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

Do-Hyung KIM1, Gyu-Tae BAE1 and Joo-Young LEE1, 2*

1Department of Textiles, Merchandising and Fashion Design, Seoul National University, Korea
2Research Institute for Human Ecology, Seoul National University, Korea

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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 (\(T_r\)), 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 \(T_r\), \(T_{sk}\) 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 clo1, 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 (\(V_{O2}\)) while walking4), a 15–20% increment in \(V_{O2}\) during high-intensity treadmill walking (5 km h⁻¹ at 7.5% gradient)5) and a significant reduction in maximal oxygen uptake capacity (\(V_{O2max}\)) ranging from 8 to 20%6–8). Increases in metabolic rate and reduction in \(V_{O2max}\) 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
dissipation from the skin aggravates the accumulation of body heat. According to a survey of 796 Japanese firefighters\(^9\), 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 system\(^10\).

Body cooling systems have been applied through precooling, 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 colleagues\(^11\), 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 PPE\(^17\).

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-hypotonic-hypovolemia during exercise in heat is confirmed by increased core body temperature\(^19\), an increase in plasma osmolality along with increased plasma sodium and chloride concentration\(^19\), a decrement of local sweat secretion\(^19\), a decrease in plasma volume\(^19\), and an elevation of plasma lactic acid concentration which may lead to decreased heat capacity of circulating blood\(^20\).

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 improved\(^25\) and reaction time was significantly faster when subjects were hydrated\(^26\). 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 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 documented\(^30\). Faster reaction time when subjects were hydrated\(^30\) might 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 ± 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 m\(^2\) 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 the 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 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 clo 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 absorbing papers (4 × 4 cm²; 8 pieces for each region) through weighing the total mass before and after every trial on an electronic scale (ABB204, 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:

\[
    \text{sk} = 0.07T_{\text{forehead}} + (0.0875T_{\text{chest}} + 0.0875T_{\text{abdomen}} + 0.0875T_{\text{upper back}} + 0.0875T_{\text{loin}} + 0.14T_{\text{forearm}} + 0.05T_{\text{hand}} + 0.19T_{\text{frontal thigh}} + 0.13T_{\text{calf}} + 0.07T_{\text{foot}}.
\]

Physiological strain index (PSI) was calculated using Moran and colleagues’ (1998)’s equation:

\[
\text{PSI} = 5 \left( T_{\text{ret}} - T_{\text{re0}} \right) \times (39.5 - T_{\text{ret}})^{-1} + 5 \left( \text{HR}_{\text{t}} - \text{HR}_{0} \right) \times (180 - \text{HR}_{0})^{-1}.
\]

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 ± 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 midle 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 ± 0.2°C (CON), 37.6 ± 0.2°C (DO), 37.7 ± 0.3°C (CO) and 37.7 ± 0.2°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, $T_{sk}$
was on average 1.3°C lower for CD (33.6 ± 0.6°C) than for CON (34.9 ± 0.8°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 ± 0.5°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 ± 0.5°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.
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, 1.1 ± 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).

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

| Phase (min) | Control | DO | CO | CD | p-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 ± 1.3b | 33.1 ± 1.2b | 29.5 ± 2.5a | 28.6 ± 3.0a | p<0.001 |
| Exercise (35–40 th) | 36.5 ± 0.5b | 35.6 ± 0.4b | 29.0 ± 4.6a | 29.4 ± 4.2a | p<0.001 |
| Recovery (55–60 th) | 36.9 ± 0.4b | 35.9 ± 0.4b | 31.9 ± 2.6a | 29.4 ± 4.2a | p<0.001 |
| Abdomen temp. (°C) | | | | | |
| Rest (5–10 th) | 35.5 ± 0.5b | 34.5 ± 1.0ab | 34.1 ± 1.3a | 33.9 ± 0.7a | p<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 ± 0.8 | 35.8 ± 0.8 | 35.0 ± 1.4 | 33.9 ± 0.8 | N.S |
| Upper back temp. (°C) | | | | | |
| Rest (5–10 th) | 35.7 ± 0.6b | 35.0 ± 0.4ab | 35.8 ± 0.5a | 34.1 ± 1.1a | p<0.05 |
| Exercise (35–40 th) | 37.2 ± 0.3b | 36.3 ± 0.8ab | 36.1 ± 1.0ab | 35.8 ± 0.9a | p<0.05 |
| Recovery (55–60 th) | 37.1 ± 0.3b | 36.4 ± 0.2b | 36.1 ± 1.1ab | 35.2 ± 1.5a | p<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) | 34.8 ± 0.9 | 34.6 ± 0.6 | 34.4 ± 1.4 | 34.5 ± 0.9 | N.S |
| Recovery (55–60 th) | 36.8 ± 0.4a | 35.9 ± 0.3ab | 35.8 ± 0.5a | 35.5 ± 0.7a | p<0.05 |
| Hand temp. (°C) | | | | | |
| Rest (5–10 th) | 35.5 ± 1.0 | 34.9 ± 0.9 | 34.9 ± 1.1 | 34.7 ± 1.0 | N.S |
| Exercise (35–40 th) | 35.9 ± 0.7b | 35.4 ± 0.6ab | 35.3 ± 0.4ab | 34.4 ± 0.7a | p<0.05 |
| Recovery (55–60 th) | 35.4 ± 0.8b | 34.9 ± 0.7ab | 34.2 ± 0.8a | 34.2 ± 0.7a | p<0.05 |
| Waist temp. (°C) | | | | | |
| Rest (5–10 th) | 36.9 ± 0.8 | 36.1 ± 0.7 | 36.2 ± 0.5 | 35.8 ± 0.8 | N.S |
| Exercise (35–40 th) | 37.1 ± 0.5b | 36.4 ± 0.3ab | 36.4 ± 0.4a | 36.2 ± 0.6a | p<0.05 |
| Recovery (55–60 th) | 37.1 ± 1.1b | 33.4 ± 0.7ab | 33.3 ± 0.9a | 33.4 ± 0.7b | p<0.05 |
| Thigh temp. (°C) | | | | | |
| Rest (5–10 th) | 34.6 ± 1.1b | 33.4 ± 0.7ab | 33.3 ± 0.9a | 33.4 ± 0.7b | p<0.05 |
| Exercise (35–40 th) | 36.5 ± 0.5b | 35.9 ± 0.4ab | 35.6 ± 0.9a | 35.4 ± 0.7a | p<0.05 |
| Recovery (55–60 th) | 37.1 ± 0.4a | 36.2 ± 0.5ab | 36.1 ± 0.7a | 36.1 ± 0.4a | p<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.
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 \((p<0.05)\; \text{CON} \ 2.5 \pm 1.2, \ \text{DO} \ 1.5 \pm 0.9, \ \text{CO} \ 1.5 \pm 1.0 \ \text{and CD} \ 0.9 \pm 0.7)\) (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 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, helemts, 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 colleagues\(^{17}\) 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 body 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 demand\(^{37}\). Recovery HR is an index of cardiovascular demands and high HR during recovery indicates that the body is not dissipating heat fast enough\(^38\). In the present study, both skin cooling
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 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. Shvartz\(^{43}\) 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

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**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.
stroke volume and increases HR\(^{19}\). 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 colleagues\(^{44}\) 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 temperatures\(^{44}\). 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 recovery\(^{44-47}\), which lead to reduced PSI\(^{48}\) and increased exercise tolerance time\(^{49}\), but another considerable number of research found no core body temperature benefit from wearing cooling garments\(^{50-52}\).

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 colleagues\(^{54}\), 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 load\(^{55}\) to 3% per kg\(^{56}\). 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\(^{41,42,57}\). Shvartz\(^{58}\) mentioned that sweat rate in hot environments decreased by about 16–22% from neck cooling, which inhibits sudomotor activity\(^{59}\). This decrease in sweat rate is directly proportional to the area of the skin cooled\(^{60}\). 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) | Experimental clothing | Exercise mode | Main outcomes by cooling |
|-------------|----------|-------------------------|--------------------------------------|---------|-----------------------|---------------|--------------------------|
| Nishihara et al. (2002) | 4 males | ① No cooling, ② Cooling vest A ③ Cooling vest B | [Cooling vest A] Ice vest with 6 bags [20 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 rec (110 min) | · Lower chest temp. · TS, SS, TC improved |
| Sigurbjörn et al. (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 et al. (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, VO₂ & Tre. · RPE improved (score 1) & TS improved (score 1) |
| Webster et al. (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%VO₂max) | · Lowered Tre, Tsk · TSR (10–23%) · No effect on HR · Tolerance time, TS & SS improved |
| Yoshida et al. (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/m²) | · Lowered Tre, Tsk, HR & TSR · TS improved |
| Hamada et al. (2006) | 7 males | ① Fan cooling (2.5 m/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 Try, SR and HR · no effect on Tre · TS improved |
| Choi et al. (2008) | 12 males | ① No cooling, ② ③ 2 Cooling scarfs, ④ Cooling hat, ⑤ Cooling vest, ⑥ ⑦ 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 et al. (2011) | 10 males | ① Seminude 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 |
| Author (yr)          | Subjects | Experimental condition | Cooling method (Total clothing mass) | Ta (°C) Ha (%RH) | Experimental clothing | Exercise mode | Main outcomes by cooling |
|----------------------|----------|------------------------|--------------------------------------|-----------------|-----------------------|---------------|--------------------------|
| Stannard et al. (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 et al. (2012)  | 7 male cyclists | ① No cooling, ② Ice cooling vest | 4 packs (1 kg) | 30°C, 40% | Cycle wear | Cycling at 80% VO<sub>2max</sub> | No effect on Tre & Tsk, Lowered trunk temp, 21.5% Tolerance time improved |
| Hooset al. (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 et al. (2014)| 9 males | ① No cooling, ②③ 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 et al. (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 Tsk & Tsk, TS improved |
| Bartkowiak et al. (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 et al. (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 et al. (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 et al. (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<sub>2max</sub> | Lowered in Tre, No effect on tolerance time, RPE improved |

Ta: Air temperature; Ha: Air humidity; TS: Thermal sensation; SS: Sweat sensation; TC: Thermal comfort; Tre: Rectal temperature; HR: Heart rate; TSR: Total sweat rate; RPE: Ratings of perceived exertion; Tsk: Skin temperature; Tty: Tympaonic 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 hypothalamus\(^{62}\) is central for the interaction between thermoregulation and fluid balance\(^{24}\). In this context, the cooling effect of fluid ingestion on workers' bodies in hot environments may be synergic. McLe llan 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 plasma\(^{19}\). 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 ± 219 g·h\(^{-1}\), 0.7% body mass; 37.8 ± 0.2°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 7933\(^{67}\) and ISO 9886\(^{68}\) allows a maximum sweat loss of 1.3 kg per hour. Similar body mass loss was found in Chou and colleagues\(^{69}\) and they showed a 1.3 kg loss from wearing aluminized firefighters' turnout jacket and 0.8 kg loss from wearing general protective clothing. Hyponhydration of 2–3% has little or no measurable effects on physiological strain and no effect of on psychophysical strain or performance\(^{70}\). A milder level of hyponhydration (2.3–2.5% body mass) impaired tolerance time while wearing PPE in heat but core temperature was not affected\(^{28}\). Akerman et al.\(^{70}\) concluded that 2% body mass hyponhydration 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 weight\(^{71}\). 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 exercise\(^{19}\). 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 conditions. Another 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 conditions. 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 rate, 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.

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**References**

1. Barr D, Gregson W, Reilly T (2010) The thermal ergonomics of firefighting reviewed. Appl Ergon 41, 161–72. [Medline] [CrossRef]
2. Holmér I, Kuklane K, Gao C (2006) Test of firefighter’s turnout gear in hot and humid air exposure. Int J Occup Saf Ergon 12, 297–305. [Medline] [CrossRef]
3. Dorman LE, Havenith G (2009) The effects of protective clothing on energy consumption during different activities. Eur J Appl Physiol 105, 463–70. [Medline] [CrossRef]
4. Sköldström B (1987) Physiological responses of fire fighters to workload and thermal stress. Ergonomics 30, 1589–97. [Medline] [CrossRef]
5. Graveling R, Johnson J, Butler D, Crawford JO, Love R, Mclaren W (1999) Study of the degree of protection afforded by firefighter’s clothing. FRDG, FRDG Publishing Report No. 1/99, London.
6. Dreger RW, Jones RL, Petersen SR (2006) Effects of the self-contained breathing apparatus and fire protective clothing on maximal oxygen uptake. Ergonomics 49, 911–20. [Medline] [CrossRef]
7. Lee JY, Kim S, Jang YJ, Baek YJ, Park J (2014) Component contribution of personal protective equipment to the alleviation of physiological strain in firefighters during work and recovery. Ergonomics 57, 1068–77. [Medline] [CrossRef]
8. Louhevaara V, Ilmarinen R, Griefahn B, Künemund C, Mäkinen H (1995) Maximal physical work performance with European standard based fire-protective clothing system and equipment in relation to individual characteristics. Eur J Appl Physiol Occup Physiol 71,
9) Tochihara Y, Chou C, Fujita M, Ogawa T (2005) Protective clothing-related heat stress on firefighters in Japan. In: Environmental Ergonomics XI, Holmer I, Kulane K, Gao C (Ed.), Ystad: Sweden, 137–9.

10) Lee JY, Park J, Park H, Coca A, Kim JH, Taylor NA, Son SY, Tochihara Y (2015) What do firefighters desire from the next generation of personal protective equipment? Outcomes from an international survey. Ind Health 53, 434–44. [Medline] [CrossRef]

11) Kenny GP, Schissler AR, Stapleton J, Piamonte M, Binder K, Lynn A, Lan CQ, Hardcastle SG (2011) Ice cooling vest on tolerance for exercise under uncompensable heat stress. J Occup Environ Hyg 8, 484–91. [Medline] [CrossRef]

12) Barr D, Reilly T, Gregson W (2011) The impact of different cooling modalities on the physiological responses in firefighters during strenuous work performed in high environmental temperatures. Eur J Appl Physiol 111, 959–67. [Medline] [CrossRef]

13) Carter JB, Banister EW, Morrison JB (1999) Effectiveness of rest pauses and cooling in alleviation of heat stress during simulated fire-fighting activity. Ergonomics 42, 299–313. [Medline] [CrossRef]

14) House JR, Holmes C, Allsopp AJ (1997) Prevention of heat strain by immersing the hands and forearms in water. J R Nav Med Serv 83, 26–30. [Medline]

15) Selkirk GA, McLellan TM, Wong J (2004) Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. J Occup Environ Hyg 1, 521–31. [Medline] [CrossRef]

16) Zhang Y, Bishop PA, Casaru C, Davis IK (2009) A new hand-cooling device to enhance firefighter heat strain recovery. J Occup Environ Hyg 6, 283–8. [Medline] [CrossRef]

17) House JR, Lunt HC, Taylor R, Milligan G, Lyons JA, House CM (2013) The impact of a phase-change cooling vest on heat strain and the effect of different cooling pack melting temperatures. Eur J Appl Physiol 113, 1223–31. [Medline] [CrossRef]

18) Brown A, Vargas LF, Davila YC, Berrious L (2007) Palatability and voluntary intake of three commercially available sports drinks and unflavored water during prolonged exercise in hot and humid conditions. Med Sci Sports Exerc 39, S315.

19) Sawka MN, Montain SJ, Latzka WA (2001) Hydration and thermoregulation effects on thermoregulation and performance in the heat. Comp Biochem Physiol A Mol Integr Physiol 128, 679–90. [Medline] [CrossRef]

20) Zurovski Y, Eckstein L, Horowitz M (1991) Heat stress and thermal dehydration: lactic acidemia and plasma volume regulation. J Appl Physiol 1985 71, 2434–9. [Medline] [CrossRef]

21) Gopinathan PM, Pichan G, Sharma VM (1988) Role of dehydration in heat stress-induced variations in mental performance. Arch Environ Health 43, 15–7. [Medline] [CrossRef]

22) Serwah N, Marino FE (2006) The combined effects of hydration and exercise stress on choice reaction time. J Sci Med Sport 9, 157–64. [Medline] [CrossRef]

23) Noakes TD (1993) Fluid replacement during exercise. Exerc Sport Sci Rev 21, 297–330. [Medline] [CrossRef]

24) Sawka MN, Young AJ, Latzka WA, Neufer PD, Quigley MD, Pandolf KB (1992) Human tolerance to heat strain during exercise: influence of hydration. J Appl Physiol 1985 73, 368–75. [Medline] [CrossRef]

25) Cian C, Barraud PA, Melin B, Raphael C (2001) Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. Int J Psychophysiol 42, 243–51. [Medline] [CrossRef]

26) Solera A, Salazar W, Passe D (1999) Influence of dehydration and rehydration on cognitive processes. Med Sci Sports Exerc 31, 905. [CrossRef]

27) Schlader ZJ, Chapman CL, Sarker S, Russo L, Rideout TC, Parker MD, Johnson BD, Hostler D (2017) Firefighter work duration influences the extent of acute kidney injury. Med Sci Sports Exerc 49, 1745–53. [Medline] [CrossRef]

28) Cheung SS, McLellan TM (1998) Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. J Appl Physiol 1985 84, 1731–9. [Medline] [CrossRef]

29) McLellan TM, Frim J, Bell DG (1999) Efficacy of air and liquid cooling during light and heavy exercise while wearing NBC clothing. Aviat Space Environ Med 70, 802–11. [Medline]

30) Mejuto G, Chalmers S, Gilbert S, Bentley D (2018) The effect of ice slurry ingestion on body temperature and cycling performance in competitive athletes. J Therm Biol 72, 143–7. [Medline] [CrossRef]

31) Lee JY, Choi JW, Kim H (2008) Determination of body surface area and formulas to estimate body surface area using the alginate method. J Physiol Anthropol 27, 71–82. [Medline] [CrossRef]

32) ISO 9920 (2007) Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. International Organization for Standardization, Geneva.

33) Moran DS, Shitzer A, Pandolf KB (1998) A physiological strain index to evaluate heat stress. Am J Physiol 275, R129–34. [Medline]

34) Baeck YJ, Jung D, Son SY, Lee JY (2018) Comparisons between Shikoro-type helmet with no hood and typical fire protective helmets with hood in a hot and humid environment. Ergonomics 61, 420–8. [Medline] [CrossRef]

35) Smith DL, Manning TS, Petruzzello SJ (2001) Effect of strenuous live-fire drills on cardiovascular and psychological responses of recruit firefighters. Ergonomics 44, 244–54. [Medline] [CrossRef]

36) Butts CL, Smith CR, Ganio MS, McDermott BP (2017) Physiological and perceptual effects of a cooling garment during simulated industrial work in the heat. Appl Ergon 59 Pt A, 442–8. [Medline] [CrossRef]
37) CEN TC 162 (2002) Protective clothing for firefighters—Performance requirements for protective clothing for firefighting. European Committee for Standardization, London.

38) Logan PW, Bernard TE (1999) Heat stress and strain in an aluminum smelter. Am Ind Hyg Assoc J 60, 659–65. [Medline] [CrossRef]

39) Bomalaski SH, Chen YT, Constable SH (1995) Continuous and intermittent personal microclimate cooling strategies. Aviat Space Environ Med 66, 745–50. [Medline]

40) Nishihara N, Tanabe S, Hayama H, Komatsu M (2002) A cooling vest for working comfortably in a moderately hot environment. J Physiol Anthropol Appl Human Sci 21, 75–82. [Medline] [CrossRef]

41) Richardson G, Cohen JB, McPhate DC, Hayes PA (1988) A personal conditioning system based on a liquid-conditioned vest and a thermolectric supply system. Ergonomics 31, 1041–7. [Medline] [CrossRef]

42) Constable SH, Bishop PA, Nunneley SA, Chen T (1994) Intermittent microclimate cooling during rest increases work capacity and reduces heat stress. Ergonomics 37, 277–85. [Medline] [CrossRef]

43) Shvartz E (1970) Effect of a cooling hood on physiological responses to work in a hot environment. J Appl Physiol 29, 36–9. [Medline] [CrossRef]

44) Choi JW, Kim MJ, Lee JY (2008) Alllevation of heat strain by cooling different body areas during red pepper harvest work at WBGT 33 degrees C. Ind Health 46, 620–8. [Medline] [CrossRef]

45) Bennett BL, Hagan RD, Huey KA, Minson C, Cain D (1995) Comparison of two cool vests on heat-strain reduction while wearing a firefighting ensemble. Eur J Appl Physiol Occup Physiol 70, 322–8. [Medline] [CrossRef]

46) Epstein Y, Shapiro Y, Brill S (1986) Comparison between different auxiliary cooling devices in a severe hot/dry climate. Ergonomics 29, 41–8. [Medline] [CrossRef]

47) Webster J, Holland EJ, Sleivert G, Laing RM, Niven BE (2005) A light-weight cooling vest enhances performance of athletes in the heat. Ergonomics 48, 821–37. [Medline] [CrossRef]

48) McFarlin BK, Henning AL, Venable AS, Williams RR, Best Sampson JN (2016) A shirt containing multistage phase change material and active cooling components was associated with increased exercise capacity in a hot, humid environment. Ergonomics 59, 1019–25. [Medline] [CrossRef]

49) Hasegawa H, Takatori T, Komura T, Yamasaki M (2005) Wearing a cooling jacket during exercise reduces thermal strain and improves endurance exercise performance in a warm environment. J Strength Cond Res 19, 122–8. [Medline]

50) Duffield R, Dawson B, Bishop D, Fitzsimons M, Lawrence S (2003) Effect of wearing an ice cooling jacket on repeat sprint performance in warm/humid conditions. Br J Sports Med 37, 164–9. [Medline] [CrossRef]

51) Hamada S, Masafumi T, Szygula Z, Adachi K (2006) Effect of partial body cooling on thermophysiological responses during cycling work in a hot environment. J Therm Biol 31, 194–207. [CrossRef]

52) Lopez RM, Cleary MA, Jones LC, Zuri RE (2008) Thermoregulatory influence of a cooling vest on hyperthermic athletes. J Athl Train 43, 55–61. [Medline] [CrossRef]

53) Smolander J, Kuklane K, Gavhed D, Nilsson H, Holmér I (2004) Effectiveness of a light-weight ice-vest for body cooling while wearing fire fighter’s protective clothing in the heat. Int J Occup Saf Ergon 10, 111–7. [Medline] [CrossRef]

54) Kamon E, Kenney WL, Deno NS, Soto KL, Carpenter AJ (1986) Readdressing personal cooling with ice. Am Ind Hyg Assoc J 47, 293–8. [Medline] [CrossRef]

55) Givoni B, Goldman RF (1971) Predicting metabolic energy cost. J Appl Physiol 30, 429–33. [Medline] [CrossRef]

56) Rintamaki H (2005) Protective clothing and performance in cold environments. In: The 3rd International Conference on Human Environment System, Tokyo, Japan, September 12–15.

57) Frim J (1989) Head cooling is desirable but not essential for preventing heat strain in pilots. Aviat Space Environ Med 60, 1056–62. [Medline]

58) Shvartz E (1976) Effect of neck versus chest cooling on responses to work in heat. J Appl Physiol 41, 668–72. [Medline] [CrossRef]

59) Veghte JH, Webb P (1961) Body cooling and response to heat. J Appl Physiol 16, 235–8. [Medline] [CrossRef]

60) Banerjee MR, Elizondo R, Bullard RW (1969) Reflex responses of human sweat glands to different rates of skin cooling. J Appl Physiol 26, 787–92. [Medline] [CrossRef]

61) Cheuvront SN, Kolka MA, Cadarette BS, Montain SJ, Sawka MN (2003) Efficacy of intermittent, regional microclimate cooling. J Appl Physiol 1985 94, 1841–8. [Medline] [CrossRef]

62) Silva NL, Boullant JA (1984) Effects of osmotic pressure, glucose, and temperature on neurons in preoptic tissue slices. Am J Physiol 247, R335–45. [Medline]

63) Fortney SM, Nadel ER, Wenger CB, Bove JR (1981) Effect of acute alterations of blood volume on circulatory performance in humans. J Appl Physiol 50, 292–8. [Medline] [CrossRef]

64) González-Alonso J, Mora-Rodríguez R, Coyle EF (2000) Stroke volume during exercise: interaction of environment and hydration. Am J Physiol Heart Circ Physiol 278, H321–30. [Medline] [CrossRef]

65) Montain SJ, Coyle EF (1992) Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. J Appl Physiol 1985 73, 1340–50. [Medline] [CrossRef]

66) Sawka MN, Toner MM, Francesconi RP, Pandolf KB (1983) Hydration and exercise: effects of heat acclimation, gender, and environment. J Appl Physiol 55, 1147–53.
ISO 7933 (2004) Ergonomics of the thermal environment–Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. International Organization for Standardization, Geneva.

ISO 9886 (2004) Evaluation of thermal strain by physiological measurements. International Organization for Standardization, Geneva.

Chou C, Tochihara Y, Kim T (2008) Physiological and subjective responses to cooling devices on firefighting protective clothing. Eur J Appl Physiol 104, 369–74. [Medline] [CrossRef]

Akerman AP, Tipton M, Minson CT, Cotter JD (2016) Heat stress and dehydration in adapting for performance: good, bad, both, or neither? Temp Austin 3, 412–36. [Medline] [CrossRef]

Nadel ER, Lamb DR, Murray R (1988) Temperature regulation and prolonged exercise.

Siegel R, Maté J, Brearley MB, Watson G, Nosaka K, Laursen PB (2010) Ice slurry ingestion increases core temperature capacity and running time in the heat. Med Sci Sports Exerc 42, 717–25. [Medline] [CrossRef]

Siegel R, Maté J, Watson G, Nosaka K, Laursen PB (2012) Pre-cooling with ice slurry ingestion leads to similar run times to exhaustion in the heat as cold water immersion. J Sports Sci 30, 155–65. [Medline] [CrossRef]

Morris NB, Coombs G, Jay O (2016) Ice slurry ingestion leads to a lower net heat loss during exercise in the heat. Med Sci Sports Exerc 48, 114–22. [Medline] [CrossRef]

McQuerry M, Den Hartog E, Barker R, Ross K (2016) A review of garment ventilation strategies for structural firefighter protective clothing. Text Res J 86, 749–64. [CrossRef]

Bakri I, Lee JY, Nakao K, Wakabayashi H, Tochihara Y (2012) Effects of firefighters’ self-contained breathing apparatus’ weight and its harness design on the physiological and subjective responses. Ergonomics 55, 782–91. [Medline] [CrossRef]