

A novel vest with dual functions for firefighters: combined effects of body cooling and cold fluid ingestion on the alleviation of heat strain

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Received October 8, 2018 and accepted June 25, 2019

Published online in J-STAGE June 29, 2019

Abstract: This study investigated the separate and combined effects of skin cooling and cold fluid ingestion on the alleviation of heat strain when wearing protective firefighting clothing at an air temperature of 30°C with 50%RH. A vest with the dual functions of cooling and providing sports drink supply (1.2% body mass) was developed. Eight males participated in the following four conditions: control [CON], drinking only [DO], cooling only [CO], and both cooling and drinking [CD]. The results showed that rectal (T_{re}), mean skin temperature (T_{sk}) and heart rate (HR) during recovery were lower for CD than for CON ($p < 0.05$), while no significant differences between the four conditions were found during exercise. CO significantly reduced mean T_{sk} and HR and improved thermal sensation, whereas DO was effective for relieving thirst and lowering HR in recovery. In summary, the combined effect of skin cooling and fluid ingestion was synergistically manifested in T_{re} , T_{sk} and thermal sensation in recovery. **Practitioner Summary:** The present results provide data on a novel vest that contributes to alleviating firefighters' heat strain. Because a cooling vest after melting may be a burden for firefighters, this study indicates a practical way to reduce the additional weight load of the vest by drinking the melted fluid of the cooling packs.

Key words: Cooling vest, Skin cooling, Hydration, Firefighters, Heat strain

Introduction

Firefighting is one of the most physically demanding occupations, inducing a high rate of heat-related disorders. In hot environments, in particular, firefighting personal protective equipment (PPE) exacerbates heat strain by increasing metabolic rate due to its weight (up to 26 kg) and thermal insulation of up to 2.44 clo^{1, 2)} as well as by inhibiting dry and evaporative heat dissipation from the

skin to the air due to the encapsulating clothing layers. There are numerous studies investigating the additional metabolic costs of wearing firefighting PPE in various environmental conditions. For example, firefighting PPE results in a 115 W·m⁻² increment in metabolic rate during heavy work³⁾, a 0.8–1.2 l·min⁻¹ increments in oxygen uptake ($\dot{V}O_2$) while walking⁴⁾, a 15–20% increment in $\dot{V}O_2$ during high-intensity treadmill walking (5 km h⁻¹ at 7.5% gradient)⁵⁾ and a significant reduction in maximal oxygen uptake capacity ($\dot{V}O_{2max}$) ranging from 8 to 20%^{6–8)}. Increases in metabolic rate and reduction in $\dot{V}O_{2max}$ due to the heavy PPE led to a 0.5–1.0°C·hr⁻¹ rise in core body temperature⁷⁾ and to a 27% reduction in tolerance time, respectively⁸⁾. The restriction of dry and evaporative heat

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dissipation from the skin aggravates the accumulation of body heat. According to a survey of 796 Japanese firefighters⁹⁾, approximately 50% of firefighters experienced heat disorders during firefighting. Another international survey on the next generation of PPE in Australia, Japan, Korea and US with 1,672 structural firefighters reported that among various elements, an automatic body cooling system was chosen as the most important element along with the location monitoring system¹⁰⁾.

Body cooling systems have been applied through pre-cooling, intermittent cooling for breaks, or post-exercise cooling. Cooling agents, such as ice packs, gel frozen packs, phase change material (PCM), circulated liquid or air fans have been proposed for workers, athletes and patients. According to Kenny and colleagues¹¹⁾, wearing an ice vest under full PPE significantly improved exercise time and attenuated physiological strain during exercise. However, the cooling garments are heavy and restrict body movement which is especially a burden after melting because the cooling effect of such garments is eliminated. In addition, rapidly removing or exchanging cooling vests after melting might not be feasible for firefighters due to their protective clothing (e.g., bunker jacket and pants). Most investigations of firefighters' body cooling were conducted after work or during breaks^{12–16)}. Few studies have investigated the effect of cooling during work while wearing firefighting PPE¹⁷⁾.

The limited water vapor permeability of PPE causes excessive sweat production for firefighters. Excessive sweating under heat stress without any fluid ingestion often results in dehydration. Brown *et al.*¹⁸⁾ investigated urine specific gravity (USG) in 190 firefighters prior to participation in simulated firefighting activities and found that firefighters in a dehydrated state (USG >1.020) showed greater cardiovascular strain than firefighters in a euhydrated state (USG <1.020) (HR 151 ± 3.4 vs. 135 ± 9.3 bpm). Progressive body fluid losses during exercise in heat increases body temperature and plasma tonicity and decrease blood volume. The hyperthermic-hypertonic-hypovolemia during exercise in heat is confirmed by increased core body temperature¹⁹⁾, an increase in plasma osmolality along with increased plasma sodium and chloride concentration¹⁹⁾ a decrement of local sweat secretion¹⁹⁾, a decrease in plasma volume¹⁹⁾, and an elevation of plasma lactic acid concentration which may lead to decreased heat capacity of circulating blood²⁰⁾.

It is also reported that dehydration is associated with significant deterioration in mental function^{21, 22)} and decrements in exercise tolerance time^{23, 24)}. Short-term memory

was improved²⁵⁾ and reaction time was significantly faster when subjects were hydrated²⁶⁾. Schlader *et al.*²⁷⁾ reported that chronic kidney disease from workers who regularly undertake physical work in hot conditions was related to hyperthermia and dehydration. Even though some results showed no difference between dehydration and hydration, this inconsistency is due to the level of dehydration and the severity of uncompensable heat stress^{28, 29)}. Providing cold drinking water to minimize dehydration can be an effective intervention strategy to offset the impact of heat stress. The effects of drinking ice slurry on the body temperature of cyclists has been documented³⁰⁾. Faster reaction time when subjects were hydrated²⁶⁾ might be extremely beneficial for firefighters who need to make snap judgments under emergency situations. However, fluid ingestion on a regular basis might not be feasible for firefighters due to the pressing situations they respond to and due to having firefighting tools in both hands.

As described above, the beneficial effects of skin cooling and fluid ingestion during exercise in heat are supported by extensive research, but few investigations were undertaken to determine the combined synergistic effects of skin cooling and cold fluid drinking. Thus in this study we developed a novel vest with the double functions of skin cooling and cold fluid drinking for firefighters. We decided to fill the cooling packs with frozen sports drink, so that firefighters can drink cold fluids as the cooling packs melt. This is an original contribution of the present study. This study was undertaken to investigate the separate and combined effects of skin cooling and cold fluid drinking using the novel vest during exercise while wearing firefighters' turnout jacket and pants in a hot environment. We hypothesized that skin cooling only would more effectively alleviate heat strain than only drinking cold fluids; and the combined impact of skin cooling with drinking cold fluids would be smaller than the sum of the separate effects of skin cooling and cold fluid drinking.

Methods

Subjects

Eight healthy young males participated in this study (mean \pm SD: 23 ± 2.5 yr in age, 171.9 ± 3.9 cm in height, 68.3 ± 7.6 kg in body weight, and 1.8 ± 0.1 m² in body surface area). Body surface area was estimated using the formula of Lee *et al.*³¹⁾. Subjects were instructed to abstain from alcohol and strenuous exercise for 48 h, along with food and caffeine for 3 h prior to scheduled tests. All experiments were conducted in July and August (summer).

Prior to obtaining written informed consent, the subjects were informed of the purpose and potential risks of the present study. This study was approved by the Institutional Review Board of Seoul National University (IRB No. 1803/001-002).

Developing of a novel vest and experimental procedures

Main fabric of a dual function vest (290 g and 1,100 g in the total mass of the vest without any cooling packs and with four cooling packs, respectively) was a mesh consisting of 70% polyester and 30% spandex. The vest had four pockets to keep disposable frozen packs of sports drink (200 ml per pack × 4 packs=800 ml; 1.2% of body mass) and flexible straws from each frozen pack were interconnected inside so that the frozen sports drink (7.8% carbohydrate-electrolyte; Powerade Isotonic, Coca-cola company, Atlanta) was usable for drinking as it melted (Fig. 1). In the pilot tests, we tried to use mineral water for drinking, but firefighters who participated in the pilot tests as subjects recommended to change mineral water to sports drink to replace carbohydrate and to reduce any possible smell of plastic tubing system. The cooling packs were kept in a freezer at -20°C for 3 h before experiments. The surface temperature of the frozen cooling pack was on average 6.9°C when measured on the 33°C skin-simulated hot plate surface at an air temperature of 30°C with 50%RH for 60 min. The frozen pack started to melt at 40–50 min on the hot plate but started to melt at 20–30 min when was worn on the human body and subjects drank all of the packs (800 ml) during their trials.

Subjects participated in the following four experimental conditions: control (CON), drinking only (DO), cooling only (CO) and both cooling & drinking (CD). The experimental order was counterbalanced to avoid any familiarization effect. Each condition was conducted on separate and nonconsecutive days at identical times. For the control

condition, subjects wore the vest without any cooling pack with firefighting turnout jacket and pants. In the DO condition, subjects wore the vest with non-frozen sports drink packs, while in the CO and CD conditions subjects wore the vest with frozen sports drink packs. For the CO condition, subjects did not drink from the vest. Subjects drank the sports drink regularly every 5 min from the exercise to recovery sessions in the DO condition, while in the CD condition subjects drank the sports drink starting from when the frozen packs melted (after about 10 min of exercise) regularly every 5 min. Subjects were asked to keep the amount of drinking every 5 min at the same level and there was no drink left inside the cooling packs at the end of the 60-min exposure. The starting temperature of sports drink for the DO condition was at 19.1°C when put into the vest and increased to 27.5°C by the end of exercise.

Subjects were required to maintain their hydration state at a normal level for 24 h prior and were prohibited any drinking for 2-h before their participation. As soon as they arrived at the experimental room, we checked their hydration state to make sure their urine specific gravity (1.004 to 1.025) and their rectal temperature to make sure it was within the normal range of 37.0 ± 0.5°C. All trials were performed in a climate chamber at an air temperature of 30°C and a relative humidity of 50%. A trial consisted of a 10-min rest on a chair followed by 30-min 5.5 km hr⁻¹ exercise on a treadmill and a 20-min recovery in a sitting position on the chair. Subjects wore cotton undershorts (80 g), cotton t-shirts (133 g), cotton short pants (157 g), cotton socks (80 g), the dual function vest (290 g) and running shoes (600 g) with firefighting turnout jacket (3,398 g) and pants (1,781 g). For the control condition, the estimated clothing insulation (I_T) was approximately 2.1–2.3 clo³²) and total clothing and PPE weight was 6.52 kg. Trials were terminated when rectal temperature (T_{re}) reached 39.2°C, heart rate reached 85% of their maximal heart

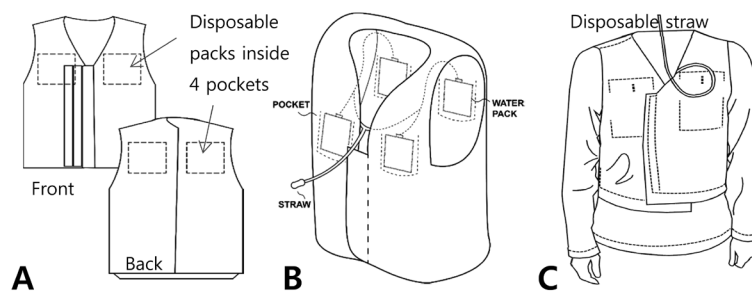


Fig. 1. A newly-developed vest with dual functions of skin cooling and drinking fluids. Front and back view before putting sports drink packs and tubing (A), side view with sports drink packs and tubing (B) and front view with sports drink packs and tubing (C).

rate, or if any subject felt unable to continue the exercise.

Measurements

Rectal temperature (T_{re}) was measured every 5 s using a data logger with thermistor (LT-8A, Gram Corporation, Japan) which was inserted around 16 cm beyond the anal sphincter. Ear canal temperature (T_{ear}) was measured using the same data logger with an earphone thermistor sensor, which was inserted around 2.5 cm inside the ear canal. Skin temperatures (T_{sk}) were measured every 5 s using thermistor probes at 10 body regions [the forehead, upper chest, abdomen, upper back, forearm, dorsal hand, rear waist, thigh, calf, and dorsal foot] using the same type of thermistors that were used to measure T_{re} . Subjects weighed themselves on a calibrated body scale (F150S-ID2, Sartorius, Germany, resolution of 1 g) before and after each trial for estimating total sweat rate. To estimate the evaporative sweat rate, we measured experimental clothing before and after trial as well. Local sweat rates were estimated on the back and chest using moisture absorptive papers ($4 \times 4 \text{ cm}^2$; 8 pieces for each region) through weighing the total mass before and after every trial on an electronic scale (AB204, Mettler Toledo, Switzerland) and the values were estimated for a 60-min value. Heart rate was measured every 5 s throughout the trial using a chest belt and a watch (RC3, Polar electro, Finland). Blood pressure was measured four times at the 0th min, 8th min, 40th min and 55th min using a digital blood pressure monitor and a cuff (HEM-7200, Omron, Japan). Urine specific gravity was measured using a device (ATAGO, Japan, PAL-10S) before and after the trial.

Thermal sensation, thermal comfort, sweat sensation and thirst sensation were recorded every 10 or 11 min at the 6th, 17th, 27th, 37th, 47th and 57th min using the following categorical scales: 17-point thermal sensation with 9 categories (4 very hot, 3.5, 3 hot, 2.5, 2 warm, 1.5, 1 slightly warm, 0.5, 0 neutral, -0.5, -1 slightly cool, -1.5, -2 cool, -2.5, -3 cold, -3.5, -4 very cold); 7-point thermal comfort (3 very comfortable, 2 comfortable, 1 a little comfortable, 0 not both, -1 a little uncomfortable, -2 uncomfortable, -3 very uncomfortable), 7-point sweat sensation (3 very dry, 2 dry, 1 a little dry, 0 neither, -1 a little wet, -2 wet, -3 very wet) and 7-point thirst sensation with 7 categories (0 no thirsty, 0.5, 1 a little thirsty, 1.5, 2 thirsty, 2.5, 3 very thirsty). Subjects were asked about their thermal sensation, thermal comfort and sweat sensation for the overall, chest and back regions. During exercise, ratings of perceived exertion (RPE) which ranged from score 6 (no exertion at all) to 20 (maximal exertion) were

recorded every 10 min. Subjects chose the category that matched their experience every 10 min and experimenters filled in their responses on experimental sheets. We interviewed subjects for information concerning their demographics and health habits, such as smoking/drinking/sleeping. The interview also included a self-health evaluation along with assessment of their expectations for their own fire protective helmets and hoods.

Data analysis

The weighted mean skin temperature was calculated according to a modified Hardy and DuBois' 12-point formula: $T_{sk} = 0.07T_{forehead} + (0.0875T_{chest} + 0.0875T_{abdomen} + 0.0875T_{upper\ back} + 0.0875T_{loin}) + 0.14T_{forearm} + 0.05T_{hand} + 0.19T_{frontal\ thigh} + 0.13T_{calf} + 0.07T_{foot}$. Physiological strain index (PSI) was calculated using Moran and colleagues³³. (1998)'s equation: $PSI = 5(T_{ret} - T_{re0}) \times (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \times (180 - HR_0)^{-1}$. The PSI values were calculated on a scale from 0 (no strain) to 10 (maximal strain). All quantitative data were expressed as the mean of the last 5 min of each period and the standard deviation of the mean (mean \pm SD). Repeated-measure analyses of variance (ANOVA) were used to identify differences in physiological responses among the four conditions. Tukey's post hoc test was used to assess the parameters that displayed significant differences in ANOVA. The Kruskal-Wallis test was used to verify differences in non-parametric variables (thermal sensation, thermal comfort, sweat sensation, thirst sensation and RPE) among the four conditions. The Mann-Whitney test was used to identify between-groups differences with Bonferroni correction. In the present study, there was no subject who stopped their participation in the middle of trials and the sample size was the identical for the four conditions ($N=8$). Statistical analyses were performed with SPSS 23.0. Significance was set at $p < 0.05$.

Results

Rectal, ear canal and mean skin temperature (T_{re} , T_{ear} , and T_{sk})

No significant differences in rectal temperature (T_{re}) among the four conditions were found at rest, during exercise and recovery, showing the average T_{re} of $37.8 \pm 0.2^\circ\text{C}$ (CON), $37.6 \pm 0.2^\circ\text{C}$ (DO), $37.7 \pm 0.3^\circ\text{C}$ (CO) and $37.7 \pm 0.2^\circ\text{C}$ (CD) during exercise (Fig. 2A). In recovery, T_{re} for DO, CO and CD declined, while T_{re} for CON maintained or showed a progressive rise (Fig. 2B, $p < 0.05$). There was a significant difference in mean skin temperature (T_{sk}) among the four conditions ($p < 0.05$, Fig. 3A). At rest, T_{sk}

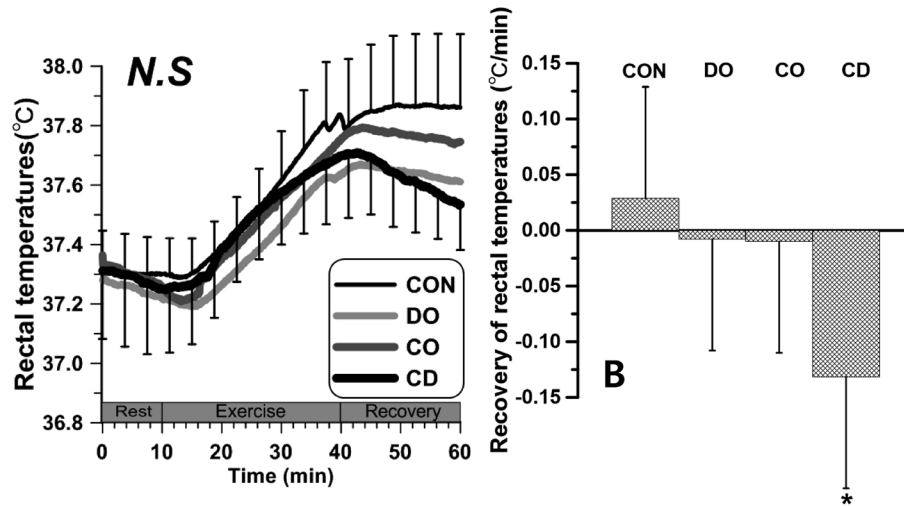


Fig. 2. The time courses of rectal temperature ($p=0.911$ at rest, $p=0.461$ during exercise, and $p=0.166$ in recovery) (A) and the changes in rectal temperature for recovery (B). CON: control; DO: drinking only; CO: cooling only; CD: cooling with drinking. $*p<0.05$.

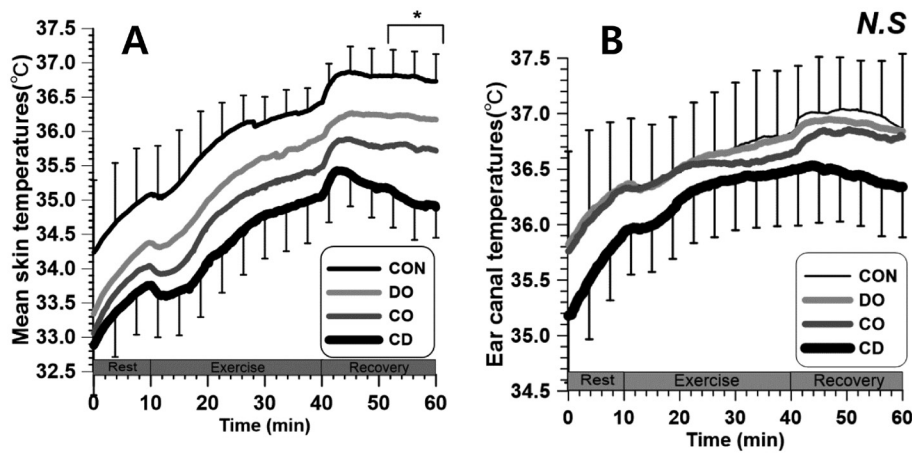


Fig. 3. The time courses of mean skin temperature (A) and the ear canal temperature (B). CON: control; DO: drinking only; CO: cooling only; CD: cooling with drinking. $*p<0.05$.

was on average 1.3°C lower for CD ($33.6 \pm 0.6^{\circ}\text{C}$) than for CON ($34.9 \pm 0.8^{\circ}\text{C}$). During recovery, T_{sk} was significantly lower for CD ($p<0.001$) and CO ($p=0.024$) when compared to CON but no difference between CD and CO was found. Also there was no difference between DO and CON. In particular, T_{sk} during recovery fell ($34.9 \pm 0.5^{\circ}\text{C}$) while T_{sk} for the other three conditions was maintained ($p<0.05$). Ear canal temperature (T_{ear}) was lower for CD ($36.4 \pm 0.5^{\circ}\text{C}$) than other three conditions but no significant differences were found among the four conditions (Fig. 3B).

Local skin temperatures (T_{sk})

Among the ten skin temperature measurements, trunk

and thigh temperatures showed significant differences according to condition. Chest and thigh temperatures were significantly lower for CD and CO than DO and CON (Table 1, $p<0.05$). Upper back temperature was lower for CD than for CON (Table 1, $p<0.05$). Abdomen, waist, forearm and hand temperatures showed lower values for CD or CO compared to DO or CON, depending on the period of exposure (Table 1). Forehead, calf, and foot temperatures did not show any differences among the four conditions. For DO, there was no significant effect on skin temperatures.

Table 1. Regional skin temperatures of the four conditions: control, drinking (DO), skin cooling (CO) and both (CD)

	Phase (min)	Control	DO	CO	CD	<i>p</i> -value
Forehead temp. (°C)	Rest (5–10 th)	35.9 ± 0.4	35.8 ± 0.3	36.0 ± 0.3	35.8 ± 0.3	N.S
	Exercise (35–40 th)	36.6 ± 0.5	35.2 ± 2.3	36.3 ± 0.3	36.1 ± 0.3	N.S
	Recovery (55–60 th)	36.3 ± 1.2	35.6 ± 1.4	36.0 ± 0.5	35.5 ± 0.7	N.S
Chest temp. (°C)	Rest (5–10 th)	34.4 ± 1.3 ^b	33.1 ± 1.2 ^b	29.5 ± 2.5 ^a	28.6 ± 3.0 ^a	<i>p</i> <0.001
	Exercise (35–40 th)	36.5 ± 0.5 ^b	35.6 ± 0.4 ^b	29.0 ± 4.6 ^a	29.4 ± 4.2 ^a	<i>p</i> <0.001
	Recovery (55–60 th)	36.9 ± 0.4 ^b	35.9 ± 0.4 ^b	31.9 ± 2.6 ^a	29.4 ± 4.2 ^a	<i>p</i> <0.001
Abdomen temp. (°C)	Rest (5–10 th)	35.5 ± 0.5 ^b	34.5 ± 1.0 ^{ab}	34.1 ± 1.3 ^a	33.9 ± 0.7 ^a	<i>p</i> <0.05
	Exercise (35–40 th)	35.6 ± 0.4	35.1 ± 1.1	34.2 ± 1.2	34.2 ± 1.1	N.S
	Recovery (55–60 th)	36.8 ± 0.4	35.8 ± 0.8	35.0 ± 1.4	33.9 ± 0.8	N.S
Upper back temp. (°C)	Rest (5–10 th)	35.7 ± 0.6 ^b	35.0 ± 0.4 ^{ab}	34.8 ± 0.5 ^{ab}	34.1 ± 1.1 ^a	<i>p</i> <0.05
	Exercise (35–40 th)	37.2 ± 0.3 ^b	36.3 ± 0.8 ^{ab}	36.1 ± 1.0 ^{ab}	35.8 ± 0.9 ^a	<i>p</i> <0.05
	Recovery (55–60 th)	37.1 ± 0.3 ^b	36.4 ± 0.2 ^b	36.1 ± 1.1 ^{ab}	35.2 ± 1.5 ^a	<i>p</i> <0.05
Forearm temp. (°C)	Rest (5–10 th)	34.9 ± 1.0	34.5 ± 0.8	34.2 ± 1.0	34.3 ± 0.9	N.S
	Exercise (35–40 th)	36.4 ± 0.5	35.9 ± 0.4	36.0 ± 0.6	36.0 ± 0.5	N.S
	Recovery (55–60 th)	36.6 ± 0.4 ^b	35.9 ± 0.3 ^{ab}	35.8 ± 0.5 ^a	35.5 ± 0.7 ^a	<i>p</i> <0.05
Hand temp. (°C)	Rest (5–10 th)	34.8 ± 0.9	34.6 ± 0.6	34.4 ± 1.4	34.5 ± 0.9	N.S
	Exercise (35–40 th)	35.5 ± 1.0	34.9 ± 0.9	34.9 ± 1.1	34.7 ± 1.0	N.S
	Recovery (55–60 th)	35.9 ± 0.7 ^b	35.4 ± 0.6 ^b	35.3 ± 0.4 ^b	34.4 ± 0.7 ^a	<i>p</i> <0.05
Waist temp. (°C)	Rest (5–10 th)	35.4 ± 0.8 ^b	34.9 ± 0.7 ^{ab}	34.2 ± 0.8 ^a	34.2 ± 0.7 ^a	<i>p</i> <0.05
	Exercise (35–40 th)	36.9 ± 0.8	36.1 ± 0.7	36.2 ± 0.5	35.8 ± 0.8	N.S
	Recovery (55–60 th)	37.1 ± 0.5 ^b	36.4 ± 0.3 ^{ab}	36.4 ± 0.4 ^a	36.2 ± 0.6 ^a	<i>p</i> <0.05
Thigh temp. (°C)	Rest (5–10 th)	34.6 ± 1.1 ^b	33.4 ± 0.7 ^{ab}	33.3 ± 0.9 ^a	33.4 ± 0.7 ^{ab}	<i>p</i> <0.05
	Exercise (35–40 th)	36.5 ± 0.5 ^b	35.9 ± 0.4 ^{ab}	35.6 ± 0.9 ^a	35.4 ± 0.7 ^a	<i>p</i> <0.05
	Recovery (55–60 th)	37.1 ± 0.4 ^b	36.2 ± 0.5 ^{ab}	36.1 ± 0.7 ^a	36.1 ± 0.4 ^a	<i>p</i> <0.05
Calf temp. (°C)	Rest (5–10 th)	34.7 ± 0.6	34.2 ± 0.5	34.1 ± 0.5	34.2 ± 0.7	N.S
	Exercise (35–40 th)	35.5 ± 1.9	36.0 ± 0.4	36.1 ± 0.4	35.3 ± 0.8	N.S
	Recovery (55–60 th)	36.6 ± 0.8	36.1 ± 0.6	36.4 ± 0.5	35.2 ± 1.6	N.S
Foot temp. (°C)	Rest (5–10 th)	34.0 ± 1.6	33.6 ± 1.7	34.2 ± 1.5	33.8 ± 1.8	N.S
	Exercise (35–40 th)	36.6 ± 1.1	36.8 ± 0.7	36.6 ± 0.7	36.6 ± 0.5	N.S
	Recovery (55–60 th)	36.7 ± 0.5	36.2 ± 0.3	36.5 ± 0.2	36.4 ± 0.3	N.S

Data are expressed as means and standard deviations (SD).

DO: Drinking only; CO: Cooling only; CD: Cooling & Drinking.

N.S: Not significant; ^{a,b}, ^{ab}: Significant differences among the four conditions by a Tukey's post hoc.

Heart rate and blood pressure

Heart rate (HR) did not show any significant differences among the four conditions at rest and during exercise, but was lower for the CO, DO, and CD than for the CON during recovery (Fig. 4, *p*<0.05; last 5 min average was 110 ± 16 bpm for CON, 95 ± 10 bpm for DO, 94 ± 13 bpm for CO, 89 ± 15 bpm for CD). There were no significant differences in blood pressure among the four conditions, but systolic pressure for recovery was greater for CON at 146 ± 16 mmHg than for the other three conditions (139 ± 9 mmHg for DO, 138 ± 10 mmHg for CO, and 137 ± 8 mmHg for CD).

Sweat rate and urine specific gravity

There were no significant differences in total sweat rate

between the four conditions (472 ± 219 g h⁻¹ for CON, 549 ± 284 g h⁻¹ for DO, 329 ± 133 g h⁻¹ for CO, and 400 ± 96 g h⁻¹ for CD). Local sweat rates on the back (1.2 ± 0.6 g h⁻¹ for CON, 1.5 ± 0.7 g h⁻¹ for DO, 1.3 ± 0.8 g h⁻¹ for CO, 1.3 ± 0.7 g h⁻¹ for CD) and the chest (1.4 ± 0.6 g h⁻¹ for CON, 1.8 ± 0.6 g h⁻¹ for DO, 1.3 ± 0.6 g h⁻¹ for CO, 1.1 ± 0.8 g h⁻¹ for CD) did not show any differences between the four conditions. Urine specific gravity increased after the 60-min exposure for CON and decreased for DO, CO and CD, but no statistically significant differences in specific urine gravity was found among the four conditions (After the 60-min exposure: 1.021 ± 0.01 g h⁻¹ for CON, 1.013 ± 0.01 g h⁻¹ for DO, 1.017 ± 0.01 g h⁻¹ for CO, and 1.016 ± 0.01 g h⁻¹ for CD).

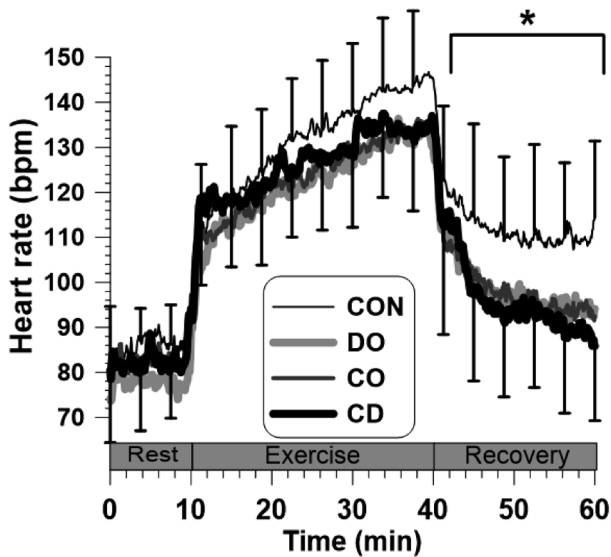


Fig. 4. Time courses of heart rate.
 CON: control; DO: drinking only; CO: cooling only; CD: cooling with drinking. * $p < 0.05$.

Subjective perceptions

Subjects felt less hot or more cool for CD than for CON ($p < 0.05$) and the difference was greater for recovery than for exercise (overall thermal sensation at the end of exercise: 2.9 ± 0.4 for CON, 1.9 ± 1.0 for DO, 2.1 ± 1.3 for CO, and 0.3 ± 1.0 for CD) (Fig. 5A). Thermal sensation on the chest was lower than the values on the back for CO and CD (Fig. 5BC). Subjects expressed less discomfort for CD than for CON on both the chest and back regions ($p < 0.001$). Also, subjects felt less wet on both chest and back regions for CD than for CON ($p < 0.05$). Subjects were also less thirsty for CD ($p = 0.004$) and CO ($p = 0.002$) than for CON. There were no differences in ratings of perceived exertion (RPE), between the four conditions (at the last of exercise: 13.8 ± 2.1 for CON, 12.5 ± 2.1 for DO, 12.8 ± 1.8 for CO, and 12.0 ± 1.5 for CD).

Physiological strain index (PSI)

PSI did not show any significant differences at rest and during exercise, but PSI was higher for CON than for CD during recovery ($p < 0.05$; CON 2.5 ± 1.2 , DO 1.5 ± 0.9 , CO 1.5 ± 1.0 and CD 0.9 ± 0.7) (Fig. 6).

Discussion

The separate effects of either wearing cooling garments or ingesting fluids under heat stress have been well-documented. The present study is, however, original in

that it explores the combined effect of skin cooling and cold fluid ingestion on alleviating heat strain. This idea could be most effectively applied to workers who have poor access to drinking water under heat stress. The first hypothesis of this study, skin cooling would be more effective to alleviate heat strain than fluid ingestion, was accepted from the reduced skin temperature and concomitant improvements in thermal sensation and comfort. However, skin cooling or fluid ingestion had a similar positive influences of lowering increased heart rate and physiological strain index (PSI), while drinking fluid was more effective for relieving thirst sensation than skin cooling. The second hypothesis, the combined effect of skin cooling and cold fluid ingestion (CD condition) would be weaker than the sum of the individual effects in the CO and DO conditions, was also partially accepted. More detailed discussion are as follows.

Consequence of alleviating heat strain during recovery

An important finding of the present study was that the combined effect of skin cooling and cold fluid ingestion was more influential during recovery than during exercise. In general, firefighters repeat a bout of work (30-min, 45-min or 60-min) and rest due to their SCBAs. During breaks at actual scenes of fire, firefighters typically take advantage of passive cooling (taking off their bunker jacket, pants, helmets, hood, boots, gloves, etc.), active cooling (using portable fans or cooling sprays, wearing cooling garments, etc.) or drinking water. Many previous investigations reported progressive increases in core temperature when wearing firefighting PPE even during recovery in heat^{7, 34, 35}. In the present study, however, T_{re} for those wearing the cooling vest or drinking fluid did not progressively increase during recovery (Fig. 2). House and colleagues¹⁷ had similar results using cooling vests (a cotton outer with a cotton mesh liner) with PCM-melting temperatures of 20°C and 30°C; these vests were effective in suppressing rising core temperature during recovery, but not during exercise. Butts *et al.*³⁶ found that PSI was lower while wearing a cooling garment after the second work bout and during recovery. Suppressing rising body core temperature during recovery is beneficial for expanding heat sink for the next bout of work. During recovery in heat, HR greater than 120 bpm is considered a high level of heat strain and below 110 bpm is considered to have little or no excessive physiological demand³⁷. Recovery HR is an index of cardiovascular demands and high HR during recovery indicates that the body is not dissipating heat fast enough³⁸. In the present study, both skin cooling

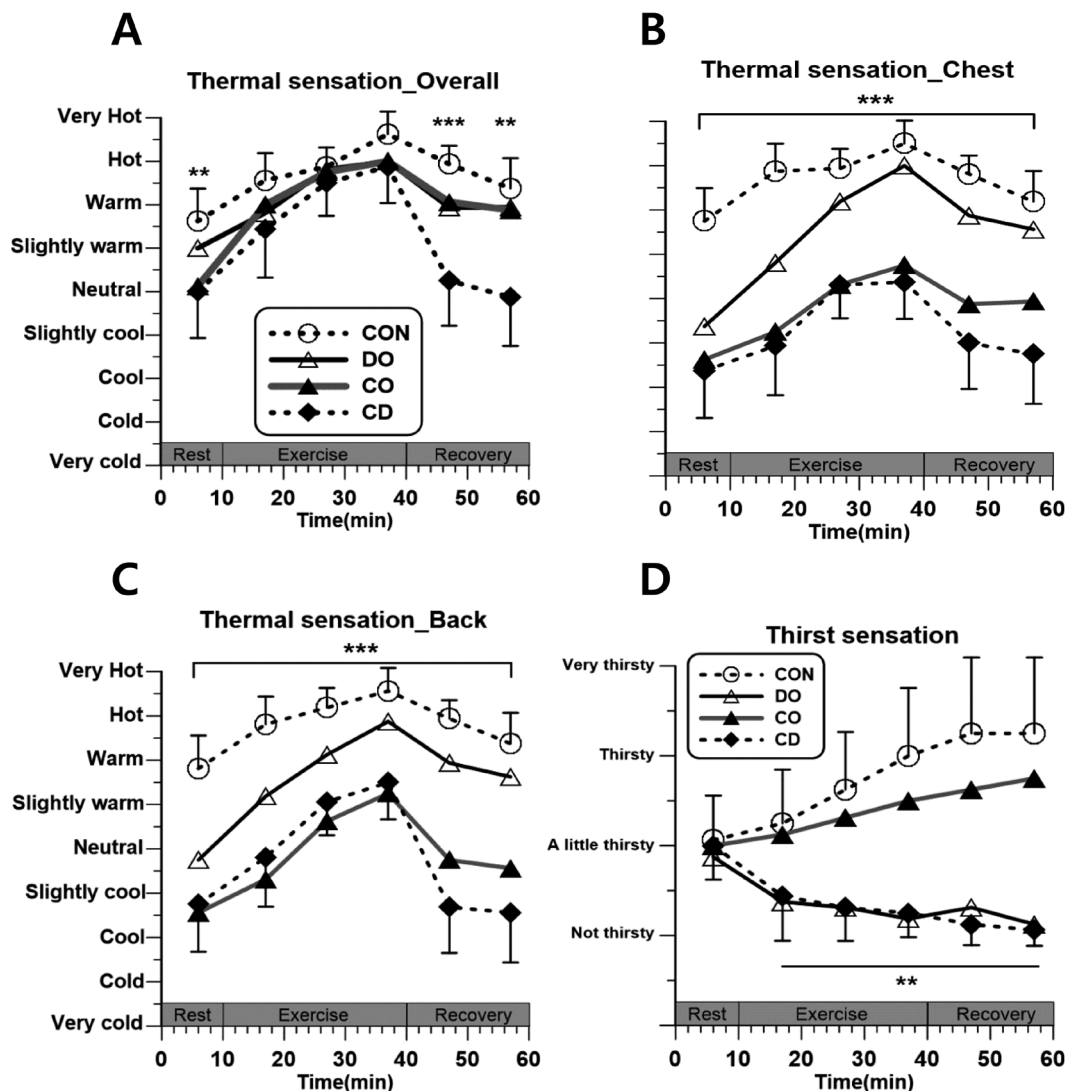


Fig. 5. Time courses of thermal sensation of overall (A), chest (B), back (C) and thirst sensation (D). CON: control; DO: drinking only; CO: cooling only; CD: cooling with drinking. ** $p < 0.01$, *** $p < 0.001$.

and fluid ingestion were effective for keeping HR under 110 bpm during recovery for CO (94 ± 13 bpm), DO (95 ± 10 bpm) and CD conditions (89 ± 15 bpm) when considering that the recovery HR for CON was on average 110 ± 16 bpm (Fig. 4).

Main effects of trunk skin cooling

It has been well documented that skin cooling reduces in heart rate^{39–41}. For the present results, recovery heart rate was lower for CD and CO than for CON. Under heat stress, the cutaneous blood vessels are vasodilated, venous return is decreased and heart rate increases to maintain stroke volume. Similarly, in hot environments, heart rate decreases from body cooling. Cold-induced cutaneous

vasoconstriction elicits increases in cardiac filling, thus allowing for better maintenance of cardiac output via stroke volume. Subsequently, this results in reduced cardiovascular strain during exercise under heat stress along with faster recovery. Shvartz⁴³ reported that heart rate was less when wearing a cooling hood than in the absence of cooling. House *et al.*¹⁷ also demonstrated significantly decreased heart rate at the end of exercise and during recovery while wearing cooling vests in the heat when comparing the control condition. Furthermore, we found the significant reduction in heart rate for DO, CD and CD during recovery when compared to the heart rate for CON. During hypohydration, decreased blood volume reduces central venous pressure and cardiac filling which reduces

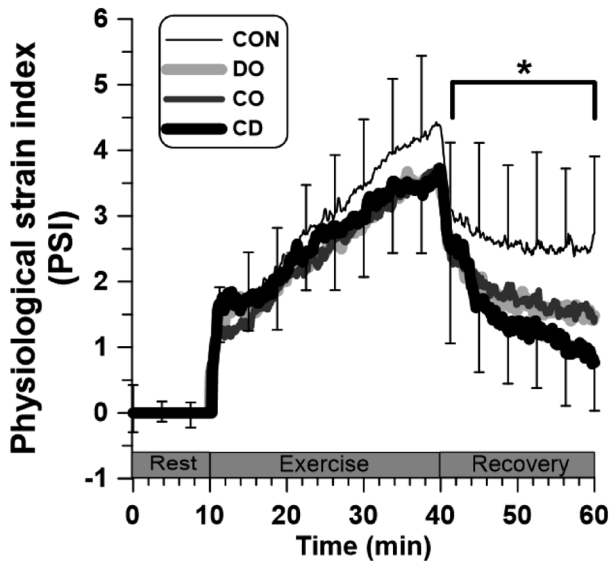


Fig. 6. Time courses of PSI change. CON: control; DO: drinking only; CO: cooling only; CD: cooling with drinking. * $p < 0.05$.

stroke volume and increases HR¹⁹). The mechanism of reduction in HR for DO in the present study could be conversely inferred from the influence of hypohydration on heart rate.

Another interesting finding from the present results is the significant effect of trunk cooling on thigh temperature. Wearing the cooling vest induced lower thigh temperature during all phases when compared to CON or DO (Table 1). A similar phenomena was found in Choi and colleagues⁴⁴) as well. Wearing a cooling vest lowered thigh temperature approximately 1.0°C whereas no significant effects were found for arm, hand, calf, and foot temperatures⁴⁴). In the present study, lowered thigh temperature starting from the rest phase might be due to the reduction in temperature of cutaneous blood supply from the heart imposed by cooling the trunk region, which would in turn cool the blood returning to the heart from the thigh. If we could measure esophageal temperature, the evidence for this lowered thigh temperature might be more clear. As most of the temperature reduction in the present study occurred within 10 min of wearing the cooling vest, the cooling benefit would be evident during a subsequent bout of leg work. Namely, firefighters can start working with expanded heat storage capacity because cold tissues act as a heat sink storing greater amounts of heat generated and delaying heat transfer to the core.

Concerning the effects of trunk cooling is whether or not core body temperature is affected. As demonstrated in

Table 2, the effects of body cooling on core body temperature, sweat rate and cardiovascular responses are inconsistent according to cooling capacity, duration of cooling (pre-, mid-, and/or post-cooling), intensity of exercise, or the degree of heat stress. The present study found that wearing the cooling vest lowered the rise of T_{re} during recovery more rather than during exercise, and the beneficial influence became greater when adding cold fluid ingestion. A considerable number of investigations reported the beneficial effect of wearing cooling garments on core body temperature during exercise or recovery⁴⁴⁻⁴⁷), which lead to reduced PSI⁴⁸) and increased exercise tolerance time⁴⁹), but another considerable number of research found no core body temperature benefit from wearing cooling garments⁵⁰⁻⁵²).

We assume that wearing the cooling vest might be effective for reducing T_{re} during exercise especially if the cooling capacity were greater than that of the present study. Greater cooling efficacy for a greater cooling capacity is to be expected. Smolander *et al.*⁵³) reported the mean heat loss from the torso due to their ice vest was 74 W·m⁻²(42 W, 272 kJ). Another study reported heat capacity 80–143 cal·g⁻¹(assumes skin temperature of 36°C)⁴⁷). According to Kamon and colleagues⁵⁴), a 1-kg ice vest would allow a 10% improvement in performance time during work in the heat. In the present study, the melting of the frozen packs on the hot plate took about 40–50 min and required about 334 kJ (80 kcal). The physical demand of wearing PPE has been well documented in terms of metabolic cost and the increases in metabolic cost have been 1% per kg of added load⁵⁵) to 3% per kg⁵⁶). Because the present vest with cooling packs weighs only 1.1 kg, the cooling capacity of the vest can cover the metabolic increase due to the added load.

Lastly is the well established fact of skin cooling reducing total sweat rate in hot environments^{41, 42, 57}). Shvartz⁵⁸) mentioned that sweat rate in hot environments decreased by about 16–22% from neck cooling, which inhibits sudomotor activity⁵⁹). This decrease in sweat rate is directly proportional to the area of the skin cooled⁶⁰). However, the results of the present study do not agree with these previous reports, and this may be due to the only moderate intensity of exercise (combined with heat stress) resulting in the 0.7% loss of total body mass of the present study.

Additional effects of cold fluid ingestion

It is thought that heat stress, itself, is a stronger stressor than dehydration because hyperthermia is more fatal than dehydration for workers in hot environments. However,

Table 2. Studies on the influence of cooling garments on alleviating heat strain during exercise and recovery in heat

Author (yr)	Subjects	Experimental condition	Cooling method (Total clothing mass)	Ta (°C) Ha (%RH)	Experimental clothing	Exercise mode	Main outcomes by cooling
Nishihara <i>et al.</i> (2002)	4 males	① No cooling, ② Cooling vest A ③ Cooling vest B	[Cooling vest A] Ice vest with 6 bags [120 g/bag] on chest and 10 bags [100 g/each] on back (2.1 kg)	30°C, 37%	Long shirt and pants (0.88 clo)	10-min rest, 90-min walking, 10-min rev (110 min)	· Lower chest temp. · TS, SS, TC improved
Sigurbjörn <i>et al.</i> (2004)	17 runners	① No cooling, ② Cooling vest during warm-up (precooling)	Ice vest with 8 ice packs (450–500 ml/pack); 2 on chest, 2 on stomach, 2 on shoulder and 2 on lower back (4.5 kg)	30°C, 50%	T-shirts & short pants	38-min warm up, 5-km run	· Blunting increases of Tre & HR · TC improved · Run time shorten
Smolander <i>et al.</i> (2004)	4 firefighters	① No cooling, ② Ice cooling vest	Ice vests with 5 packs (1.0–1.1 kg)	45°C, 30%	Firefighter's PPE (21–23 kg)	30-min waking × 4 times with 5-min rest for each	· 10 bpm lower HR & 13% smaller TSR (approx. 50 g) · lower trunk temp; · no effect on extremity temp, VO ₂ & Tre. · RPE improved (score 1) & TS improved (score 1)
Webster <i>et al.</i> (2005)	16 athletes	① No cooling, ② Ice vest A, ③ Ice vest B, ④ Ice vest C (precooling)	(2.8–3.0 kg)	37°C, 50%		30-min run (70%VO ₂ max)	· Lowered Tre, Tsk · TSR (10–23%) · No effect on HR · Tolerance time, TS & SS improved
Yoshida <i>et al.</i> (2005)	6 males	No cooling, water perfused suit and vest with water temp of 14, 20, and 26°C (7 conditions)	Water suits (86% CBSA); Water vest (25% CBSA)	WBGT 28°C	Fencing uniforms	20-min cycling × 3 times (250 W/m ²)	· Lowered Tre, Tsk, HR & TSR · TS improved
Hamada <i>et al.</i> (2006)	7 males	① Fan cooling (2.5m/s), ② Ice cooling (last 20-min exe cooling)	ice pack on the bilateral carotid (500 g)	30°C, 40%	Trunks	40-min bicycle	· Lowered Tty, SR and HR · no effect on Tre · TS improved
Choi <i>et al.</i> (2008)	12 males	① No cooling, ②③ 2 Cooling scarfs, ④ Cooling hat, ⑤ Cooling vest, ⑥⑦ Combinations	Scarf A (0.07 kg, 0.4% BSA cooled); Scarf B (0.2 kg, 0.8%); Hat (0.5 kg, 0.8%); Vest (0.8 kg)	33°C, 65%	Long sleeved shirts & pants	120-min simulated red pepper harvest work	· Vest: lowered Tre, Tsk, and HR · lowered PSI · TS improved
Kenny <i>et al.</i> (2011)	10 males	① Semimute with no cooling, ② NBC suit with cooling vest, ③ NBC suit without cooling	Ice packs (4.1 kg)	35°C, 65%	NBC protective suit	120-min walking	· Lowered in Tes (0.3°C) and HR (10 bpm) · TS, RPE (2 scores), & Tolerance time improved

Table 2. Continued

Author (yr)	Subjects	Experimental condition	Cooling method (Total clothing mass)	Ta (°C) Ha (%RH)	Experimental clothing	Exercise mode	Main outcomes by cooling
Stannard <i>et al.</i> (2011)	8 male runners	① No cooling, ② Cooling vest (precooling)	4 pockets (2 on chest, 2 on back)	24-26°C, 29-33%	T-shirts & short pants	10-km running (about 42 min)	· No effect on Tre, HR, RPE & TS
Luomala <i>et al.</i> (2012)	7 male cyclists	① No cooling, ② Ice cooling vest	4 packs (1 kg)	30°C, 40%	Cycle wear	Cycling at 80% VO ₂ max	· No effect on Tre & Tsk · Lowered trunk temp · 21.5% Tolerance time improved
House <i>et al.</i> (2013)	10 males	① No cooling, ②③④⑤ PCM cooling vests with 0, 10, 20, 30°C melting points	2 packs (1 kg/pack)	40°C, 46%	Firefighting clothing	45-min stepping and 45-min recovery	· Lowered in Tre, Tsk, HR & TSR
Teunissen <i>et al.</i> (2014)	9 males	① No cooling, ②③④ 2 cooling vests	4 cool pads (1 kg); Water perfusion (4 kg)	30°C, 50%	EU firefighters' coverall	30-min walking and 10-min recovery	· Lowered Tsk & TSR · No effect on Tre, HR · TS improved
Butts <i>et al.</i> (2017)	16 males	① No cooling, ② PCM cooling vest	8 pockets (chest, abdomen, back, thighs and hamstrings) with melting point at 10°C (-3.6 kg)	35°C, 53%		55-min exercise	· Lowered Tre & Tsk · TS improved
Bartkowiak <i>et al.</i> (2017)	6 adults	① No cooling, ② Cooling vest	Liquid cooling (cooling capacity 300 W)	30°C, 40%	Aluminized PPC	45-min walking	· Lowered Tsk · TS improved
Chan <i>et al.</i> (2017)	140 construction workers	① No cooling, ② Cooling vest (break-cooling)	8 PCM packs cooling vest with 2 ventilation fans; 80 g/pack. Melting point 28°C. 2 on the chest, 2 on the abdomen, 4 on the back (1.26 kg)	WBGT 29-31°C	Work wear (field study)	Construction work	· RPE 0.93-1.34 improved
Butts <i>et al.</i> (2017)	20 males	① No cooling ② PCM cooling vest	Set to change phase at 10°C (-3.6 kg)	34°C, 55%	Coverall suit	20-min simulated work × 2 times	· Lowered HR, Tsk, Tre, PSI, PeSI, & HS · RPE, thirst, TS improved
Mejuto <i>et al.</i> (2018)	7 cyclists	① Fluid ingestion, ② Ice slurry ingestion (pre), ③ Ice slurry ingestion (pre + mid)	-1°C ice slurry	32°C, 50%	Cycle wear	45-min cycling × 3 times at 70% VO ₂ max	· Lowered in Tre · No effect on tolerance time · RPE improved

Ta: Air temperature; Ha: Air humidity; TS: Thermal sensation; TC: Thermal comfort; Tre: Rectal temperature; HR: Heart rate; TSR: Total sweat rate; RPE: Ratings of perceived exertion; Tsk: Skin temperature; Ty: Tympanic temperature; SR: Sweat rate; PSI: Physiological strain index; NBC: Nuclear, biological and chemical; TSR: Total sweat rate; PeSI: Perceived strain index; HS: Heat strain.

heat strain and dehydration are strongly interrelated and may act synergistically. Cheuvront *et al.*⁶¹⁾ suggest that the physical proximity of thermosensitive and osmosensitive neurons in the preoptic anterior hypothalamus⁶²⁾ is central for the interaction between thermoregulation and fluid balance²⁴⁾. In this context, the cooling effect of fluid ingestion on workers bodies in hot environments may be synergic. McLellan *et al.*²⁹⁾ found that sweat rate was greater for the euhydrated condition than for the 2.3% dehydrated condition. It is clear that progressive body water losses induce hypertonic-hypovolemia (i.e., increased plasma tonicity and decreased blood volume), which reduces dry and evaporative heat loss through alterations in the core temperature threshold for initiation of skin blood flow and sweating^{19, 61)}. Many studies have observed a greater rise in core body temperature during exercise in hot environments for hypohydrated participants than for euhydrated participants^{63–66)}. Resting plasma volume decreases in a linear manner that is proportionate to the hypohydration level and plasma osmolality increases because sweat is ordinarily hypotonic relative to plasma¹⁹⁾. Reduced sweating conserves body fluid and results in reduced heat loss and increased hyperthermia. Taken together, sweating decreases proportionally to the degree of body water deficit.

However, we found no significant differences between total and local sweat rates or between skin and rectal temperatures in the four conditions. This lack of difference could be a result of the milder level of heat stress and exercise intensity of the present study (total sweat rate $472 \pm 219 \text{ g}\cdot\text{h}^{-1}$, 0.7% body mass; $37.8 \pm 0.2^\circ\text{C}$ in rectal temperature at the end of exercise for the control) compared to the levels of dehydration of previous studies. Also, participants in the present study were rehydrated with 800 ml from the cooling packs (1.2% body mass). ISO 7933⁶⁷⁾ and ISO 9886⁶⁸⁾ allows a maximum sweat loss of 1.3 kg per hour. Similar body mass loss was found in Chou and colleagues⁶⁹⁾ and they showed a 1.3 kg loss from wearing aluminized firefighters' turnout jacket and 0.8 kg loss from wearing general protective clothing. Hypohydration of 2–3% has little or no measurable effects on physiological strain and no effect of on psychophysical strain or performance⁷⁰⁾. A milder level of hypohydration (2.3–2.5% body mass) impaired tolerance time while wearing PPE in heat but core temperature was not affected²⁸⁾. Akerman *et al.*⁷⁰⁾ concluded that 2% body mass hypohydration does not measurably exacerbate heat-induced reductions in cerebral perfusion during passive heat stress but a 3% body mass exacerbates orthostatically-induced reductions in perfusion when normothermic and standing, independently of blood

pressure. Dehydration begins to present a problem when body water loss exceeds 3% of body weight⁷¹⁾. In sum, there should be no effect on core body temperature from a mild level of dehydration (up to 3% body mass). In this regard, the present results agree with the previous ones. In general, increases in core body temperatures are associated with increases in metabolic rate and/or decreases in evaporative heat dissipation. No difference in rectal temperature are occurred because dehydration has very little influence on total sweat rates; DO rectal temperatures were statistically identical as the value of CON or CO.

There are similar studies reporting the effect of ice slurry ingestion on the reduction of rectal temperature, heart rate and skin temperature (0.8–1.4% body mass)^{30, 72–74)}. However, those studies were conducted on cyclists wearing light clothing. The effect of air flow and ice slurry on skin and core body temperature when cycling wearing light sport wear can be exaggerated. The increase in the heart rate for dehydrated condition under heat stress is explained by a fluid deficit induced decrease in cardiac output, which is compensated by the increased HR. Hypohydration elicits an increase in HR and a decrease in stroke volume during submaximal exercise¹⁹⁾. It is of interest to note that the reduction in HR for DO occurred in recovery without any difference in total body mass, which was not the case for CON. Morris *et al.*⁷⁴⁾ found lower skin blood flow after ice slurry ingestion, which may be associated with the reduction in heart rate for the DO condition.

Another interesting finding was that cold fluid ingestion relieved thirst sensation even though total sweat rates were identical. That is, subjects sweated at a similar level for the four conditions but they felt less thirst for the DO and CD when compared to CON and CO. This indicates that thirst sensation is not linearly related to the total body fluid but might be more related to local sensation inside the mouth.

Limitations and suggestions

One may question whether there is any practicability of the novel vest that we developed for active firefighters wearing their respiratory masks. However, firefighters' tasks consist of various activities including rescuing without their self-contained breathing apparatus (SCBA). According to a review by McQuerry *et al.*⁷⁵⁾, firefighting activities account for 10 to 20% of all tasks, and up to 99% of a firefighter's time may be spent performing other tasks where no threat of heat and flame exist. As the fabric of the novel vest is polyester mesh spandex, the novel vest should be avoided from the fire flame, and can be used in such cases to reduce firefighters' heat strain especially

in summer. The SCBA (approximately 11–15 kg) had a significant increase on the oxygen consumption and metabolic rate⁷⁶), but subjects wore firefighting protective clothing without SCBA in the present study. Further studies will determine the cooling effect of the novel vest when wearing SCBA. Also, when firefighters face flash fire, the microclimate temperature inside the bunker jacket could be high enough to melt those packs. A flash fire test on a flame manikin is needed to make sure those packs are safe within the firefighter turnout jacket.

The second limitation was associated with the ergonomic design of the vest. We originally designed the vest to closely adhere to the body skin using stretchable mesh spandex fabric and adjustable velcro tape so that the conductive cooling effect is maximized and the thermal insulation due to air gaps between the skin and the vest is minimized. However, there may have remained some space between cooling packs and the skin during body movement especially for the back regions. This might be one of the reasons that the chest temperature was lower than the back temperature during trials. In this regard, the amount of cooling packs is a moot point. The present study provided 800 ml · hr⁻¹ of sports drink (1.2% of body mass) in total. The amount was appropriate for the current protocol because subjects sweated on average of 472 g · h⁻¹ for the control condition. In terms of the additional weight burden, the 1.1 kg (800 ml sports drink + 290 g vest) is not a significant increase in load for wearers. However, in case of exposure to more severe intensity work under uncompensable heat stress (about 3–5% body mass loss), the 800 ml-fluid supply would be not sufficient. Administrative experts need to consider firefighters' work and rest schedule when deciding the total amount of the cooling packs for drinking. Lastly, we did not find any positive effect of cooling or drinking on rectal temperature during exercise, but this may not be the case if we measure esophageal temperature as core temperature as the vest covers the trunk and cold fluid directly affects the esophageal region.

Conclusions

The present investigation evaluated the separate and combined effects of skin cooling and fluid ingestion using a novel vest for firefighters on alleviating heat strain during exercise and recovery in heat. The thermoregulatory advantage of skin cooling and fluid ingestion was more evident during recovery than during exercise. As expected, skin cooling was more effective for alleviating heat strain

than fluid ingestion, but cold fluid ingestion had a synergic advantage when combined with the skin cooling in lowering rectal temperature during recovery. Findings of the present study therefore are of special interest for workers with poor accessibility to drinking water under heat stress.

Conflict of Interest

No conflict of interest.

Acknowledgements

We truly appreciate subjects for their participation and Yoon-Jeong Hur and Andrew Gorski for their technical supports. This work was supported by the Ministry of Public Safety and Security under the Fire Fighting Safety & 119 Rescue Technology Research and Development Program (MPSS-Fire Fighting Safety-2015-82 & MPSS-Fire Fighting Safety-2015-76).

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