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Subjective perceptions and ergonomics evaluation of a liquid cooled garment worn under protective ensemble during an intermittent treadmill exercise

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While a personal protective equipment (PPE) ensemble effectively provides workers with protection from occupational hazards, working in a vapour-resistant ensemble increases the risk of heat illness/injuries and physiological burdens. The purpose of this study was to investigate the effect of body cooling via a liquid-cooled garment (LCG) underneath a PPE ensemble on perceived thermal strain, physiological responses and ergonomics during an intermittent treadmill exercise in warm environmental conditions. The results of the present study indicated that the concomitant wearing of LCG underneath the PPE ensemble significantly reduced subjective perception of heat and alleviated overall increase in body temperature and heart rate while no impact of wearing LCG on ergonomic features was found. The extension of the present findings to practical applications in occupational settings requires further research on a LCG system design and performance evaluations while the LCG is incorporated within the PPE ensemble.

Statement of Relevance: Implementation of a LCG underneath PPE for body cooling was investigated, focusing on its impact on individuals' perceived thermal strain, physiological responses and ergonomics. The findings of the present study indicated that body cooling via a wearable LCG underneath PPE significantly alleviated both perceived thermal and physiological strain in uncompensable heat stress condition.

Keywords: ergonomics; liquid-cooled garment; protective ensemble; subjective perceptions

Introduction

According to the National Institute for Occupational Safety and Health (2004), over 20 million workers use personal protective equipment (PPE) in occupational settings nationwide to protect them from job-related hazards and, additionally, a total of 135,000 workers could benefit from the use of PPE. Moreover, PPE ensembles that envelop the body to protect it against external hazards are crucial to protect workers in certain occupations, such as first responders and firefighters, in which regular and/or specified duty tasks involve great risk of exposure to thermal hazards and biological, chemical, radiological agents, etc. While appropriate use of PPE ensembles significantly prevents/reduces fatalities and injuries in such occupations, physical and physiological challenges from wearing PPE ensembles have been documented, such as heat stress potentially causing heat illness/injuries, reduction in work performance and a decrease in work efficiency (Nunneley 1989, White *et al*. 1989).

Numerous efforts have been made to reduce thermal stress and promote performance capabilities of individuals working underneath PPE ensembles by applying various types of personal microclimate cooling system such as liquid cooling (Speckman *et al*. 1988, Constable *et al*. 1994, Cadarette *et al*. 2006), air cooling (McLellan *et al*. 1999) and cooling vests implemented with phase changing material (Bennett *et al*. 1995, Gao *et al*. 2010) or ice (Smolander *et al*. 2004). Specifically, the studies (Speckman *et al*. 1988, Constable *et al*. 1994, Cadarette *et al*. 2006) that tested a liquid cooling system, liquid-cooled garment (LCG), underneath a PPE ensemble showed marked reduction in a level of heat stress characterised by suppression of elevation in body temperatures and heart rate (HR), contributing to sustained performance duration compared with a no-cooling condition at a given performance intensity. The results suggested that the LCG could be an effective means to significantly reduce risk of heat illness/injuries and promote work tolerance in individuals wearing a vapour-resistant PPE ensemble, especially in a warm environment, where the body's natural cooling process by evaporation is not sufficient to remove metabolic heat production.

However, the aforementioned studies did not examine how individual perception of body heat

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sensation in the LCG corresponded to changes in thermoregulatory/physiological measures. Moreover, there is little scientific data examining the effect of wearing an additional clothing layer (i.e. the LCG) on the ergonomics of the PPE ensemble and subjective comfort, which may play an important factor in user acceptance and practical application of the LCG worn in connection with a PPE ensemble. To the present authors' knowledge, there has been only one study (Leon *et al*. 2009) that investigated the impact of LCG on subjective physical comfort and movement flexibility in a LCG user wearing trial which, however, did not involve a facilitation of LCG underneath a PPE ensemble. Therefore, the purpose of this study was to investigate the impact of the concomitant wearing of a LCG underneath a PPE ensemble on subjective/physiological strains, wearing comfort and ergonomics during performance in warm environmental conditions.

Methods

Subjects

Six healthy male subjects, (mean $\pm$ SD) age: 30.5 $\pm$ 6.8 years old; height: 182 $\pm$ 8 cm; weight: 90.6 $\pm$ 12.2 kg; BMI: 27.7 $\pm$ 5.3 kg/m^2; body surface area; 2.11 $\pm$ 0.1 m^2; maximal oxygen consumption (VO_{2max}); 46.3 $\pm$ 6.6 ml/kg per min, were recruited to participate in the study after a comprehensive medical screening at a designated local medical clinic. The subjects were free of any medication/drug, smoking or alcohol use and self-reported that they maintained a physically active life style. In addition, the subjects performed a maximal graded exercise test (GXT), with electrocardiographic and pulmonary metabolic measurements, to assess functional capacity as well as to reveal evidence of undiagnosed cardiovascular disease during exercise–stress conditions. The subjects' VO_{2max} determined during the GXT was used for the determination of individual subjects' relative exercise intensity during experimental testing. Written and oral consent was obtained from all subjects after an orientation about the experimental procedures and the nature of the study, including potential risks associated with participation. The study protocol was reviewed and approved by the National Institute for Occupational Safety and Health Human Subjects Review Board.

Experimental protective ensemble and LCG

A prototype firefighting ensemble (PFE) (Morning Pride/Total fire Group, Dayton, OH, USA) with a standard self-contained breathing apparatus (SCBA) (Scott NXG2 AIRPAK with 45-min rated carbon cylinder; Scott Health & Safety, Monroe, NC, USA) was chosen for the experimental protective ensemble. While the main features of this ensemble are the same as a standard firefighting ensemble, consisting of helmet, coat, pants, gloves and boots, the study PFE included several innovations in its design aimed at providing wearer-integrated protection from hazardous materials such as nuclear, biological and chemical materials (Williams *et al*. 2011). Total carriage load imposed on the wearer by the ensemble and SCBA was 20.2 $\pm$ 0.2 kg. Detailed information on design features and ergonomics of the PFE has been reported elsewhere (Coca *et al*. 2008).

Two different LCGs, a top cooling garment (TCG) and a shortened cooling garment (SCG) were constructed, adopting previously introduced LCG design features (Koscheyev *et al*. 2004). The garments have plastic tubing sewn into fabric on the inner surface, thus the tubing is in contact with the skin for heat exchange when coolant is supplied by an external water circulator. The two LCGs are identical in their materials and design features; however, body surface areas covered by the plastic tubing were different, in that the TCG covers only head and forearm while the SCG covers head, forearm, torso (chest, back, side abdomen) and thigh. Although the greater coverage of body surface area in the SCG provides a greater level of heat extraction than the TCG, it increases the garment weight and is likely to impose more restriction on body movement due to the increased amount of tubing distributed over the body. The specifications of the TCG and SCG are summarised in Table 1. The design features of the SCG regarding design process, tubing distribution and body surface coverage are well explained elsewhere (Kim and LaBat 2010).

Procedures

Prior to testing, subjects visited the laboratory for pre-experimental preparation, which included ensemble and LCG fit testing and an exercise familiarisation

Table 1. Specifications of the study liquid cooled garments.

	Weight (kg)[a]	Garment material	Tubing length (m)	Tubing ID/OD (mm)	Flow rate (kg/min)[b]
TCG	0.40	Spandex PE	15.3	Tygon tubing	0.20
SCG	0.95		55.0	2.4/4.0	0.65

TCG = top cooling garment; SCG = shortened cooling garment.
[a]Garment weight when tubing is filled with water.
[b]Flow rate when garment is not worn under the pumping flow rate of 15 kg/min.

session. Subjects were first fitted to PFE (ensemble and gears including helmet, gloves, boots and SCBA backpack straps) and the two types of LCGs among various sizes. To ensure proper fit, the subjects provided their verbal feedback on perceived wearing comfort and movement while LCG fit was also examined in terms of proper contact between skin and LCG tubing. Following the fit testing, subjects were instructed in and performed the putting on/taking off procedures of the PFE and LCG. For the exercise familiarisation, the subjects wore the PFE and SCBA assigned to them and performed a treadmill exercise at a relative workload of 50% VO_{2max} for 20 min. While no data were collected during the familiarisation session, except HR and electrocardiographic for safety reasons, the subjects were carefully observed to ensure their exercise performance capability underneath protective clothing. After the completion of the pre-experimental preparation, all subjects participated in three sessions of the exercise protocol with randomly assigned order for control (CON) and two cooling conditions wearing TCG and SCG.

Each experimental session was separated by at least 5 d to avoid a progressive adaptation to exercise heat stress. The exercise protocol consisted of stabilisation, warm-up and three stages of treadmill exercise for 15 min and rest for 10 min between exercise periods in an environmental chamber (air temperature: 35°C, relative humidity 50%) (Figure 1). During the 5–10 min of the stabilisation period, baseline measures were obtained, followed by treadmill exercise after a 2-min warm-up stage. For the cooling conditions, cooled water at 18°C by the external water circulator (NESLAB RTE-10; Thermo Neslab Inc., Newington, NH, USA) was provided through the LCG tubing at the beginning of the warm-up stage and throughout all exercise and rest stages. The subjects' individual exercise intensity was calculated from their GXT data by taking into account the additional weight load of the gear that the subjects carried and set at 50% VO_{2max} and 75% VO_{2max} for warm-up and exercise stages, respectively. While each exercise duration was initially set for 15 min, exercise was terminated and the subjects were moved to a rest stage in the following scenarios: maintain 90% HR_{max} for 1 min, subjects' request to stop (maximal exhaustion), or indication of any physical impairment such as dyspnea or dizziness. During the rest stages, subjects were seated on a chair under the same environmental conditions, but they removed the face mask and opened the turnout jacket halfway through the procedures to promote heat dissipation (turnout jacket was completely removed at the last rest stage).

Measurements

Subjective

A visual analogue scale (VAS) was used to measure subjective thermal strain and ergonomics. As seen in Figure 2, the VAS used in this study was of unipolar design and consisted of a horizontal line with the two extreme ends designated as 'none' at the left end and 'maximal' at the right end. To familiarise subjects with the procedure, they were given both a verbal orientation and measurement trials for each of the subjective measurements. A separate scale was used for each measurement category at each stage to avoid retrospective contamination of continued measurements during experimental trials (Leon *et al.* 2008). Thermal comfort, heat perception and fatigue were measured at baseline and at completion of each exercise bout. Subjective ratings on ergonomics, such as mobility (upper body, lower body, arm and leg), overall body discomfort, clothing flexibility, fit, and putting on/taking off ease, were measured at pre- (baseline) and post-experimental sessions. In addition, subjects were asked to report the most important factor that had influenced their judgement on

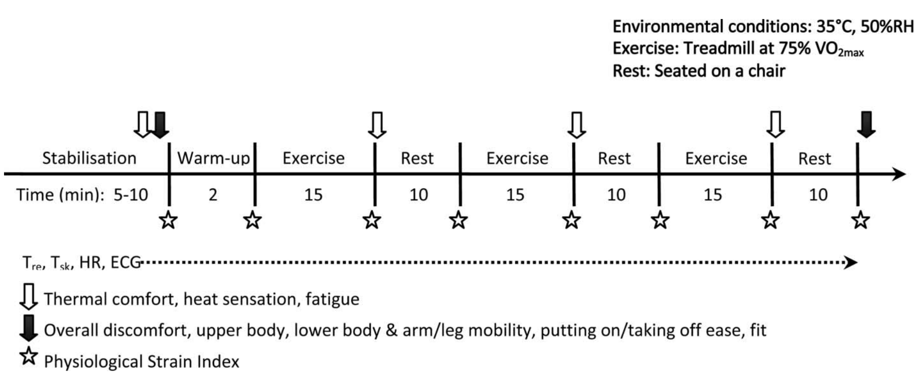

Figure 1. Summary of experimental protocol and measurements. RH = relative humidity; VO_{2max} = maximal oxygen consumption; T_{re} = rectal temperature; T_{sk} = skin temperature; HR = heart rate; ECG = electrocardiograph.

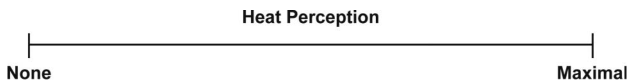

Figure 2. Example of a visual analogue scale (VAS) for assessing subjective perception of heat sensation. The two anchors of the scale were described to subjects as 'none' designating no feeling of heat and 'maximal' for feeling the greatest amount of heat ever experienced.

perceived overall body discomfort. In this measurement, subjects selected from a five category criteria set: (1) heat in the gear; (2) humidity and/or wetness in the gear; (3) ensemble weight; (4) fit and/or mobility in the gear; (5) other factors (such as fatigue, breathlessness).

Physiological

Body core temperature was obtained from the rectal temperature (T_{re}) via a rectal probe (4600 precision rectal thermometer; YSI Temperature, Dayton, OH, USA) inserted 13 cm beyond the anal sphincter. Mean skin temperature (T_{sk}) was calculated using a previously determined formula (Ramanathan 1964) from the readings of skin sensors (skin temperature logger: SQ2020–1F8; skin sensors: Grant probe high precision thermistors, type EUS-UU-VL5–0, Grant Instruments Ltd, Shepreth Cambridgeshire, UK) attached to four skin sites (upper chest, front shoulder, anterior thigh and shin) by adhesive surgical tapes. T_{re} and T_{sk} readings were collected and monitored by means of a customised data acquisition system and the data were summarised in 1 min averages. HR (Polar heart rate monitor series 610; Polar Electro, Lake Success, NY, USA) was continuously monitored during the entire experimental sequence. In addition, a physiological strain index (PSI) was calculated from the subjects' HR and T_{re} recorded throughout a session using the following equation (Moran *et al.* 1998):

$$PSI = 5(T_{ret} - T_{re0}) \bullet (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \bullet (180 - HR_0)^{-1},$$

where T_{re} and HR are measured values at the time t, end of each exercise and rest stage, and T_{re0} and HR_0 are baseline measurements. PSI ranges between 0 and 10 and falls into the five heat strain categories; no/little (0–2); low (3–4); moderate (5–6); high (7–8); very high (9–10).

Statistical analysis

All subjective variables measured using VAS were first converted to numeric equal interval scales between 0 (none) to 100 (maximal) for statistical analysis. The variables were then calculated as means and SD for each subject and grouped for each condition: CON; TCG; SCG. Repeated measures ANOVA were used to determine main effects and interactions of each variable across conditions. The variables analysed in a two-way (conditions $\times$ stages) ANOVA included thermal comfort, heat sensation, fatigue, PSI; delta values were first calculated for overall discomfort and all other ergonomic measurement variables and then analysed in one-way ANOVA across conditions. Greenhouse-Geisser correction was adopted for the test of within-subjects sphericity and the LSD adjustment was chosen for post-hoc pairwise comparisons. Statistical significance was accepted when $p < 0.05$.

Results

Subjective strain

While the subjects consistently expressed a higher level of thermal comfort in TCG and SCG than in CON, no statistical difference was found among the three conditions (Table 2). However, there was a significant difference in subjective heat perception in both stages ($p < 0.001$) and conditions ($p = 0.044$). In all conditions, heat sensation continuously increased through each measurement point except for levelling off at the end point heat sensation in the SCG. Pairwise comparison of the three conditions showed that the subjects felt significantly warmer in CON than in TCG ($p = 0.007$) and SCG ($p = 0.040$), but no statistical difference was found between TCG and SCG ($p = 0.478$). Perceived fatigue also appeared to consistently increase through each stage ($p < 0.001$) in all conditions. Also, both the magnitude of increase and overall fatigue were lower in TCG and SCG than in CON; however, pairwise comparison showed significant differences among conditions only at the end stage; CON $>$ TCG $=$ SCG ($p = 0.012$).

Physiological strain

There was a significant difference in PSI in both stages ($p < 0.001$) and conditions ($p = 0.013$). As shown in Figure 3a, level of physiological strain was progressively elevated between bouts of exercise and rest compared with the previous stage, whereas SCG significantly reduced physiological strain by one or more PSI levels than CON and SCG during all rest stages and the last exercise stage ($p < 0.05$). However, cooling effects of TCG on T_{re} and HR did not meet statistical significance compared with CON. Figure 3b shows the time course of T_{re} and HR corresponding to a level of PSI at each experimental stage. There was

Table 2. Summary of subjective ratings on thermal comfort, heat perception, and fatigue.

	Baseline			End of exercise 1			End of exercise 2			End of exercise 3		
	CON	TCG	SCG	CON	TCG	SCG	CON	TCG	SCG	CON	TCG	SCG
Thermal comfort	65.0 (11.1)	73.0 (13.3)	67.9 (16.5)	57.0 (13.7)	71.0 (21.7)	67.2 (22.1)	56.0 (19.9)	62.2 (20.9)	69.0 (17.2)	57.7 (14.6)	66.8 (27.9)	65.8 (23.7)
Heat perception	29.2* (13.2)	15.7 (9.9)	18.2 (9.8)	71.7* (9.2)	56.0 (17.9)	46.8 (27.9)	75.2* (18.3)	62.0 (14.2)	56.2 (28.3)	80.3* (15.7)	66.3 (12.4)	49.2 (21.6)
Fatigue	12.7 (9.3)	11.5 (7.4)	10.3 (9.0)	46.3 (22.7)	31.5 (20.8)	38.0 (21.4)	56.3 (21.4)	53.3 (17.6)	48.3 (21.0)	65.3* (23.2)	50.2 (19.8)	48.8 (25.9)

CON = control; TCG = top cooling garment; SCG = shortened cooling garment.
*Indicates a statistical difference compared with TCG and SCG ($p < 0.05$).
Note: Values are mean (SD); n = 6.

initially no difference, but a similar magnitude of increase in T_{re} and HR until the end of the first exercise. During each rest stage, however, it was observed that SCG elicited a significantly slower increase in T_{re} and greater recovery in HR than CON and TCG. Also, a rate of increase (°C/min) in T_{re} and T_{sk} was significantly lower in SCG (0.015 and 0.021) than in CON (0.026 and 0.046) and TCG (0.021 and 0.039) ($p < 0.05$) while a rate of absolute increase in T_{re} and HR during the exercise period was not significantly different among conditions. Figure 3c shows the time course of T_{sk} combined with the average heat flow during exercise and rest stages in TCG and SCG. It can be seen that the rate of heat flow in TCG did not produce a significant cooling effect on the skin surface compared with CON, whereas SCG significantly suppressed elevation in T_{sk} throughout all exercise and rest stages.

Ergonomics

For all conditions, the subjects expressed a higher level of overall discomfort at the post-exercise measurement (Table 3). The increase in overall discomfort was significantly greater in CON ($p = 0.007$) and TCG ($p = 0.011$) than SCG. Interestingly, the majority of the subjects chose 'the fit and/or mobility in the gear' as the factor that most influenced their overall body discomfort at the pre-exercise measurement in all conditions (Figure 4). There were, conversely, noticeable differences in the selection of discomfort factors among the conditions at the post-exercise measurement in that four out of six ratings in the CON condition were given to 'heat in the gear', while no subjects in SCG selected this factor as the most important discomfort factor. In addition, no subjects provided examples in the 'other factors' category that might have contributed to overall body discomfort. There was no statistical difference in body mobility, ensemble flexibility, fit or putting on/taking off ease among the three conditions ($p > 0.05$) (Table 3). These results suggest that wearing a TCG or SCG underneath PFE to reduce heat stress did not negatively impact any ergonomic characteristics of the ensemble during exercise.

Discussion

The present study examined: 1) the effects of body cooling via a LCG on subjective and physiological strains; 2) whether implementation of a LCG resulted in a decrement in ergonomics while individuals in a PPE ensemble perform exercise in the heat. The results of the study indicate that both subjective and physiological heat strains were significantly decreased

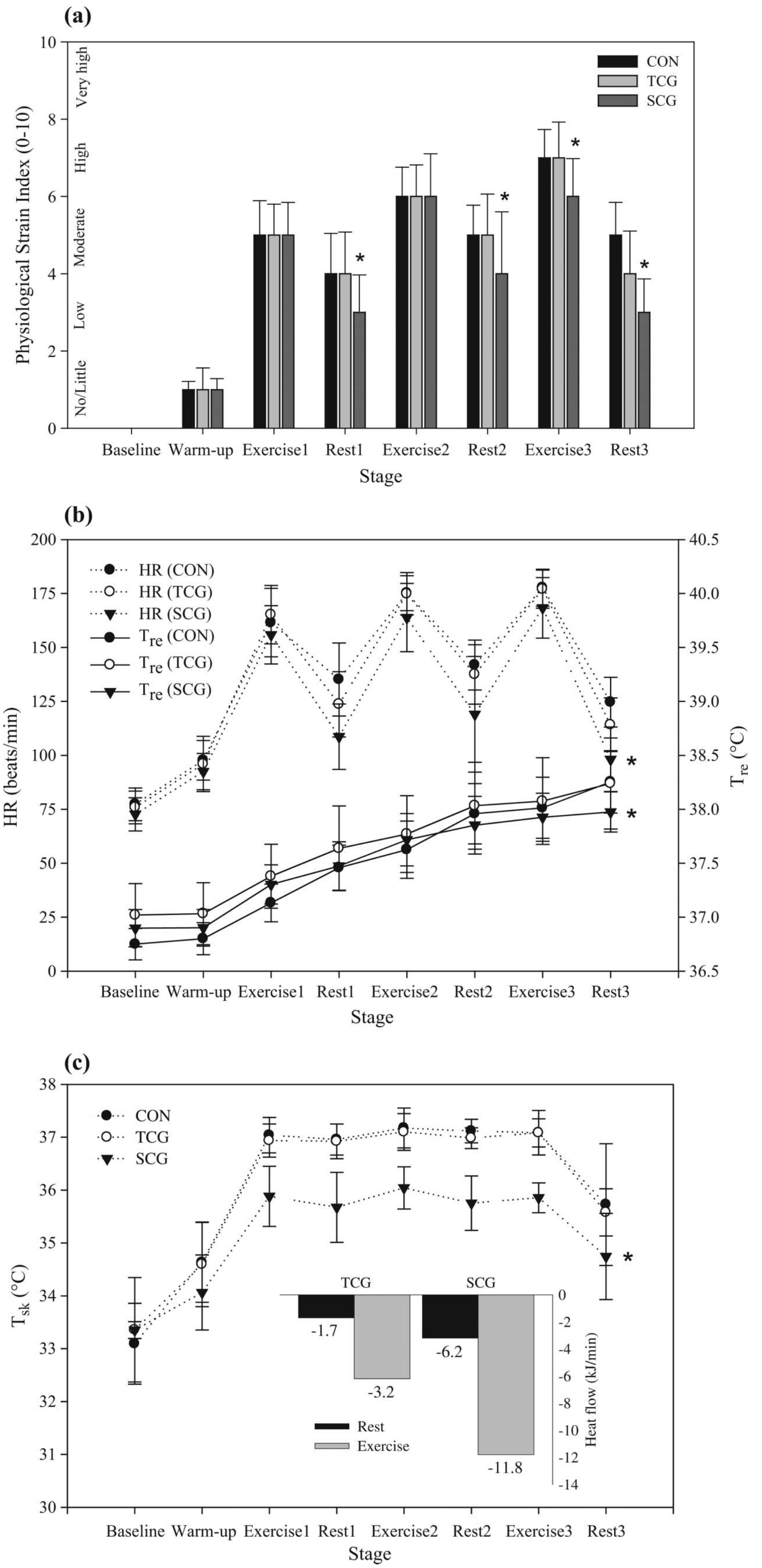
(a)
Physiological Strain Index (0-10)
No/Little
Low
Moderate
High
Very high
CON
TCG
SCG
Baseline Warm-up Exercise1 Rest1 Exercise2 Rest2 Exercise3 Rest3
Stage
(b)
HR (CON)
HR (TCG)
HR (SCG)
Tre (CON)
Tre (TCG)
Tre (SCG)
HR (beats/min)
Tre (°C)
Baseline Warm-up Exercise1 Rest1 Exercise2 Rest2 Exercise3 Rest3
Stage
(c)
CON
TCG
SCG
Tsk (°C)
TCG
SCG
-1.7
-3.2
-6.2
-11.8
Rest
Exercise
Heat flow (kJ/min)
Baseline Warm-up Exercise1 Rest1 Exercise2 Rest2 Exercise3 Rest3
Stage

Table 3. Summary of subjective ratings on prototype firefighting ensemble ergonomics.

	Pre			Post		
	CON	TCG	SCG	CON	TCG	SCG
Overall discomfort	34.7 (10.4)	22.2 (9.9)	34.5 (13.6)	73.0 (9.7)*	59.2 (16.6)*	53.0 (20.1)
Upper body mobility	64.5 (16.8)	76.0 (14.0)	70.2 (23.7)	68.3 (15.4)	73.7 (11.8)	70.2 (19.1)
Lower body mobility	57.5 (29.0)	83.6 (15.3)	73.8 (24.8)	65.5 (20.3)	84.5 (10.7)	69.7 (14.0)
Arm and leg mobility	70.2 (18.1)	78.5 (12.8)	70.8 (23.6)	71.3 (16.9)	78.2 (12.1)	70.8 (13.1)
Flexibility	58.2 (25.9)	69.8 (16.0)	64.8 (28.6)	59.9 (22.0)	73.0 (12.6)	67.0 (18.7)
Fit	64.1 (20.5)	72.8 (15.5)	66.3 (23.5)	69.4 (14.0)	67.0 (17.3)	67.0 (21.3)
Putting on ease	66.2 (21.6)	67.8 (22.8)	66.6 (21.4)	–	–	–
Taking off ease	–	–	–	61.8 (19.1)	67.2 (17.9)	50.7 (26.5)

CON = control; TCG = top cooling garment; SCG = shortened cooling garment.
*Indicates a statistical difference compared with SCG ($p < 0.05$).
Note: Values are mean (SD); n = 6.

when the subjects wore a LCG (SCG) underneath the PFE compared with CON. Even though there was no statistically significant difference in thermal comfort, there was a trend showing a decrease in thermal comfort in CON compared with TCG and SCG. Furthermore, the perception of heat was significantly higher in CON than in the other cooling conditions. These findings may indicate that the subjects' thermal comfort during uncompensable heat stress was strongly associated with the subjective perception of heat, while other factors such as humidity and/or wetness had relatively less influence on subjective thermal comfort. This explanation is further supported by the results from the overall discomfort measurements, in which subjects reported significantly greater increments in discomfort in CON and TCG than SCG and frequently chose 'heat in the gear' as the most important factor influencing their judgements of discomfort levels. While these results need to be interpreted with caution due to the fact that no statistical analysis was performed for discomfort influencing factors, data from another study (Kim *et al.* 2011) indicated that microclimate temperature inside protective clothing at post-exercise was approximately 7°C higher in a no cooling trial than in a cooling trial in which subject wore a LCG. Thus, it appears that an increased perception of heat due to an accumulation of metabolic heat trapped inside the ensemble rather than humidity or wetness may be an important factor in subjective thermal and overall discomfort perceptions during physical performance within protective clothing. Increments in physiological strain were also significantly blunted in the SCG compared with the other conditions. Specifically, a total increase in T_{re} was significantly less in SCG (1.08°C) than in CON (1.50°C) and TCG (1.22°C) whereas average HR recovered during the 10 min rest period to a significantly greater extent in SCG (–58 beats/min) than CON (–41 beats/min) and TCG (–51 beats/min). This significant reduction in HR contributed to a consistently lower level of PSI in SCG during rest periods and the third bout of exercise.

The current study supports the effectiveness of body cooling via a LCG in reducing the thermoregulatory and physiological responses to heat stress and is consistent with previous investigations (Speckman *et al.* 1988, McLellan *et al.* 1999). The rate of heat removal in SCG, in which a cooling tube is distributed over the body surface area with higher heat exchange capability (Koscheyev *et al.* 2002), was approximately 200 Watts with an inlet water temperature of 18°C. However, the TCG, in which the cooling tube covered only a limited body surface area, the head and forearm, was not as effective as the SCG in terms of effectively alleviating either subjective or physiological heat strain compared with CON. While a number of previous studies (Fox *et al.* 1962, Shvartz 1970, Nunneley 1989, Koscheyev *et al.* 2002) reported the effectiveness of head cooling (with/without neck area) in terms of a significant decrease in body temperature and improvement in thermal comfort, it seems that the amount of cooling provided via a TCG in the current experimental setting might not have been sufficient to alleviate a significant portion of

Figure 3. Physiological strain index during each stage across the conditions (a), heart rate (HR) and rectal temperature (T_{re}) responses (b) and skin temperature (T_{sk}) responses and estimated heat flow (c) in top cooling garment (TCG) and shortened cooling garment (SCG) conditions. (n = 6). CON = control. *Indicates statistical significance ($p < 0.05$). Heat flow was estimated from mass flow rate (kg/min) × the specific heat of water (4.18 kJ/kg per°C) × the difference between inlet and outlet coolant temperature (°C).

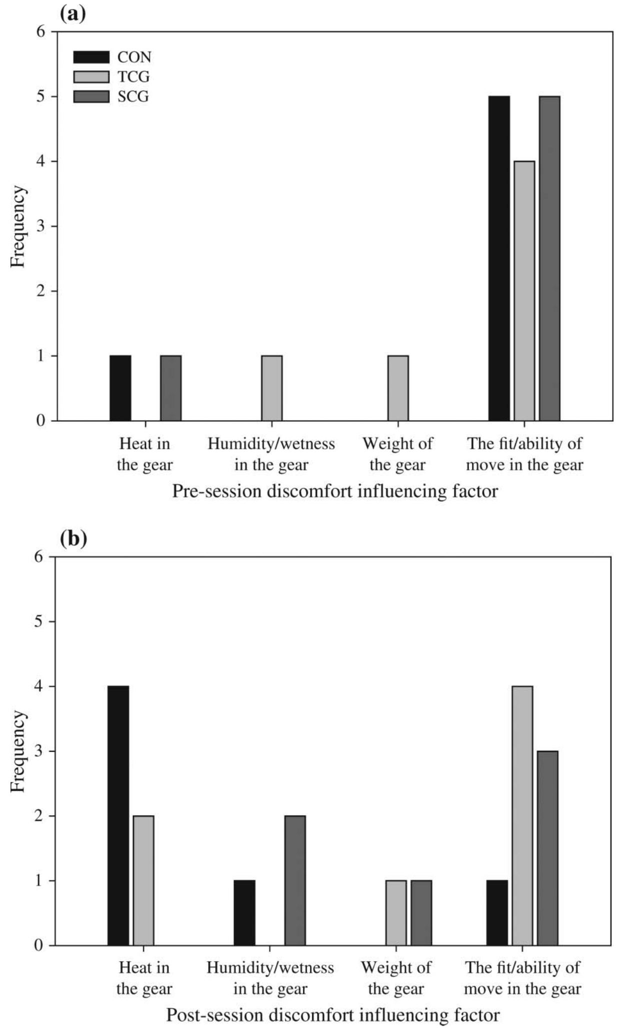

Figure 4. Frequency of discomfort influencing factors for pre- (a) and post-session (b), (n = 6; one subject in top cooling garment (TCG) condition at the post-session measurement reported two factors). CON = control; SCG = shortened cooling garment.

uncompensable heat stress to the extent that the subjects perceived any comfort and/or distinct changes in physiological responses were achieved. However, head cooling showed improvement in both subjective and physiological measurements compared with CON, but failed to achieve statistical significance.

Another significant finding of the present study was that wearing a LCG underneath the ensemble did not cause any significant decrements in the subjects' perceived ergonomic features or usability. While the use of a PPE ensemble is of great benefit among workers/personnel who are at risk of exposure to hazardous materials and/or conditions in their occupational sites, several studies have voiced concerns about ergonomic limitations imposed by PPE ensembles (Huck 1988, 1991, Akbar-Khanzadeh *et al.* 1995, Stull 2000, Szczecinska and Lezak 2000, Coca *et al.* 2008). As previous studies have pointed out, improper selection or poor designs of PPE can lead to reduction in fit, possibly restrict wearers' mobility and movement and adversely affect their comfort (Huck 1988, 1991, Akbar-Khanzadeh *et al.* 1995). Also, impaired comfort (perceived discomfort) resulting from wearing and/or being equipped with PPE reduces user acceptance and willingness to use the PPE. More importantly, disregarding ergonomic factors in PPE may create a secondary hazard in the workplace, such as reduced vision, decreased manual dexterity or tripping/slipping (Nunneley 1989, Stull 2000). Although objective measurements and/or analysis of ergonomics such as range of motion and occupational repetitive action were not performed in the present study, the finding that subjects did not perceive movement/performance restrictions under the experimental cooling conditions is of significance in pursuing practical applicability and user acceptance of LCG underneath a PPE ensemble.

While body cooling via a LCG is effective in mitigating heat stress and improving comfort, as documented by the present study and a number of previous investigations (Nunneley 1970, Speckman *et al.* 1988, McLellan *et al.* 1999, Flouris and Cheung 2006), during the experimental trials some practical issues were observed, which should be considered. Although there was no significant influence of the LCG on reported putting on/taking off ease, the additional process of wearing a LCG required more time for putting on/taking off the entire protective clothing system. This process could possibly delay the response time for emergency first responders responding to incidents. A solution to this problem may be to incorporate the LCG into the inner surface of the protective clothing so that individuals could easily put on/take off the system without the need for separate putting on/taking off of individual components. Additionally, the weight of the LCG system is an important factor to consider for practical application. The net weight of the LCGs in the present study was 0.40 and 0.95 kg for TCG and SCG, respectively, when tubing is filled with water. It should also be noted that any liquid cooling system requires additional devices, which generally consist of a heat exchanger, power supply, flow pump, etc. (Flouris and Cheung 2006), resulting in further increasing the system weight that a wearer carries. Since the present study used an external device rather than a portable unit to operate the LCG, the effect of the additional weight of the complete system separated from the weight of the protective clothing during physical performance was not assessed. Therefore, the effect of this additional weight on the subject was not determined. A study by McLellan *et al.* (1999) pointed out that the cooling advantage outweighs an elevation in metabolic rate due to additional load carriage of a cooling system (up to 10 kg) until the point where the cooling rate is greater than the additional metabolic rate. Thus, the net weight of the system in terms of cooling capacity and potential to increase weight load also needs to be taken into account for the practical application of LCG in individuals working in PPE ensembles.

It is worth noting that the subjects in the present study reported some decrements in ratings on PFE ergonomic features in LCG trials compared with CON. However, these decrements did not reach statistical significance. According to design features of up-to-date LCGs (Flouris and Cheung 2006), the total weight (0.5–2.5 kg) and tubing length (90–110 m) distributed over the body are greater than those of LCGs tested in the present study (Table 1). Thus, the possibility exists that wearing a LCG underneath a protective ensemble may negatively affect a wearer's movements and/or certain ergonomic features during work. Future research will be required to examine a concomitant wearing of a LCG and protective ensemble, which takes into account both ergonomic and design features of a LCG regarding practical application to a field of interests.

In summary, the findings of the present study indicated that body cooling via a wearable LCG, specifically a SCG in the present study, underneath the protective clothing (firefighter ensemble) significantly alleviated both perceived thermal and physiological strain in an uncompensable heat stress condition. Moreover, wearing a LCG underneath the protective clothing did not restrict the movement of individuals nor decrease ergonomic features of the protective clothing system. The extension of these results to practical application in occupational settings requires further research on the integration of LCGs and PPE ensembles with a consideration of the system design and performance.

Study limitations

Limitations of the study are the small number of subjects and their gender. The relatively small sample size (six subjects), which may have been too undersized to detect a true difference (β-error) between the three conditions, could have affected the results of the study. However, other studies have utilised similar numbers and also achieved statistical significance. Although the US firefighter population is 5% female, it was not possible to recruit female subjects in the present study.

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Disclaimer

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