported that the subjects felt thermally neutral at the level where the forearm temperature was about 32℃ with little skin temperature gradient. Pimental (1991) discovered that a rise in forearm skin temperature may positively affect the thermal perception synergistically. These results imply that not only reducing skin temperature deviation, but also maintaining an appropriate level of skin temperature is important. Coupled with the findings in the current study, heating the back and upper arms with an active heating garment may have a positive impact on maintaining the forearm temperature at a constant level of 32℃ without any significant gradient during the prolonged exposure to the extremely cold ambience.

The present study hypothesised that wearing an active heating shirt would show a positive effect on thermal sensation and thermal comfort. Compared to non-heated condition, it is obvious that the two shirt-wearing conditions improved the subjective responses. Notably, comparing the two heating conditions one another, it is hard to tell that the more thermal sensation goes up, the more the wearer necessarily feel thermally comfortable. The subjects reported there was improvement in thermal sensation, and at the end of the exercise phase they felt a little warm without any significant difference between the two heating conditions. Unlike the thermal sensation, however, the subjects felt significantly more thermally comfortable during heating the back and upper arms.

4.3. Limitations

The present study has some limitations as follows. The results of the present study were obtained only from healthy men in their 20s. However, the thermoregulatory responses caused by exposure to a cold environment varies depending on sex and age. Females were found to be more susceptible to cold than males in physiological and subjective responses and shivering was mobilised at relatively high environmental temperature (Kaikaew et al., 2018). With ageing, core temperature becomes vulnerable to the cold along with a decrease in skin vascular contraction ability (Inoue et al., 1992). It is difficult to apply the results of the present study to male and female in all ages as the thermoregulatory response varies according to sex and age. In this light, further comparative studies to evaluate the heating strategy considering demographic factors are necessary for developing heating garments.

All experiments in the present study were conducted in a climatic chamber with a temperature of -9.1℃ and the level of insensible airflow. However, in harsher environments, the results of the current study are hard to be applied. For example, Cortili et al. (1996) found that the subjects reported severe pain in their hands and feet in an ambient environment of -20℃. Moreover, thermal transfer properties of the clothing largely depend on the degree of airflow (Gonzalez, 1989). O'Brien et al. (2011) discovered that the higher the wind speed is, the higher the evaporative resistance ratio and also the airflow has rare effect on low-permeable PPE therefore a low evaporative resistance ratio. In the present study, wearing an active heating shirt prevented the hand skin temperature from dropping rapidly and there was no significant difference found in foot skin temperature among the three conditions even under the no shirt-wearing condition. Since the shirt was designed not to cover hands, it is hard to say that the active heating shirt would minimise a decrease in a peripheral skin temperature in colder environments with higher airflow and humidity.

Every subject performed exercise of walking at 4 km · h^{-1} in the current study. Rissanen et al. (1996) compared the amount of finger temperature reduction in a standing position and walking and found the greater decrease during the subjects' standing. Nimmo (2004) noted that the intensity of exercise hugely affects generating the metabolic heat to offset cold stress. Pugh (1967) also observed more shivers at an exercise intensity of less than 30% $\dot{V}O_{2max}$ were mobilised in a cold environment with more air while the subjects wearing wet clothing. In contrast, with more exercise intensity (60% $\dot{V}O_{2max}$), there were rare effects of the severity of environments. Further studies are needed to investigate the effects of an active heating shirt for the workers who usually work in static postures such as standing sentry.

For the last, the present study did not take into account the effects of clothing weight and number of layers. Several previous studies mentioned that the weight and layers of clothing increase oxygen uptake (Teitlebaum & Goldman, 1972; Withey, 1974). Duggan (1988) also quantified the effect of multilayered clothing on the energy cost of stepping and figured out that 3-4% increased per layer, attributing to hobbling due to the bulkiness. Dorman & Havenith (2009) also determined that the metabolic rate increased by 2.7% per kg when walking at 5 $km \cdot h^{-1}$. In the current study, subjects wore two layers on their upper bodies in the control condition and a total of three layers including a vest of 1.8 kg in the two heating conditions, so it is necessary to further examine the effect of clothing weight and layers for developing optimal heating garments.

Chapter 5. Conclusions

This study was to evaluate thermoregulatory effects of body regional heating using a liquid-perfused shirt in a cold environment. The present study showed specifically meaningful derivation of the effect of differential body regions both quantitatively and qualitatively in a cold environment. We can sum up with those four findings. Firstly, no difference in heat insertion to the body between heating the combination of chest and upper back and of upper back and upper arms. Secondly, both shirt-wearing conditions was effective in terms of maintaining the mean skin temperature, reducing the amount of oxygen consumed, and elevating the thermal sensation. Thirdly, the forearm skin temperature was higher under the condition of heating the upper back and upper arms than of heating the chest and upper back as well as hand temperature during the recovery phase. And for the last, subjects felt more thermally comfortable for heating the back and upper arms than heating the chest and back. Likewise, shivering sensation was less reported during heating the back and upper arms compared to heating the chest and back. To conclude, both “Chest/Back” and “Back/Upper arm” heating are effective to maintain body temperature and support thermal perception in cold environments. In the case of non-exercise, “Chest/Back” heating may be more effective in maintaining mean skin temperature, but when walking or moving both arms, “Back/Upper arm” heating is subjectively more advantageous for manual workers.

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초 록

본 연구는 내부표면온도가 42℃인 액체 순환 셔츠를 이용하여 (1) 일정한 열유량이 주입되는 상체 능동 가온이 생리적, 심리적 반응에 미치는 영향을 조사하고자 하였다. 또한 (2) 극한의 한랭 환경에 노출된 작업자를 위한 체온 유지에 효과적인 최적의 가온 부위 조합을 제안하고자 하였다. 총 10명의 건강한 20대 남성들이 (1) Control(비가열), (2) ChestBack(가슴과 등을 가열), (3) BackArm(등과 상완을 가열)의 세 가지 조건의 실험에 참여하였다. 1회 실험은 10분 휴식기, 60분 운동, 그리고 10분 회복기로 구성되었다. 모든 실험은 온도 −9.1 ± 0.6℃의 인공기후실에서 진행되었다. 두 가온 조건 ChestBack과 BackArm의 열유량은 유의한 차이 없이 평균 398 kcal · h^{-1} 수준이었다. 세 가지 조건 간 직장온의 유의한 차이는 발견되지 않았지만, 한랭 환경에 80분 노출되는 동안 직장온 증가는 대조군에 비해 가온 셔츠를 입은 두 조건에서 유의하게 더 컸다(P = 0.012). 평균 피부 온은 대조군에 비해 두 가온 조건에서 유의하게 높았지만, 두 가온 조건 간 유의차는 발견되지 않았다. 특히 전완 피부온은 가슴과 등을 가열하는 조건보다 등과 상완을 가열하는 조건에서 유의하게 높았고, 80분간의 노출 동안 큰 변화 없이 일정하게 유지되는 경향을 보였다(P = 0.042). 손등 피부온 역시 대조군에 비해 가온 셔츠를 입는 두 가지 조건에서 한랭 노출 후반기에 유의하게 높은 것으로 나타났다(P < 0.005). 두 가온 조건에서 평균 산소 섭취량은 노출 시간 전반에 걸쳐 대조군에 비해 유의하게 적었다(P < 0.005). 한서감은 세 조건 간 유의차가 발견되었고(P < 0.01), 운동 종료 시점부터 회복기가 끝날 때까지

대조군에 비해 두 가온 조건에서 약 2~3점 더 높았으며, 피실험자들은 가온 조건에서 '약간 따뜻함'을 느낀다고 응답하였다. 온열 쾌적감도 한서감과 유사한 결과가 발견되었지만, 등과 상완을 가온하는 조건에서 유의하게 높은 개선이 관찰되었다(P < 0.01). 인지된 전율감의 경우 등과 복부를 포함해 팔, 다리와 같은 사지말단에서 등과 상완을 가온하는 조건에서 빈도가 적게 보고되었다. 요약하자면, 혹한 환경에 노출된 작업자를 위한 능동 가온 방한복을 개발할 때 '가슴/등'과 '등/상완' 가온 조합 모두 체온 유지에 기여할 것이다. 그러나 작업 특성상 사지의 잦은 동작을 고려한다면 효과적인 전완온과 손등온의 유지를 보인 '등/상완' 가온 조합이 작업 효율을 향상시킬 뿐만 아니라 전율을 감소시킬 것으로 사료된다. 본 연구 결과는 겨울철 한랭 환경에 노출된 작업자의 체온유지를 위한 발열의류 개발 시 효과적인 기초자료로 활용 가능하다.

주요어: 한랭 스트레스, 위팔, 직장온, 말초 부위 피부온, 한서감, 산소 소비량, 전율감

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