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Effectiveness of a field-type liquid cooling vest for reducing heat strain while wearing protective clothing

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Abstract. This study examined the effectiveness of a field-type liquid cooling vest (LCV) worn underneath an impermeable protective suit on heat strain during walking. Eight men walked for 60 min at a moderate speed (3.0 km/h) wearing the suit in a warm environment (33°C, 60% relative humidity) without (control, CON) or with the LCV. A smaller increase in rectal temperature was recorded in participants in the LCV than in the CON condition (37.6 ± 0.1°C vs. 37.9 ± 0.1°C, $p<0.05$). Walking while wearing the LCV reduced the level of physiological heat strain, as measured by the mean skin temperature (35.5 ± 0.1°C vs. 36.3 ± 0.1°C), chest sweat rate (13.5 ± 3.0 mg/cm^2/h vs. 16.6 ± 3.8 mg/cm^2/h), chest cutaneous vascular conductance (349 ± 88% vs. 463 ± 122%), body weight loss (0.72 ± 0.05% vs. 0.93 ± 0.06%), and heart rate (101 ± 6 beats/min vs. 111 ± 7 beats/min) ($p<0.05$, for all comparisons). These changes were accompanied by a decrease in thermal sensation and discomfort. These results suggest that a field-type LCV attenuates exertional heat strain while wearing impermeable protective clothing.

Key words : Core temperature, Thermal strain, Microclimate cooling, Hypohydration, Heat stress

Introduction

Workers who are exposed to hazards, such as biological, chemical or radiological agents, must wear personal protective equipment. An increase in metabolic heat production during work combined with high ambient temperature and humidity can lead to a progressive increase in body heat content. Because restrictive clothing inhibits heat dissipation, prolonged work while wearing personal protective equipment may lead to hyperthermia and heat illness.

Some microclimate cooling systems have been found to inhibit the increase in heat strain in workers wearing personal protective equipment[1, 2]. Cold or natural air ventilation, liquid cooling and phase-change material garments each have a beneficial cooling effect. However, microclimate cooling systems have inevitable ergonomic problems such as the additional weight and layers, and restriction of body movement. Among these cooling systems, natural air ventilation garments are lightweight and can be used for non-tethered cooling systems[3, 4], but providing complete protection from hazards while wearing protective clothing remains a problem.

In liquid cooling garments (LCGs), cool liquid is circuited inside tubes embedded in the garment with the help of a battery-powered pump[1]. Once the liquid is warmed by the body, it is circulated to a refrigeration control unit

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where it is recooled. Because early LCGs were developed for use by astronauts in the hostile aerospace environment[5], the weight of the control unit was not a concern. In one study, use of a stationary cooling system, in which a pump delivered cool water from a regulated water bath at 15°C to a whole-body garment, limited the increase in core temperature increased to only 0.4°C during a 2-h exercise in participants wearing protective clothing; this contrasted with a 2.0°C increase in participants wearing protective clothing without the cooling system[6]. Although the optimal design of an LCG was investigated in a theoretical model[7], few studies have reported on the practical use of an LCG in a non-tethered cooling system. Bartkowiak *et al.*[8] reported on the effectiveness of an "active" LCG system (tube-lined long sleeve underwear) used during walking in a warm condition while wearing protective clothing. Although the LCG system was mobile, the weight of the cooling unit was almost 10 kg, and the wearer had to carry around it when moving.

Grahn *et al.*[9] described a "wearable" LCG system comprising a hydration backpack and tube-lined palmar pads. They compared the effectiveness for reducing heat strain between the wearable LCG and an LCG with a stationary cooling system while wearing protective clothing and found no difference. Because further developments of cooling systems comprising a coolant, battery, and pump are expected in the near future, it is important to determine the effectiveness of the latest portable LCG for reducing heat strain.

In the present study, we evaluated the effectiveness of a commercially available field-type (non-tethered, wearable) LCG on heat strain in participants exercising while wearing protective clothing. The LCG comprised a tube-lined water-perfusion vest and coolant containing a backpack worn underneath protective clothing. We hypothesized that the use of the LCG would reduce physiological and psychological heat strain during light exercise while wearing protective clothing.

Subjects and Methods

Participants

Eight healthy men volunteered for the present study. The general characteristics of the participants were: age, 36.0 ± 9.8 yr; height, 174.9 ± 5.0 cm; and body mass, 67.1 ± 5.9 kg (mean ± SD). All experimental procedures were approved by the Human Research Ethics Committee of the National Institute of Occupational Safety and Health, Japan, in 2016. The participants were informed of the experimental procedures and potential risks, and all signed a consent form.

Microclimate cooling

The field-type LCG tested in this study was a commercially available vest (TSCB-17001, Hitachi Power Solutions Co., Hitachi, Japan). The tube-lined water-perfusion vest was made of 100% polyester and was laminated around small-diameter silicon tubing (1.6 mm, internal diameter) divided into multiple parallel circuits. The total estimated tubing length for the vest was 16 m and the total weight of the vest was 0.4 kg. The vest was connected to a coolant-containing backpack, which measured 240 × 430 × 60 mm, and water was pumped via a rechargeable battery at a rate of 300 ml/min. To recool the water in the backpack, a silicon bag through which water was circulated was bookended between the ice packs. To maintain the temperature of the ice packs and water, the inside of the backpack was covered by thermal insulating materials. The outside of the backpack was made of polyester and nylon to make it waterproof. The total weight of the backpack was 3.4 kg. The inlet and outlet temperatures of the tubing were recorded using thermistor probes (LT-ST08-00, Gram Corp., Saitama, Japan) that were attached to the external side of the tubing by tape and wrapped by the materials of the vest. Although the temperature of the water was not measured directly, we analyzed the energy uptake by the water using the inlet and outlet temperatures of the tubing.

Experimental protocols

The study was performed in two climate chambers. One chamber was a thermoneutral room with an ambient temperature of 25°C and 40% relative humidity (RH). The other was a heated room with an ambient temperature of 33°C and 60% RH. In both rooms, the wind speed was 0.4 m/s.

The volunteers performed two experimental trials: one wearing the LCV (LCV trial) and the other a control trial without the LCV (CON). These two tests were repeated at a 1-wk interval in a balanced order. The volunteers refrained from consuming any beverages containing caffeine or alcohol from the night before the day of the experiment. They ate a light meal 3 h before the experiment and then reported to the laboratory. After drinking 200 ml of water and voiding completely, each volunteer entered the thermoneutral room wearing a T-shirt (100% polyester, 160 g) and shorts (100% polyester, 64 g). No water was provided until the end of the experiment. After a 30-min first acclimation period, physiological sensors and probes were attached, and baseline measurements were obtained with the participant in a seated position. After the 30-min baseline period, in both the CON and LCV trials the volunteer put on a round-neck T-shirt with long sleeves (100% polyester, 174 g), long underwear (100% polyester, 226 g), cotton gloves (100% cotton, 18 g), rubber gloves (100% natural rubber, 37 g), socks (100% cotton, 58 g), work shoes (1,030 g), high-density polyethylene coveralls (Tyvek®, DuPont, Wilmington, DE, USA; 160 g), a full-face gas mask (354 g) and a helmet (426 g). Fifteen minutes later, in the LCV trial, the participant put on the vest and backpack over the long sleeve shirt, and the cooling system was started. To confirm that the system was working properly, the participant continued to rest for 10 min, after which he moved to the heated room and remained seated for another 5 min. After rating his perception, each participant walked on a treadmill (SportsArt Fitness T650, Woodinville, WA, USA) for 30 min at 3 km/h. Following a 10-min break, the participant walked again for 30 min. During the break, the volunteer remained seated in the heated room.

Measurements

Rectal temperature (T_{rec}) was measured continuously using a thermistor probe (701 J, Nikkiso-Therm, Tokyo, Japan) self-inserted by the participant to 12 cm beyond the rectal sphincter. Skin temperature (T_{skin}) was also monitored continuously using thermistor probes (010, Nikkiso-Therm) placed on the forehead, back, chest, forearm, dorsal side of the hand, thigh, calf and dorsal side of the foot. These temperature data were recorded using LT loggers (LT-8, Gram Corp.) at 1-min intervals. The mean T_{skin} was calculated using the following equation and the temperatures of the regional areas [0.07 T_{skin} on forehead + 0.35 (T_{skin} on chest + T_{skin} on back)/2 + 0.14 T_{skin} on forearm + 0.05 T_{skin} on dorsal hand + 0.19 T_{skin} on thigh + 0.13 T_{skin} on calf + 0.07 T_{skin} on dorsal foot][10]. The rate of body heat storage (W) was calculated as the change in body heat content per time. The body heat content was calculated as the average body temperature (in°C) × body mass (in kg) × 3.47 (mean specific heat capacity of the body, in $kj \cdot °C^{-1} \cdot kg^{-1}$)[11]. Average body temperature was determined using thermometry (with weightings of 0.9 T_{rec} and 0.1 mean T_{skin})[11].

Blood pressure (right brachial artery) and heart rate (three-lead electrocardiogram) were measured and recorded using a Tango exercise blood pressure monitor (SunTech, Morrisville, NC, USA). Sweat rate on the chest was monitored by dew point hygrometry (OKS-04HM, Skiken, Nagoya, Japan). Blood flow in the chest skin was estimated using laser Doppler flowmetry (LDF; FLO-C1, Omegawave, Tokyo, Japan). To connecting the cables to each device (sphygmomanometer, electrocardiograph, dew point hygrometer, and laser Doppler flowmeter), the cables were put through a hole around the waist, and the hole was closed by tape. The LDF data are expressed as the percentage change from the averaged value of the baseline period. Cutaneous vascular conductance (CVC) was calculated as the LDF value divided by the mean arterial pressure and is expressed as the percentage change from the baseline value. Body weight was measured before and after the experiment with the participant wearing only undershorts.

Thermal sensation and comfort, and physical and psychological fatigue were assessed using a visual analog scale. In the ratings of thermal sensation and comfort, we used a 200 mm visual analog scale, where 'coldest' or 'most uncomfortable' was indicated on the extreme left and scored as −10, 'hottest' or 'most comfortable' was indicated on the extreme right and scored as 10, and 'neutral' indicated on the center and scored as 0[12, 13]. The length from 0 point was determined as the rating value. The volunteers were instructed to separate carefully the thermal sensation from comfort by asking them to report their current thermal perception; that is, how much they felt the ambient temperature had increased or decreased and how much they liked or disliked the thermal condition, respectively. We also asked them to separate their thermal perceptions for 'the whole body' and 'torso'. Although it is debated whether a categorical (numerical) scale, the visual analog scale, or both combined is more valid for the assessment of subjective thermal sensation[14, 15], we selected the visual analog scale to assess possible regional differences (whole body versus torso) for each thermal sensation and comfort. For evaluating fatigue, we used a 100 mm visual analog scale, where the minimal rating was scored as 0 (indicated 'not fatigued at all') and the maximal rating as 10 (indicated 'extremely fatigued').

Statistics

Two-way analysis of variance (ANOVA) with repeated measures (using trial and time as the main effects) was performed. If a significant F-value was observed, Bonferroni's least significant difference post hoc test was performed to identify the difference at a specific time point. The null hypothesis was rejected at $p<0.05$. All analyses were performed using StatView 5.0 software (SAS Institute, Cary, NC, USA). Values are expressed as means ± SEM.

Results

Physiological strain

T_{rec} increased significantly during walking in both the CON and LCV trials (Fig. 1 (a), $p<0.05$), but T_{rec} from 5 min after the beginning of walking to the end of walking was lower in the LCV than in the CON ($p<0.05$). Mean T_{skin} was also lower in the LCV trial than in the CON trial immediately after wearing the LCV (Fig. 1 (b), $p<0.05$). T_{skin} values on the back and chest were lower in the LCV than in the CON trial (Fig. 1 (c) and (d), $p<0.05$). T_{skin} on the back decreased significantly immediately after wearing the LCV (Fig. 1 (c), $p<0.05$) and remained below the baseline, whereas the T_{skin} increased during walking in the CON trial ($p<0.05$). The increase in T_{skin} on the chest was delayed in the LCV compared with the CON trial (Fig. 1 (d)). The mean heat storage rates were greater in the CON than in the LCV trial (30 ± 2 W vs. 21 ± 2 W, $p<0.05$). Increases in heart rate and sweat rate were lower in the latter half of walking in the LCV than in the CON trial (Fig. 2 (a) and (b), $p<0.05$). Blood pressure did not change in the two trials (data not shown). The increase in%CVC was smaller throughout the walking in the LCV than in the CON trial (Fig. 2 (c), $p<0.05$). The percentage reduction in body weight after walking was greater in the CON than in the LCV trial (0.93 ± 0.06% vs. 0.72 ± 0.05%, $p<0.05$).

Psychological strain

Thermal sensation of the whole body increased during walking in both the CON and LCV trials (Fig. 3 (a), $p<0.05$), but the increases were smaller in the LCV than in the CON trial throughout the walking exercise ($p<0.05$). In parallel, thermal comfort of the whole body decreased during walking in both the CON and LCV trials (Fig. 3 (b), $p<0.05$), but the decreases were smaller in the LCV than in the CON trial throughout the walking exercise ($p<0.05$). Thermal sensation of the torso increased immediately after the walking exercise in the CON trial (Fig. 3 (c), $p<0.05$) but decreased immediately before and after the walking exercise in the LCV trial ($p<0.05$) and remained at the baseline level during walking. Thermal sensation of the torso was lower in the LCV than in the CON trial ($p<0.05$). Thermal comfort of the torso decreased from 15 min after the beginning of walking in the CON trial (Fig. 3 (d), $p<0.05$) but increased immediately before and after the walking exercise in the LCV trial ($p<0.05$). Thermal comfort was greater in the LCV than in the CON trial ($p<0.05$). Physical and psychological fatigue increased from 20 min after the beginning of walking in both the CON and LCV trials (Fig. 3 (e) and (f), $p<0.05$), but the ratings did not differ between trials.

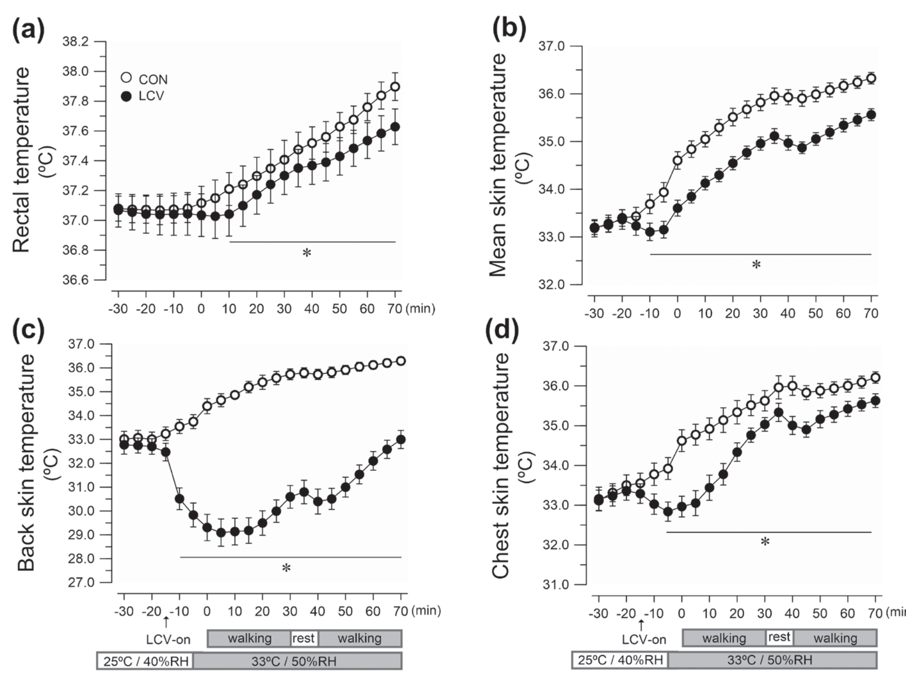

Fig. 1. Rectal temperature (a), and mean (b), back (c), and chest (d) skin temperatures in the non-cooling control (CON) and liquid cooling vest (LCV) trials. *Different (*p*<0.05) between CON and LCV. Values are mean ± SEM (*n*=8).

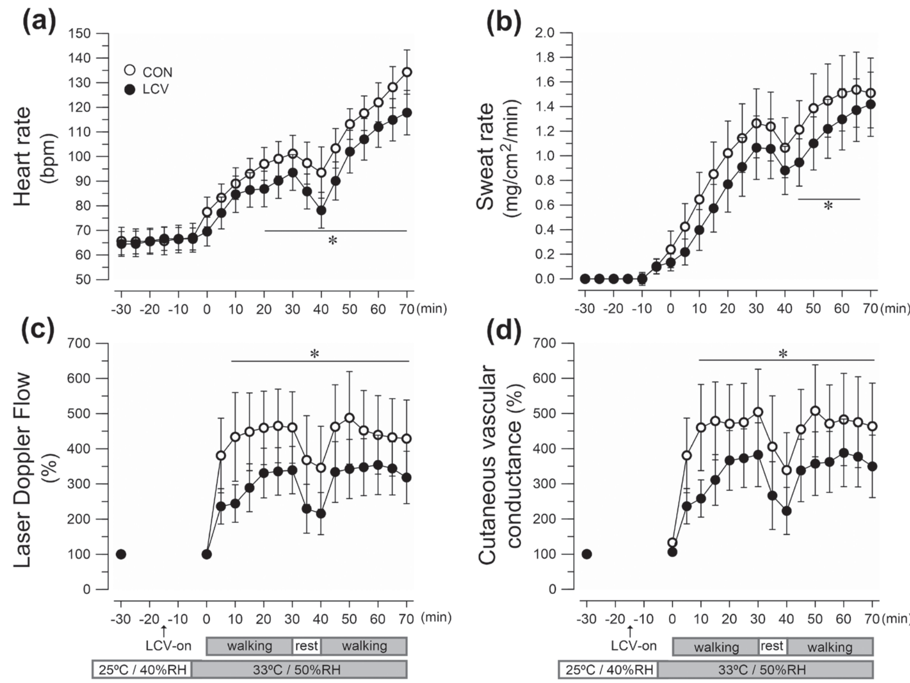

Fig. 2. Heart rate (a), sweat rate (b), laser Doppler flow (c) and cutaneous vascular conductance (d) on the chest in the non-cooling control (CON) and liquid cooling vest (LCV) trials.
*Different (p<0.05) between CON and LCV. Values are mean ± SEM (n=8).

Tubing temperatures and energy uptake by water

Figure 4 shows the inlet (to the vest) and outlet temperatures of the tubing and energy uptake by water in the LCV. Although both temperatures were stable in the thermoneutral room, moving into the heated room caused an increase in both temperatures. The differences between the inlet and outlet temperatures remained constant throughout the walking exercise (2.6 ± 0.1°C). The energy uptake by water did not change significantly throughout the experiment, but the values tended to be greater in the resting condition than during walking.

Discussion

We compared heat strain during walking while wearing protective clothing between wearing and not wearing an LCV and found that wearing the LCV reduced the physiological and psychological heat strain during two 30-min walking periods. Although the field-type cooling system was carried on the participant's back, their perception of fatigue did not increase compared with the CON trial.

In the study by Caldwell *et al.*[6], a stationary cooling system to deliver water at a constant 15°C by a pump to a whole-body LCG maintained core temperature, T_{skin} and heart rate at low levels during light exercise while wearing protective clothing compared with the no-cooling condition. Although the environmental conditions (33°C with 60% RH vs. 48°C with 20% RH) and exercise modes (walking vs. cycling) differed between our study and that by Caldwell *et al.*[6], it is useful to compare the cooling efficiency of the non-tethered and tethered systems. For core temperature, the earlier study[6] reported 38.0°C at 60 min in the control and 37.3°C in the LCG condition (baseline: 36.9°C), giving a cooling effectiveness of 65% (the extent of the reduction). In the present study, the cooling effectiveness for T_{rec} was 28% (baseline, 37.0°C; CON, 37.9°C; LCV, 37.6°C at 70 min). Similarly, the cooling effectiveness for other parameters was lower in the present study than in the study by Caldwell *et al.*[6]: mean T_{skin}, 28% vs. 65%; heart rate, 23% vs. 57%; and body weight reduction, 22% vs. 80%, respectively.

Although the inlet tube temperature was 15°C in the thermoneutral room in the present study, the temperature increased to 25°C at the end of walking (Fig. 4). The differences in the water temperature and covered body area (torso vs. whole body) may have caused the loss of cooling efficiency. By contrast, Grahn *et al.*[9] demonstrated that palm cooling by a wearable LCG reduced the rate for increase in esophageal temperature by 47% during light-intensity walking while wearing protective clothing.

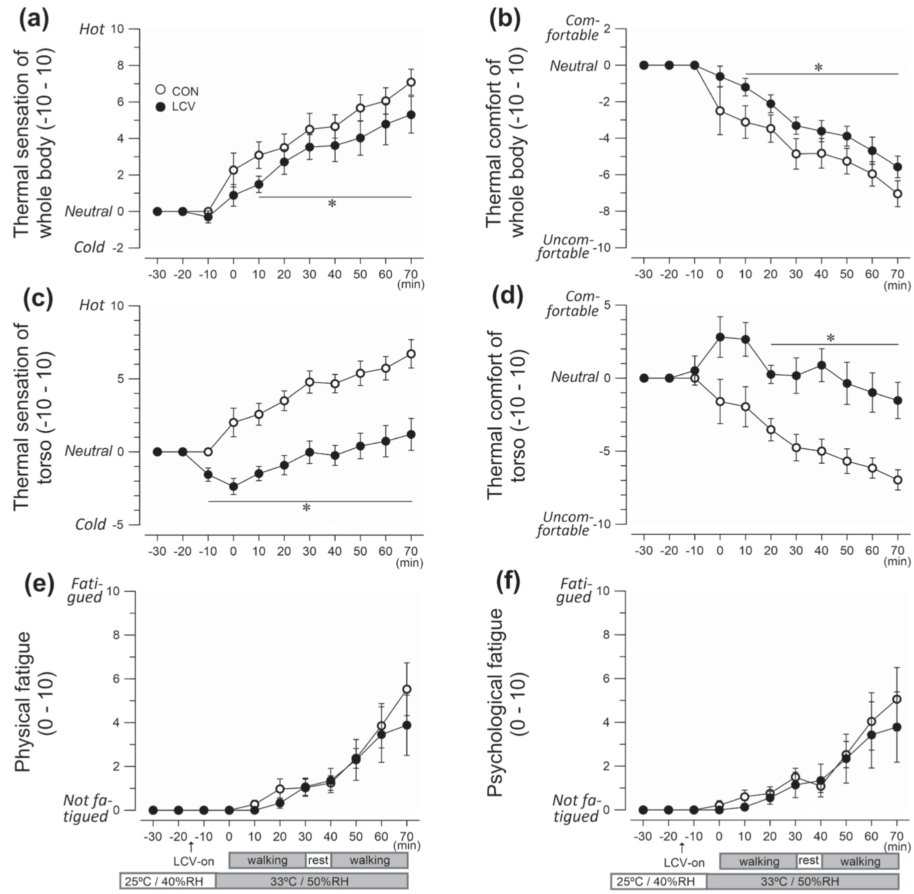

Fig. 3. Rating scores of thermal sensation of the whole body (a), thermal comfort of the whole body (b), thermal sensation of the torso (c), thermal comfort of the torso (d), physical fatigue (e) and psychological fatigue (f) in the non-cooling control (CON) and liquid cooling vest (LCV) trials.
*Different (p<0.05) between CON and LCV. Values are mean ± SEM (n=8).

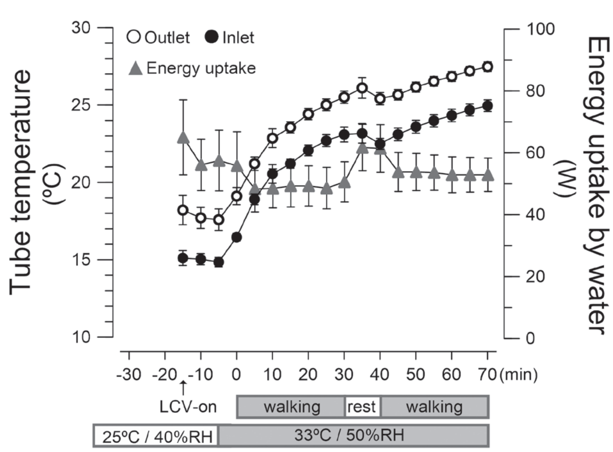

Fig. 4. Tube temperatures in the outlet and inlet to the vest and energy uptake by the water in the liquid cooling vest (LCV) trial.
Values are mean ± SEM (n=8).

Although the surface area of the palms is small, this region has unique radiator-like vascular structures underlying the glabrous skin[16]. The cooling effectiveness for core temperature was greater in the study by Grahn *et al.*[9] than in our study. The vest does not restrict body movement, unlike palmar pads and arm tube lines, and workers may select the most suitable LCG depending on their work situation.

The T_{skin} values on the back and chest were lowered in the LCV than in the CON trial throughout the walking exercise (Fig. 1 (c) and (d)), whereas the inlet tube temperature increased progressively. This torso cooling made the participants feel cold and more comfortable on their torso immediately before and after the walking exercise (Fig. 3 (c) and (d)). During the next walking period, the participants did not feel hot or uncomfortable on the torso in the LCV trial. By contrast, the thermal sensation of the whole body increased and the thermal comfort of the whole body decreased throughout the walking period (Fig. 3 (a) and (b)), whereas the participants felt 'less hot' and 'less uncomfortable' in the LCV trial than those in the CON trial. Because thermal sensation is conveyed by the warm and cold receptors in the skin and thermal comfort is affected by information from the skin and core temperatures[17], attenuating increases in mean T_{skin} and T_{rec} during walking in the LCV trial may have modulated the thermal perceptions.

The increases in physical and psychological fatigue were similar in the CON and LCV trials (Fig. 3 (e) and (f)). Because the burden of wearing the LCV might increase fatigue, these findings should be considered when using such a device in practice. However, it is possible that reliefs of the physiological strain and thermal perception attenuated the increased feeling of fatigue; that is, the weight of the LCV could have offset the reliefs. Although wearing the LCV did not appear to cause any negative effects in the present study, the mobility and ergonomic aspects should be assessed in future experiments in which participants wear the LCV with its cooling function turned off and perform agility tests.

In practice, workers who move around large working areas must use field-type microclimate cooling systems. Phase-change materials (e.g., ice packs) are also used to make garments with conductive cooling such as LCGs. A study by Muir *et al.*[18] placed frozen gel packs into the outside pockets of protective clothing with fitting straps that were secured close to wearer's body (weight: 5.2 kg). During walking at 28°C wet bulb globe temperature (34°C dry bulb temperature), the cooling effectiveness for core temperature and heart rate in participants wearing this ice-cooling system was 36% and 8% at 60 min, respectively. In Kenny *et al.*[19], the wearing of an ice-cooling vest (weight: 4.1 kg) underneath protective clothing during walking at 35°C with 65% RH reduced physiological and psychological strain. The cooling effectiveness at 60 min was 22% for core temperature and 17% for heart rate; thermal sensation and perceived exertion were also reduced by the cooling vest.

Ambient air ventilation systems (e.g., convective cooling) have been shown reduce heat strain effectively[3, 4]. Chinevere *et al.*[3] studied the effect of a ventilation system to cool the torso (weight: up to 2.3 kg) worn underneath an army combat uniform during a 60-min walk at 35°C with 75% RH. The cooling effectiveness was 13% for core temperature and 18% for heart rate compared with the same condition with participants not wearing the system. In a similar study, using a ventilation system to cool the torso (weight: up to 1.2 kg) worn underneath a battle dress uniform, Hadid *et al.*[4] found evidence of reduced physiological strain during a 120-min walk at 35°C with 60% RH; the cooling effectiveness was 30% for core temperature, 19% for heart rate, and 25% for sweat rate. These two ventilation cooling studies analyzed body heat storage rates, and the cooling effectiveness was 21%[3] and 25%[4]. In the present study, the cooling effectiveness for body heat storage was 29%, which was similar to that for core temperature.

Song and Wang[20] applied a combined cooling system and ventilation system with phase-change materials (weight: up to 3.6 kg) to both the upper and lower body worn with a standard work uniform. The cooling effectiveness for non-ventilation and phase-change materials was 40% for core temperature and 38% for heart rate during a 70-min walk at 36°C with 59% RH. Although it remains unclear how combined systems affect cooling efficiency, it is reasonable to assume that applying an LCG system to the lower body would increase cooling effectiveness.

The efficiencies in reducing heat strain measured in our study are similar to those measured in previous studies, despite the differences in weight, form, and energy supply. Our findings suggest that workers may be able to select suitable cooling systems appropriate to their workplace and conditions. The LCGs and ventilation cooling should be used with a battery. Although the working time may be dependent on the battery's duration, workers can switch on and off the cooling system at any given time as the situation demands. However, when a worker is wearing protective clothing to provide strong protection against specific hazards, the ventilation cooling system may experience some problems such as contaminant input.

The difference in heat storage between the CON and LCV trials was 9 W, whereas the cooling power of the LCV by calculating the energy uptake in circulating water was 55 W. The heat loss (46 W) indicates difficulty in cooling efficiency using LCGs. The energy uptake by water includes heat loss into outside environment. It contains also inside environment (between the LCV and skin), because T_{skin} responses in the LCV trial differed between the back and chest (Fig. 1 (c) and (d)). Improvements of the materials of the vest are needed to inhibit heat loss and fit the torso's surface.

A potential limitation to the present study was that metabolic rate was not measured during walking. The LCG burdens the wearer, and we plan a future study to measure the additional energy expenditure. Second, the exercise and heat exertion were at low levels. Further study is needs to determine whether the LCV is also effective during more intense exertion and hyperthermic conditions. Third, a potential limitation relates to whether the participants should undergo a heat acclimation period before the experiments. Although we could not measure the participants' fitness level, they were basically sedentary and were not regularly exposed to a hot work environment. Heat and exercise acclimation may allow the participant to perform more severe exertion. A fourth limitation of our study is that our participants performed exercise of only one duration while wearing the LCV, and future studies should include exercise of different durations. Because ISO 12894[21)] and the American Conference of Governmental Industrial Hygienists (ACGIH)[22)] define the core temperature threshold of 38.0°C, we should have examined how long it took for core temperature to reach this threshold in the LCV trial.

Conclusion

In the present study, we compared the physiological and psychological heat strain between exercise in participants wearing or not wearing a field-type LCV while wearing an impermeable protective suit. The increases in rectal and mean skin temperatures, heart rate, heat storage, sweat rate, and cutaneous vascular conductance on the chest during 1 h of walking were significantly lower with than without the LCV. The rating scores of thermal sensation and discomfort for the whole body were also significantly lower with than without the LCV. Increases in these perceptions of torso without the LCV disappeared in with the LCV. Although the LCV system was a burden on the wearer, the rating scores of fatigue during walking did not differ significantly between exercise with and without the LCV. Because the effectiveness of reducing heat strain was reasonable compared with other microclimate cooling systems, workers wearing protective clothing may be able to select the most suitable cooling system according to their work condition.

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