Upper- vs. Whole-Body Cooling During Exercise with Thermal Protective Clothing in the Heat

Fatemeh Mansouri; Morteza Talebian Nia; Rodrigo Villar; Stephen M. Cornish; Gordon Grant Giesbrecht

INTRODUCTION: Firefighters operating in hot environments face challenges from protective garments that restrict heat dissipation, resulting in increased core temperature, thermal discomfort, and performance decline. Cooling vests represent a viable solution. The study aim was to compare effectiveness of the same amount of cooling power to the upper body (UB) or whole body (WB) in alleviating thermoregulatory and physiological stress, enhancing cognitive function, and reducing ratings of thermal discomfort and exertion, during 60 min of exercise in a hot environment (40°C, 40% relative humidity) while wearing firefighter turnout gear.

METHODS: Eight healthy individuals (27.5 ± 3 y) participated in three conditions with either no cooling (Control) or active cooling with a liquid perfused shirt (UB cooling), or with a liquid perfused shirt and pants (WB cooling). In each trial, subjects performed three sets of 15 min of stepping (20 steps · min^{-1}) and 5 min of rest.

RESULTS: Both cooling strategies were beneficial compared to having no cooling at all. Subjects could only complete two exercise bouts during Control, but they completed all three bouts with active cooling. WB cooling provided an advantage over UB cooling for core and skin temperature, and thermal comfort and sensation. The advantage in minimizing the increase in core temperature was only evident during the third exercise bout.

DISCUSSION: Active cooling is advantageous under these conditions. WB cooling provided some benefits vs UB cooling during heavy intensity exercise; however, it is uncertain whether these benefits would be observed during light-to-moderate exercise, which more likely reflects an actual firefighting scenario.

KEYWORDS: heat illness, firefighter gear, cooling garments, thermoregulation, hot environment exercise.

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Significant heat stress is a common risk in various commercial, industrial, and emergency response operations.[1] Excessive body heating is a risk from high ambient temperature and/or humidity, as well as excessive workloads. These factors are exacerbated in some occupations by protective clothing, such as body armor, nuclear biological chemical suits, or firefighter turnout gear. For example, military, law enforcement, and firefighter personnel (e.g., airports or rocket launch sites) wear these garments during their missions to enhance their safety. However, these garments can hinder the body's ability to dissipate heat because they limit heat loss to the environment due to high insulation and low permeability to water vapor, which reduces the thermoregulatory function of sweating. Diminished heat loss can lead to an increase in core temperature (T_{co}) which can cause heat illness, reduce work output, impair cognitive function and decision-making, produce erratic behavior, and increase the likelihood of accidents. Previous research has addressed prevention of body core heating during exercise in the heat while wearing protective clothing.[2,3]

A liquid cooling garment (LCG) is a popular form of cooling technology.[4–6] It operates by using a liquid coolant, such as water or ethylene glycol, as the circulating fluid. The coolant is stored in a reservoir and circulated through a network of

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tubing inside the garment using external power, such as a battery-powered micropump. There are several studies on the effectiveness of liquid cooling vests, and some have reported them as effective for reducing physiological load[3,7] but not cognitive inhibition or attention.[3] These studies primarily examined vests that cover only the torso. Little work has been done on the effect of cooling more than the upper body (UB).

One study found that a specialized LCG covering the head, torso, thighs, and lower arms was effective in decreasing the physiological and thermal heat strain compared to an LCG that covered only the head and lower arms, or no cooling at all.[8] These results are not surprising because the specialized LCG had not only an increased surface area but also a threefold increase in flow rate. It is not known which body surface configuration would be more effective if the cooling power (e.g., the total liquid flow rate) is the same. Interestingly, head and lower arm cooling did not improve core temperature or exercise time compared to no cooling.

Koscheyev[9] cooled different body segments with 8°C water and demonstrated that cooling capacity for the UB, including torso, upper arms, and forearms (5.18 kcal · min^{-1}), was higher than for the lower body, including the thigh and calves (3.71 kcal · min^{-1}), in resting subjects. Therefore, it might seem best to apply all cooling power to the UB. However, if leg exercise is involved, heat production of, and blood flow to, the lower body will be proportionally greater, and redistributing some cooling to the lower body may be beneficial. Also, concentrating all cooling to a smaller total surface area (e.g., the UB) may result in excessive cold discomfort.

The purpose of this study was to compare the efficacy of the same cooling power applied to either UB or whole-body (WB) cooling systems in reducing physiological and thermoregulatory stress, improving subjective responses, and enhancing cognitive function during exercise in a hot environment while wearing firefighter turnout gear. It was hypothesized that cooling would be beneficial and that WB cooling would be more effective than UB cooling.

METHODS

Subjects

The experimental protocol was approved by the University of Manitoba Research Ethics Board 1 (HE2023-0101). This study was registered in ClinicalTrials.gov (NCT05890261). Eight subjects (including two women) were (mean ± SD) 27.5 ± 3 y old, 175.6 ± 8 cm tall, with body mass of 73.6 ± 12 kg and 13.8 ± 5% body fat (measured by bioelectrical impedance analysis, InBody USA, Cerritos, CA, USA). On three occasions, they wore firefighter turnout gear in a protocol including three 15-min exercise bouts (step test in 40°C air and 40% relative humidity), each followed by a 5-min rest period.

Materials

Core temperature (°C) was monitored with an ingestible pill (e-Celsius, Hérouville Saint Clair, France) that continuously monitored, recorded, and wirelessly transmitted core temperature. Skin temperature (T_{skin}, °C) was measured with small metal discs (iButton, Whitewater, WI, USA) taped to the skin at the following six sites on the left side of the body: chest, abdomen, upper arm, lower arm, anterior thigh, and anterior calf.[2,10,11] Heart rate (HR) was measured with a smart garment (tank top shirt, Hexoskin Wearable Body Metrics, Montreal, Canada) worn directly against the skin in all conditions. Oxygen consumption ($\dot{V}O_2$) was continuously monitored with a metabolic cart (Parvo Medics, UT, USA).

Sweat loss was calculated as follows. Upon arriving at the lab, subjects were weighed in the clothing that they wore to the lab (this was considered their "reference clothing"). They then changed into their exercise clothing (under shorts, sport shorts, Hexoskin shirt, and bra, if necessary). Following the exercise protocol, they removed their exercise clothing and dried their skin off. They then put on their "reference clothing" and were weighed a final time. Total sweat loss mass was calculated as follows: m_{sweat} loss = ($m_{body+reference\ clothing\ i}$) − ($m_{body+reference\ clothing\ f}$), where m_{sweat} loss is the mass of sweat lost during the entire protocol, $m_{body+reference\ clothing}$ is the mass of the subject plus the dry reference clothing worn to the lab, and $_i$ and $_f$ refer to initial and final measurements, respectively.[2]

To ensure proper hydration status prior to each trial, urine specific gravity (USG) was determined. Subjects provided a urine sample, and a reagent strip was used to determine the USG (Multistix 10 SG, Bayer). To be eligible to start a trial, a USG value equal to or below 1.020 was required, indicating minimal dehydration.[2] If the initial USG reading was 1.021 or higher, subjects were instructed to consume 2–3 cups of water, and a second test was conducted approximately 1 h later. If necessary, this process was repeated until the USG met the inclusion criteria.

Subjects rated their perceived exertion (RPE) on a scale ranging from 6 (no exertion at all) to 20 (maximal exertion).[12] They then rated their thermal sensation on a scale ranging from −3 (cold) to +3 (hot),[13] and their thermal discomfort on a scale of 0 (comfortable) to 4 (extremely uncomfortable).[14] They then rated their breathing discomfort on a scale of 1 (no discomfort) to 7 (intolerable discomfort).[15] Skin wetness was rated using a scale of 1 (dry) to 5 (soaked).[15]

Cognitive function was assessed with the mini-cog test, which is a brief screening tool.[16] This test involved two components: a three-item recall test and a clock-drawing task. First, subjects were asked to repeat three unrelated words that were spoken by the tester. They then were asked to draw a clock face including all the numbers (1–12), with the hands correctly showing a specific time that was given to them. Then they were asked to repeat the original three words in the correct order. The recall test is scored out of three points (one point for each word correctly recalled in the proper order), while the clock-drawing task is scored out of two points (one point for the correct placement of the numbers and one point for the correct time). The scores from the two components were added together. A score of 0–2 suggests cognitive impairment, while a score of 3–5 suggests normal cognitive function.

Subjects participated in three trials, each involving three 15-min exercise bouts followed by 5 min of rest, with either no cooling or one of two different cooling conditions using liquid cooling garments (e.g., long sleeved shirt and full-length pants; Allen-Vanguard, ON, Canada). Each cooling garment was inlayed with tubing at 10–15 mm intervals. The conditions were defined as follows: Control (C) with no cooling garments; UB cooling with the cooling shirt (weight, 0.4 kg) worn over the Hexoskin shirt and beneath the firefighter turnout gear; and WB cooling with both cooling shirt and pants (total weight, 0.8 kg) worn over the Hexoskin shirt and sport shorts and beneath the turnout gear. The Hexoskin shirt covered ~70% of the surface area of the cooling shirt and the sport shorts covered ~50% of the surface area of the cooling pants. The order of conditions was randomly assigned to achieve a balanced design.

The cooling garments were perfused with 2°C water at a flow rate of $1.8\,\mathrm{L \cdot min^{-1}}$ from just prior to entering the chamber until the end of the recovery period. Thermocouples measured inflow and outflow water temperatures from either the shirt (e.g., UB condition) or the combined shirt and pants (e.g., WB condition). Values were recorded every 5 min while in the chamber. The turnout gear consisted of jacket, pants, and helmet weighing a total of 6.5 kg. Subjects wore their own footwear, and they did not carry self-contained breathing apparatus.

Procedure

Each subject performed their trials at the same time of the day to control for circadian effects. They were asked to refrain from smoking, consuming alcohol, and performing moderate-to-heavy exercise within 24 h before each trial. They were also asked to drink 2–3 glasses of water and eat a moderately sized meal no less than 1 h prior to arrival.

On arrival at the laboratory, a urine sample was collected for the analysis of USG. After instrumentation, subjects sat in the laboratory [ambient temperature (T_{air}) ~20°C] for 15 min of baseline measurements (**Fig. 1**). Subjects then entered a chamber (T_{air} of 39 ± 1°C and 41 ± 4% relative humidity) where they performed a 60-min exercise and rest routine. This included three sets of 15 min of stepping exercise at a rate of 20 steps · min^{-1} (step height = 22.5 cm high), followed by a 5-min seated rest period during which the subjective and cognitive measures were taken. After completing the exercise and rest protocols, subjects then exited the chamber and sat for an additional 15 min. The entire clothing ensembles were worn throughout each 90-min protocol. The exercise test was terminated, and the subject exited the chamber if: the core temperature reached 39°C; the subject felt light-headed or nauseous; the subject indicated a wish to stop; or a researcher felt the subject should stop for any reason.

Subjective and cognitive assessments were taken at the following times (Fig. 1): 15 min prior to exercise (baseline), during the three rest periods in the chamber, and 10 min after exiting the chamber. After each subject completed their three trials, they were asked to comment on which cooling condition they preferred and why.

Statistical Analysis

The head, feet, and hands were not included in this analysis, therefore the regional area percentages for the six measured sites totaled 84% (e.g., chest, 18%; abdomen, 18%; upper arm, 9%; lower arm, 6%; anterior thigh, 18%; and anterior calf, 15%). These percentages were used to calculate area-weighted T_{skin} for the total body (all six sites), upper body (UB, four sites), and lower body (LB, two sites) according to previous work in our lab.[2]

Heat production was calculated as follows:

$$\text{Heat production}\left(\mathrm{kcal \cdot min^{-1}}\right) = \dot{V}O_2\left(\mathrm{L\,O_2 \cdot min^{-1}}\right) \cdot 4.825\ \mathrm{kcal \cdot L\,O_2}^{-1},$$

where a respiratory quotient of 0.82 for a mixed diet was assumed.

Heat removal in each cooling condition was calculated as follows:

$$\dot{Q}(\mathrm{W}) = m_w \cdot c_w \cdot (T_{out} - T_{in}) \cdot 69.7,$$

where $\dot{Q}$ = heat flow (positive values indicate loss from body); m_w = water flow rate (L · min^{-1}); c_w = specific heat of water (1 kcal · kg^{-1} · °C^{-1}); T_{out} and T_{in} = outlet and inlet water temperature respectively (°C); and 69.7 is the conversion factor (e.g., 69.7 W · kcal^{-1} · min^{-1}).

All statistical analyses were performed with the SigmaStat package within the SigmaPlot 14 (Systat Software, San Jose, CA, USA). Group results were reported as mean ± SD. All data were

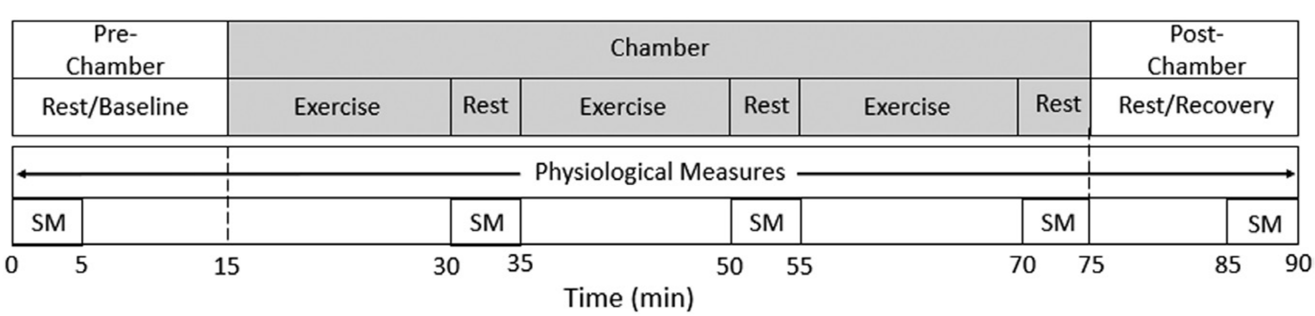

Fig. 1. Test protocol. Subjects sat in the laboratory for 15 min of rest/baseline (pre-chamber), then entered a heat chamber (T_{air}, 39 ± 1°C and 41 ± 4% RH) for 60 min. They performed three sets of 15 min of stepping exercise, followed by 5 min of rest. Subjects then exited the chamber (post-chamber) for 15 min of rest/recovery. Physiological variables were measured continuously, and subjective and cognitive measurements (SM) were made during rest periods.

subjected to a Shapiro-Wilk test for normality. Physiological measurements were continuously measured throughout each trial. Two-way analysis of variance (ANOVA) for repeated measures (for factors of time and cooling condition) was used to compare data from baseline, the end of each exercise and rest period, and the end of the recovery period. A one-way ANOVA was used to compare total sweat loss for the three conditions. Tukey's test was used for post hoc analysis of significant differences. Subjective and cognitive measures were analyzed with two-way nonparametric Friedman's ANOVA on Ranks Test if the normality test (Shapiro-Wilk) failed, while the two-way ANOVA was used if the normality test passed. When data were only available for two conditions (e.g., UB and WB at 70 min), a Wilcoxon Signed Rank Sum Test was used. A paired *t*-test compared mean heat removal between the two cooling conditions. Statistical significance was set at $P = 0.05$ for all tests.

RESULTS

USG was equal to or below 1.020 for all trials. All eight subjects completed all three exercise bouts in UB and WB conditions, but none were able to start the third exercise bout in the Control condition. Six managed to complete the second bout while two stopped 11 and 11.5 min into the second bout. Seven subjects terminated exercise because T_{co} reached 39°C, and the other one felt dizzy and could not continue. In the Control condition, all subjects rested for 5 min in the heat and then exited the chamber to rest another 15 min in the laboratory. Because no subjects were able to start a third exercise bout in the Control condition, two separate analyses were conducted. The first two-way ANOVA included all three conditions from 0–45 min and a second two-way ANOVA included just two conditions (e.g., UB and WB) from 50–90 min.

At the end of baseline, there were no inter-condition differences in T_{co} (**Fig. 2**). During the initial exercise bout, T_{co} rose similarly from baseline (~0.6°C) in all three conditions ($F = 102$, DF = 4, $P < 0.001$). Core warming was arrested during the first rest period. In the second exercise bout, at 45 min, the last point during which all subjects were still exercising, T_{co} increased significantly in Control ($P < 0.001$) and UB cooling ($P = 0.009$) but not WB cooling. At this point, T_{co} was 0.5°C higher in Control compared to both cooling conditions ($F = 49.8$, DF = 2, $P < 0.001$). Then, during the third exercise bout, T_{co} significantly increased in the UB condition (0.5°C, $F = 22.8$, DF = 4, $P < 0.001$) but not the WB condition. During the third rest period, T_{co} decreased 0.5°C in the UB ($P = 0.002$) and 0.3°C in the WB condition ($P = 0.05$). During the 15-min recovery period outside the chamber, T_{co} remained elevated during Control, decreased significantly in the UB condition ($P < 0.001$), and did not change in the WB condition. At the end of recovery, T_{co} was 1.7°C higher in Control than the two cooling conditions ($F = 49.8$, DF = 2, $P < 0.001$).

Baseline $T_{skin\ total}$ was similar for all three conditions (**Fig. 3**, top). During the first exercise bout, $T_{skin\ total}$ rose 2°C in the

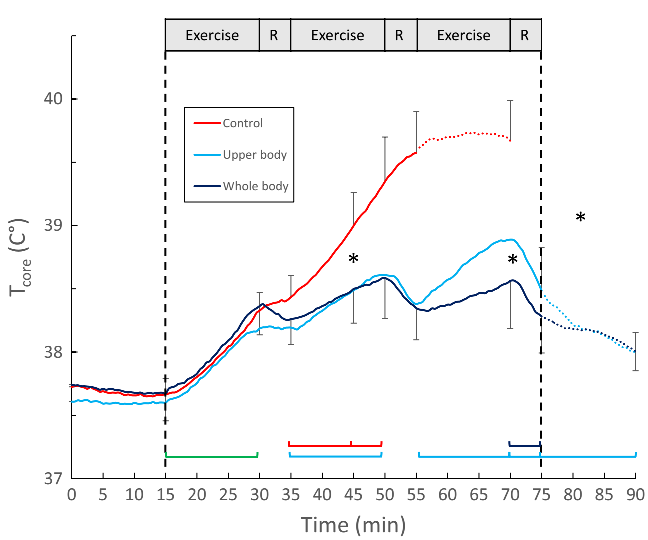

Fig. 2. Mean core temperature (T_{core}, °C) for three conditions ($N = 8$). Dotted lines show the recovery time outside the chamber (this occurred after the second exercise bout of Control). SD bars are only presented above or below lines for clarity. R = rest period; Exercise = stepping exercise at a rate of 20 steps per min; * = Significant difference between conditions ($P < 0.05$). Horizontal brackets indicate differences within each condition (red = Control; light blue = upper-body cooling; dark blue = whole-body cooling; green = all conditions) ($P < 0.05$).

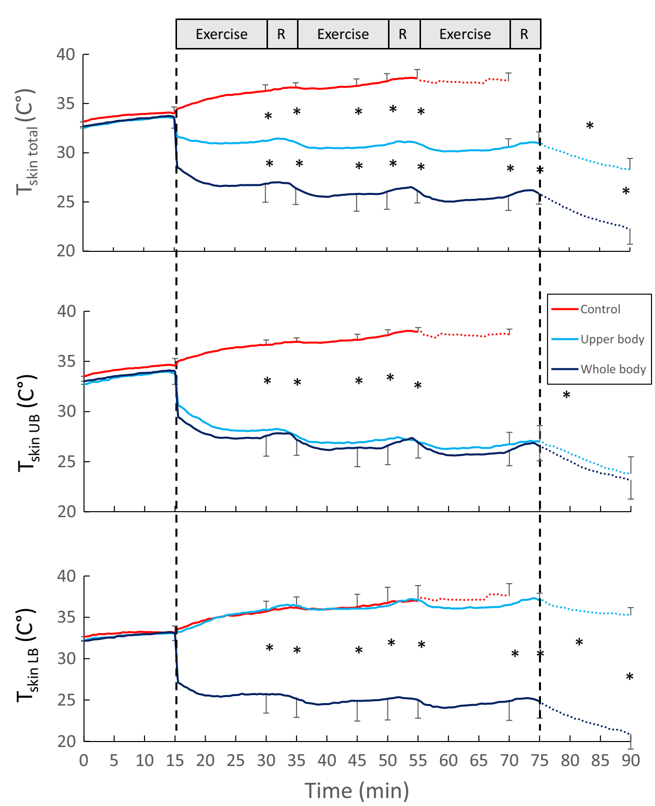

Fig. 3. Mean skin temperature (°C) for three conditions ($N = 8$). Top shows skin temperature of total body ($T_{skin\ total}$); middle shows skin temperature of upper body ($T_{skin\ UB}$); and bottom shows skin temperature of lower body ($T_{skin\ LB}$). Dotted lines show the recovery time outside the chamber. SD bars are only presented above or below lines for clarity. * = Significant difference between conditions ($P < 0.05$).

Control condition ($F = 98.4$, DF = 4, $P < 0.001$) and decreased 2°C with UB and 7°C with WB cooling ($P < 0.001$). Values were different between all three conditions ($F = 200.9$, DF = 2, $P < 0.001$). Values did not change throughout the remainder of exercise and rest periods for any condition. During the 15-min recovery period outside the chamber, values remained elevated during Control, but decreased during UB and WB cooling ($F = 66.7$, DF = 4, $P < 0.001$).

Baseline $T_{skin\ UB}$ was similar for all three conditions (Fig. 3, middle). In Control, temperature rose 2°C during the first exercise bout ($F = 102.8$, DF = 4, $P < 0.001$) and remained elevated throughout the remainder of exercise and rest periods. In the cooling conditions, temperature decreased 6°C during the first exercise bout ($P < 0.001$) and remained at these levels throughout the remainder of exercise and rest periods. At the end of the 15-min recovery periods outside the chamber, temperature decreased ~3°C in both cooling conditions ($F = 41.9$, DF = 4, $P < 0.001$) and these values were ~14°C below the Control condition ($F = 261.7$, DF = 2, $P < 0.001$).

Baseline $T_{skin\ LB}$ was similar for all three conditions (Fig. 3, bottom). In Control and UB cooling conditions, temperature rose 2.5–3.0°C during the first exercise bout ($F = 39.3$, DF = 4, $P < 0.001$) and remained elevated throughout the remainder of exercise and rest periods. During WB cooling, temperature decreased 7°C during the first exercise bout ($P < 0.001$) and remained at these levels throughout the remainder of exercise and rest periods. At the end of the 15-min recovery periods outside the chamber, temperature decreased 2°C with UB cooling and 4°C with WB cooling ($F = 75.4$, DF = 4, $P < 0.001$), with values being 2.5 and 16.5°C lower than Control, respectively ($F = 156.6$, DF = 2, $P < 0.001$).

There were no significant differences in HR between conditions during baseline (**Fig. 4**, top). Following the initial exercise bout, HR increased from baseline by 63 to 87 bpm across all three conditions ($F = 308.7$, DF = 4, $P < 0.001$) with values being higher in Control compared to both cooling conditions ($F = 12.1$, DF = 2, $P < 0.001$). After the initial rest period, HR significantly decreased by about 55 bpm across all three conditions but remained higher in the Control condition ($P < 0.001$).

During the second exercise bout, at 45 min, the last point during which all subjects were still exercising, HR significantly increased by 62 bpm in the Control condition ($F = 308.7$, DF = 4, $P < 0.001$) and by 64 bpm in the cooling conditions ($P < 0.001$). At this point, HR was higher in Control compared to both cooling conditions ($F = 12.1$, DF = 2, $P < 0.001$).

During the third exercise bout, in the cooling conditions, HR increased significantly ($F = 552.6$, DF = 4, $P < 0.001$), then during the third rest period, significantly decreased ($P < 0.001$) to values that were similar to the start of that bout. During the 15-min recovery period outside the chamber, HR decreased significantly in all conditions ($P \leq 0.002$). At the end of recovery, HR was about 40 bpm higher in Control than both cooling conditions ($F = 12.1$, DF = 2, $P < 0.001$).

Baseline heat production was similar for all three conditions (Fig. 4, bottom). In the first two exercise bouts, heat production increased significantly ($F = 283.9$, DF = 4,

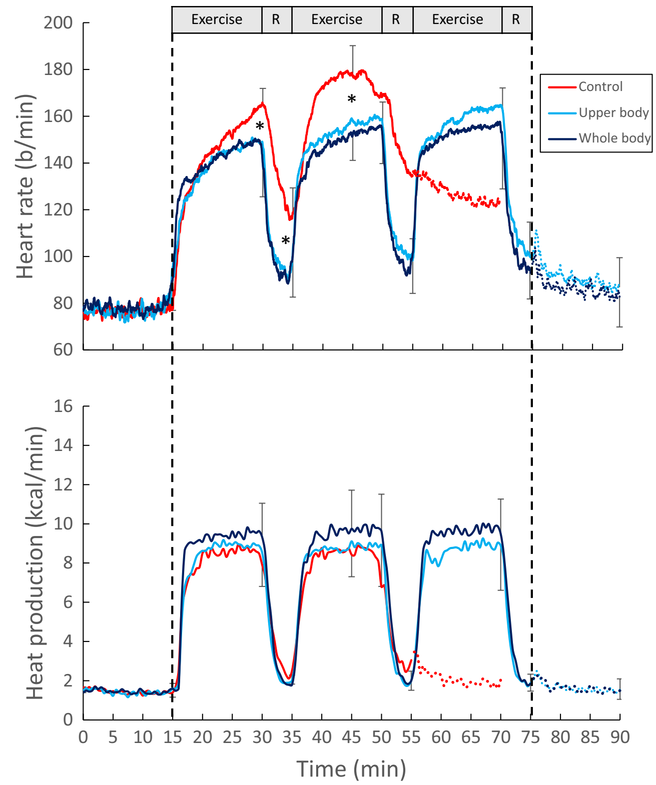

Fig. 4. Top shows mean heart rate (bpm) and bottom shows heat production ($kcal \cdot min^{-1}$) for three conditions (*N* = 8). Dotted line shows the recovery time outside the chamber. SD bars are only presented above or below lines for clarity. R = rest period; Exercise = stepping exercise at a rate of 20 steps per min; * = Significant difference between conditions ($P < 0.05$).

$P < 0.001$) and similarly in all three conditions and returned to near baseline values during rest periods. In the third exercise bout and rest period, heat production increased ($F = 165.1$, DF = 4, $P < 0.001$) and decreased similarly in the two cooling conditions.

Total sweat loss during Control (1175 ± 504 ml) was significantly greater than with WB cooling (512 ± 242 ml, $F = 13.6$, DF = 2, $P < 0.001$) but not compared to UB cooling (838 ± 169 ml; $P = 0.056$); values were not significantly different between WB and UB.

After the first exercise bout, RPE was similar for all three conditions (**Fig. 5**, top). At the end of the second exercise bout, RPE increased during both the Control condition ($F = 18.6$, DF = 1, $P < 0.001$) and the UB cooling condition ($P = 0.025$), with the Control values being higher than both cooling conditions ($F = 9.4$, DF = 2, $P \leq 0.005$). There was no difference in RPE between cooling conditions at the end of the third exercise bout.

Breathing discomfort was low (e.g., ~1.5, no discomfort to very mild discomfort) and similar in all conditions during baseline (Fig. 5, bottom). In the Control condition, breathing discomfort increased after the first exercise bout (value ~3, mild discomfort; $F = 25.2$; DF = 3; $P = 0.001$) and increased further at the end of the second exercise bout (value ~5, severe discomfort; $P < 0.001$).

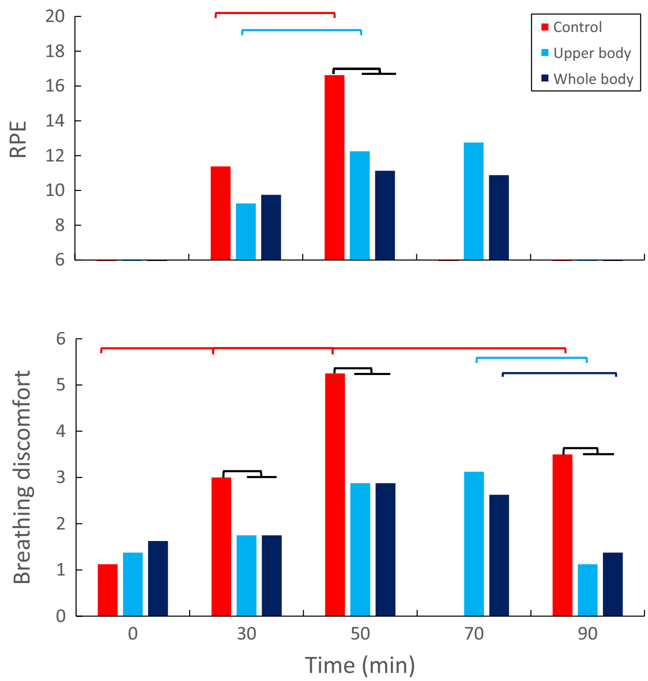

Fig. 5. Top shows mean perceived exertion (RPE) for three conditions, on a scale ranging from 6 (no exertion at all) to 20 (maximal exertion), during rest periods following each of three exercise bouts in the chamber (*N* = 8). Bottom shows mean breathing discomfort, on a scale of 1 (no discomfort) to 7 (intolerable discomfort), during pre-chamber rest, three rest periods in the chamber, and post-chamber recovery (*N* = 8). Colored horizontal brackets indicate differences within each condition (red = Control; light blue = upper-body cooling; dark blue = whole-body cooling) ($P < 0.05$). Black horizontal brackets indicate differences between conditions ($P < 0.05$).

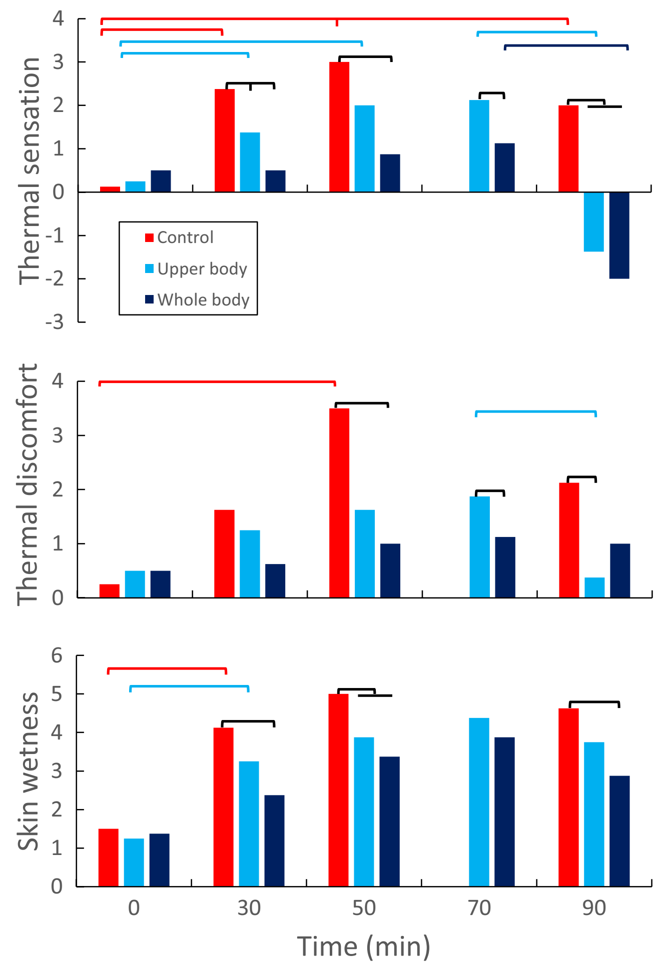

Fig. 6. Top shows median thermal sensation for three conditions on a scale ranging from −3 (cold) to +3 (hot) (*N* = 8). Middle shows mean thermal discomfort on a scale of 0 (comfortable) to 4 (extremely uncomfortable) (*N* = 8). Bottom shows mean skin wetness on a scale of 1 (dry) to 5 (soaked) (*N* = 8). Values are for three conditions during pre-chamber rest, three rest periods in the chamber, and post-chamber recovery. Colored horizontal brackets indicate differences within each condition (red = Control; light blue = upper-body cooling; dark blue = whole-body cooling) ($P < 0.05$). Black horizontal brackets indicate differences between conditions ($P < 0.05$).

Discomfort did not increase with either cooling condition and values were lower than Control after both the first ($F = 22.5$, DF = 2, $P = 0.027$) and second ($P < 0.001$) exercise bouts. Breathing discomfort did not increase in cooling conditions during the third exercise bout. At the end of the recovery period outside the chamber, breathing discomfort decreased in all three conditions (e.g., ∼2, very mild discomfort; $F = 25.2$; DF = 3; $P \leq 0.03$) and values were higher in the Control than both cooling conditions ($F = 22.5$, DF = 2, $P < 0.001$).

Thermal sensation was low (e.g., <1, neutral to slightly warm) and similar in all conditions during baseline (**Fig. 6**, top). In the Control and UB conditions, sensation increased after the first exercise bout ($F = 61.6$, DF = 3, $P < 0.001$ and $P = 0.008$, respectively) and remained elevated after the second exercise bout. Thermal sensation did not increase during WB cooling. Values were different between all three conditions at the end of the first and second exercise bouts ($F = 65.8$, DF = 2, $P \leq 0.012$). After the third exercise bout, sensation remained higher with UB cooling than with WB cooling ($F = 13.9$, DF = 1, $P = 0.02$). After 15 min of recovery outside the chamber, sensation decreased in all three conditions ($F = 61.6$, DF = 3, $P < 0.001$), with the Control condition values being higher than both cooling conditions ($F = 65.8$, DF = 2, $P < 0.001$).

Thermal discomfort was low (e.g., ∼0, comfortable) and similar in all conditions during baseline (Fig. 6, middle). Discomfort did not increase in either cooling condition in the first or second exercise bouts. However, in the Control condition, discomfort increased from baseline to the second exercise bout (e.g., 4, extremely uncomfortable; $P < 0.001$) and at this point was greater than the WB cooling ($P = 0.045$). Thermal discomfort did not increase in either cooling condition during the third exercise bout, and, at this point, the value was higher with UB cooling than with WB cooling ($F = 1.5$, DF = 1, $P = 0.042$). Then, after 15 min of recovery outside the chamber, discomfort with UB cooling decreased (e.g., ∼0, comfortable; $P < 0.001$) and, at this point, UB cooling had lower values compared to the Control condition ($P = 0.045$).

Skin wetness was low (e.g., ~1.5, dry to somewhat dry) and similar in all conditions during baseline (Fig. 6, bottom). During the first exercise bout, wetness increased similarly and significantly with Control and UB cooling ($F = 58.2$, DF = 3, $P < 0.001$) but not with WB cooling. During the second exercise bout, skin wetness did not increase in any condition, but at this point, Control values were greater than both cooling conditions ($F = 23.1$, DF = 2, $P \leq 0.0.13$). During the third exercise bout, values did not change in either cooling condition. At the end of the 15-min recovery period outside the chamber, skin wetness had not decreased in any condition. At this point, wetness was higher in Control than with WB cooling ($P < 0.001$) but not compared to UB cooling. Throughout the entire duration of the protocol, there were no significant differences in cognitive function across all three conditions ($P = 0.179$).

Four of eight subjects preferred the WB cooling conditions because their legs felt too warm during UB cooling. Of the other four subjects, three preferred the UB condition because they felt too cold during WB cooling, and one felt that the pants created too much restriction to motion during WB cooling.

During the 60-min period in the chamber, heat removal for each cooling condition was consistent except for a brief decrease during rest periods. Average heat removal with WB cooling (785 ± 68 W) was greater than with UB cooling (667 ± 95 W; t = 3.8; DF = 7; $P = 0.007$).

DISCUSSION

To our knowledge, this is the first study to compare the effectiveness of applying the same cooling power to either the UB or the WB in mitigating physiological and thermal stress, enhancing subjective responses, and improving cognitive function during exercise in a hot environment while wearing firefighter turnout gear.

Our hypothesis that cooling would be beneficial compared to Control was supported for all variables except cognition, which did not change throughout trials in any condition. Our secondary hypothesis that it would be better to apply the same amount of cooling power to the WB compared to the UB was supported for core and skin temperature, as well as thermal sensation and comfort. However, the benefits of the two cooling conditions over Control were similar for HR, RPE, breathing discomfort, and perception of skin wetness.

The benefits shown in this study of liquid cooling garments for attenuating the increase in T_{co} are consistent with previous studies during heavy exercise in the heat[3,8] and light-to-moderate exercise in the heat.[7,17] The lower T_{co} with WB cooling than with UB cooling in the third exercise bout is also consistent with results from Kim et al.,[8] who demonstrated lower T_{co} with a liquid cooling garment that covered a greater surface area. However, this garment (covering head, arms, torso, and thighs) also had a three times higher flow rate than the garment with lesser surface area (covering only head and forearms), while we used the same flow rate for both UB and WB conditions.

Our results demonstrating that cooling attenuates the increased HR during exercise in the heat are consistent with studies using a liquid cooling garment covering either the UB only[7] or WB.[3] Our results are also consistent with those of Kim et al.,[8] who demonstrated that cooling the UB or WB (with increased water flow rate) decreased HR compared to Control, although they were not different from each other. Our results showing no effect on cognitive function were also consistent with those of Aljaroudi et al.[3] This would indicate that the heat and exercise load were not enough in either study to invoke a cognitive decrease as measured by the mini-cog test.

A previous study on exercise in the heat demonstrated that a liquid cooling vest does not affect sweat rate during low-intensity exercise for 2.5 h.[7] However, with moderate-intensity exercise for 60 min, cooling resulted in a tendency for sweat to decrease (e.g., from 1090–800 ml), although this difference was not significant.[17] The present study with heavy exercise during 60 min of heat exposure demonstrated a significant decrease from 1175 ml of sweat during Control to 512 ml of sweat with WB cooling. Sweat loss during UB cooling (838 ml) was not quite significantly lower than Control ($P = 0.056$), however, it should be noted that sweat loss for Control was only for 2 exercise bouts (e.g., 40 min of exercise in the heat chamber). If subjects could have completed a third exercise bout during Control, total sweat loss would have been higher, and the difference would likely be significant. Perception of skin wetness throughout the trials was qualitatively similar to total sweat loss.

Previous studies support our subjective results, which demonstrated that cooling conditions improved thermal discomfort[17] and sensation while reducing RPE.[17] We are unaware of any similar studies addressing breathing discomfort. Ciuha et al.[7] did not see an improvement in RPE with cooling and only saw an improvement in thermal sensation for the first half of their 2.5-h protocol. This difference demonstrates the limitations of their vest, which used a 2-L reservoir filled with ice and a battery-powered pump. Although the pump functioned for the entire trials, the cooling power decreased during the second half of the trials as the ice had melted at this point, thus $T_{sk,}$ which had cooled by ~5°C in the first half, returned to baseline levels by the end of the trials. This contrasts with the present study in which an essentially infinite heat sink resulted in a continued decrease in T_{sk} through the trials. In toto, these results indicate that with light-to-moderate exercise, cooling does not affect physiological measures during shorter exercise protocols (e.g., 50–60 min)[18] but attenuates the increase in T_{co} and HR during longer exercise protocols (e.g., 2.5 h).[7] However, during heavy exercise in the heat, as in the study by Hashimoto et al.[17] and the present study, cooling improves all measured physiological variables and improves RPE and other subjective measures.

Even though heat production, and therefore oxygen consumption, was similar for all three conditions, HR was higher in the cooling conditions than Control. Since the work rate was similar for all conditions, blood flow to exercising muscles would also be similar. However, the warmer Control condition would cause an increase in thermoregulatory skin blood flow in order to dissipate heat. Cardiac output would thus be higher, which is consistent with the increased HR in this condition.

Compared to UB cooling, WB cooling decreased skin temperature by ~5°C and increased heat removal by ~18%; however, a difference in core temperature was not evident until the third exercise bout. Thermal sensation and comfort followed changes in skin temperature.

The level and type of exercise in this study did not accurately represent tasks performed during actual firefighting. A high work rate was used to increase the possibility to demonstrate differences between cooling conditions, and step exercise was easily reproducible. Greater external validity might be attained with more realistic firefighting activities.

It was not possible to determine total heat balance because heat flux was not measured. Finally, the phase of the menstrual cycle was not controlled for the two women and future studies should control for this.

These results demonstrate that either cooling strategy is beneficial compared to having no cooling at all. During heavy exercise, WB cooling provided an advantage for core and skin temperature, as well as thermal comfort and sensation. Importantly, the advantage in minimizing the increase in core temperature was only evident during the third exercise bout.

It is uncertain whether the same benefits would be observed during light-to-moderate exercise, which is likely more common during an actual firefighting scenario. At these reduced work rates, it is possible that the advantages of WB cooling may become apparent only after a longer duration of activity. Given these results and the increased cost and technical difficulty associated with also cooling the lower body, it would be preferable to develop a practical, portable system for UB cooling.

Future studies should include longer duration trials with lower exercise intensities to determine if WB cooling provides any advantage over UB cooling at these levels. If an advantage of WB cooling is demonstrated, a subsequent study could incorporate tasks that are more relevant to firefighting scenarios.

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