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ORIGINAL ARTICLE

# Efficacy of two intermittent cooling strategies during prolonged work-rest intervals in the heat with personal protective gear compared with a control condition

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## Abstract

**Introduction** Personal protective equipment (PPE) inhibits heat dissipation and elevates heat strain. Impaired cooling with PPE warrants investigation into practical strategies to improve work capacity and mitigate exertional heat illness.
**Purpose** Examine physiological and subjective effects of forearm immersion (FC), fan mist (MC), and passive cooling (PC) following three intermittent treadmill bouts while wearing PPE.
**Methods** Twelve males (27 ± 6 years; 57.6 ± 6.2 ml/kg/min; 78.3 ± 8.1 kg; 183.1 ± 7.2 cm) performed three 50-min (10 min of 40%, 70%, 40%, 60%, 50% v$VO_2$max) treadmill bouts in the heat (36 °C, 30% relative humidity). Thirty minutes of cooling followed each bout, using one of the three strategies per trial. Rectal temperature ($T_{core}$), skin temperature ($T_{sk}$), heart rate (HR), heart rate recovery (HRR), rating of perceived exertion (RPE), thirst, thermal sensation (TS), and fatigue were obtained. Repeated-measures analysis of variance (condition x time) detected differences between interventions.
**Results** Final $T_{core}$ was similar between trials ($P > .05$). Cooling rates were larger in FC and MC vs PC following bout one ($P < .05$). HRR was greatest in FC following bouts two ($P = .013$) and three ($P < .001$). $T_{sk}$, fluid consumption, and sweat rate were similar between all trials ($P > .05$). TS and fatigue during bout three were lower in MC, despite similar $T_{core}$ and HR.
**Conclusion** Utilizing FC and MC during intermittent work in the heat with PPE yields some thermoregulatory and cardiovascular benefit, but military health and safety personnel should explore new and novel strategies to mitigate risk and maximize performance under hot conditions while wearing PPE.

**Keywords** Thermoregulation · Body cooling · Heat stress · Military · Exercise

### Abbreviations

| | |
|---|---|
| ACU | Army combat uniform |
| FC | Forearm cooling |
| HR | Heart rate |
| HRR | Heart rate recovery |
| HRV | Heart rate variability |
| MC | Fan-mist cooling |
| NBC | Nuclear, biological, or chemical |
| NBM | Nude body mass |
| PC | Passive cooling |
| PPE | Personal protective gear |
| ANOVA | Analysis of variance |
| RPE | Rate of perceived exertion |
| SD | Standard deviation |
| $T_{core}$ | Rectal temperature |
| $T_{sk}$ | Mean skin temperature |
| TS | Thermal sensation |
| USG | Urine-specific gravity |
| $VO_2$max | Maximal volume of oxygen uptake |
| $VO_2$peak | Peak value of oxygen uptake |

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## Introduction

Prolonged exertion in hot environmental conditions creates a challenging scenario where cardiac output must satisfy the energetic demands of skeletal muscle, perfuse the skin to facilitate heat loss, and maintain blood pressure (Rowell 1974). Strategies to increase heat loss and mitigate unfavorable core temperature ($T_{core}$) elevations and cardiovascular impairments during physical work in the heat, such as proper hydration (Gonzalez-Alonso et al. 1998; Sawka et al. 1985; Watanabe et al. 2020), skin cooling (Ranalli et al. 2010; Giesbrecht et al. 2007; Barr et al. 2011), and internal cooling (i.e., ice slurry ingestion) (Nakamura et al. 2020) have been shown effective and practical. Elevated skin temperature ($T_{sk}$) alone is detrimental to cardiovascular performance (Sawka et al. 2012), providing the impetus for adequate skin cooling strategies in a variety of settings. Military personnel and occupational laborers are often required to wear personal protective gear in hot environments which impedes evaporative heat loss by limiting body surface area exposure (Nindl et al. 2013) and exacerbates the rise in $T_{sk}$, making these populations ideal candidates to adopt skin cooling. Full-body cold-water immersion is the gold standard for rapidly reducing $T_{core}$ during exertional heat stroke (Casa et al. 2007); however, it is not practical as a preventative measure in the field, such as during military operation/training, where Army combat uniforms (ACUs) are worn. Intermittent cooling modalities (i.e., hand/forearm immersion) administered throughout prolonged activity in controlled laboratory studies have been shown to be effective in lowering $T_{core}$ and reducing cardiovascular strain during heat stress (Cleary et al. 2014; Chou et al. 2019; Barr et al. 2011; Khomenok et al. 2008). In the field, DeGroot et al. have shown that arm immersion cooling decreases exertional heat illness severity and medical costs in a large population of Army Ranger trainees compared to control (DeGroot et al. 2015). However, the effectiveness of these modalities without full removal of personal protective gear (i.e., rolling sleeves up) as a preventative strategy is less clear.

Selkirk and colleagues (Selkirk et al. 2004) reported that firefighters exposed to 50 min of exertional work in the heat in full gear showed greater rates of $T_{core}$ cooling and reductions in heart rate with forearm immersion (~ 17 °C) compared to fan mist (MC) and passive cooling (PC) (30-min cooling). Both forearm cooling (FC) and fan-mist groups were able to exercise longer and should have improved work tolerance than controls before reaching a core temperature threshold of 39.5 °C, with forearm cooling demonstrating the greatest response (Selkirk et al. 2004). In contrast, Amorim showed that work tolerance was not enhanced during rucking in the heat (42 °C) with a combat uniform interspersed with palm cooling where only the ruck sack was removed during rest (Amorim et al. 2010). This suggests that either the lower degree of hyperthermia (38.5 °C), hotter ambient conditions, smaller body surface area cooled, or lack of gear removal could have contributed to the contrasting results of Selkirk (Amorim et al. 2010; Selkirk et al. 2004). Similar work utilized simulated firefighter drills (Yeargin et al. 2016) and treadmill walking (Barr et al. 2011) with full protective gear and applied intermittent forearm cooling at 5 °C (Yeargin et al. 2016) and ~ 19 °C (Barr et al. 2011), with both lowering gastrointestinal temperature but not heart rate (HR) (Yeargin et al. 2016; Barr et al. 2011). Thermal sensation (TS) differed in these two studies, being equivalent (Yeargin et al. 2016) and lower (Barr et al. 2011) than controls. Barr et al. also investigated $T_{sk}$ responses; FC decreased mean skin temperature ~ 1 °C compared to PC (Barr et al. 2011). In army trainees, MC was shown to reduce HR and TS during 20 min of recovery, whereas blood pressure was unaltered and $T_{core}$ slightly increased (Sefton et al. 2016). However, aside from Amorim et al. (Amorim et al. 2010), it should be noted that the subjects in the aforementioned studies fully or partially removed their gear during the cooling trials (Sefton et al. 2016; Yeargin et al. 2016; Selkirk et al. 2004; Barr et al. 2011). As gear removal itself would also lessen the thermal load by permitting more evaporative loss (decreased $T_{sk}$), particularly with MC, whether comparable benefits can be achieved in situations without gear removal is not entirely clear and would be of practical use in the field when gear cannot be removed. Khomenok et al. showed that 10 °C hand immersion between two 50-min exercise bouts while subjects wore nuclear, biological, or chemical (NBC) suits was able to decrease $T_{core,}$ $T_{sk,}$ and HR during the second bout (Khomenok et al. 2008). Additionally, a novel approach has recently utilized a custom temperature controlled (~ 16 °C) circulating water system to cool the hands *during* activity to maximize convective heat losses (Grahn et al. 2018), which mitigated esophageal temperature elevations during low intensity work in the heat with encapsulating outerwear. The same group also demonstrated effectiveness in heavily insulated individuals with the addition of sub-atmospheric pressure gradients to create a "heat sink" (Grahn et al. 2009), showing $T_{core}$ differences of > 1 °C vs controls 1 h post-exercise. However, this device is not practical in a military or sports setting to wear throughout activity.

While most studies have been performed at low-to-moderate work rates to simulate occupational conditions, it is important to determine whether similar benefits would be observed with high intensity, longer duration exercise as would be expected in a military mission/training.

Further, there are limited data on heart rate recovery (HRR) responses to various cooling modalities (i.e., FC, MC, or PC), and most studies report HR at 5 to 10 min intervals, which may miss the early recovery phase reflective of cardiac vagal reactivation (Imai et al. 1994; Coote 2010). Impaired vagal reactivation in early post-exercise recovery may precipitate decreased exercise capacity (Macartney et al. 2020). Whether this can be offset by intermittent cooling during heat stress where sympathetic outflow is elevated (Rowell 1990) is a relevant research question as faster HRR will speed cardiovascular recovery in preparation for the subsequent bout. Al Haddad et al. showed cold-water face immersion accelerated HRR at 60 s and improved post-exercise heart rate variability (HRV) (Al Haddad et al. 2010), while Buchheit et al. demonstrated cold-water immersion up to the sternum improved post-exercise HRV but not the HRR time constant after repeated sprints (Buchheit et al. 2009). Forearm cooling has been shown to acutely decrease (Selkirk et al. 2004) or have no effect (Barr et al. 2011; Yeargin et al. 2016) on HR, but lower overall physiological strain (Yeargin et al. 2016). Therefore, the primary purpose of this study was to investigate the effects of two different cooling modalities (FC, MC) compared to control (PC) during prolonged work-rest intervals in the heat with personal protective gear (ACU) on core temperature, heart rate, and heart rate recovery. In addition, we also recorded ad libitum fluid consumption, sweat rate, and subjective measures [thirst, TS, fatigue, and rate of perceived exertion (RPE)]. We hypothesized that FC would elicit greater cooling rates and HRR along with a lower end-exercise $T_{core}$ compared to MC and PC, and that FC and MC would be associated with lower thermal sensation, fatigue, and rating of perceived exertion.

## Methods

Physically active males between the ages of 18–35 [27 ± 6 years, height: 183.12 ± 6.92 cm; nude body mass (NBM): 78.29 ± 7.72 kg] with a maximal oxygen uptake ($VO_2$max) of ≥ 45 ml/kg/min (57.5 ± 6.31 ml/kg/min, 4.56 ± 0.61 L/min) were recruited for this study. Exclusion criteria included chronic conditions affecting thermoregulation, current illness/fever, cardiovascular, metabolic, or respiratory disease, musculoskeletal injury limiting physical activity, and current medication usage that influences thermoregulation (amphetamines, anticholinergics, diuretics, etc.). Medical history forms were reviewed by a medical doctor prior to clearance to participate.

Baseline testing began with measurement of urine-specific gravity (USG) via a handheld refractometer (Model TS400; Reichert Inc., Depew, NY) and urine color to confirm euhydration, along with NBM (Defender® 7000XtremeW; OHASUS Corp., Parsippany, NJ, USA). $VO_2$max was assessed on a motorized treadmill (COSMED T150DE, Rome, Italy) with continuous measure of gas exchange (TrueOne 2400; Parvo Medics, Salt Lake City, UT, USA). System calibration prior to each session was performed per the manufacturer's instructions using a standard room air gas mixture of $O_2$ and $CO_2$ and a 3L syringe over various flow rates. Participants were permitted to warm up for 5 min at a self-selected pace followed by fitting of a Hans Rudolph face mask. The treadmill was set at a fixed 2% grade and the velocity was increased in 0.5–1.0 mph increments every 3 min until volitional exhaustion.

Participants completed three exercise trials consisting of either MC, FC, or PC in a randomized crossover design (Fig. 1) using simple randomization. Prior to each trial, participants were asked to abstain from alcohol for 24 and caffeine for 12 h, respectively. NBM and hydration status (USG, urine color) were measured before and after each trial. A rectal probe (YSI, Zoll Medical Corporation, Chelmsford, MA, USA) was inserted by each participant approximately 10–15 cm past the anal sphincter to record $T_{core}$. $T_{core}$ (MP160, BIOPAC Systems Inc., Goleta, CA, USA), $T_{sk}$ (SKT100C, BIOPAC Systems Inc., Goleta, CA, USA), and HR (H7, Polar Electro Oy, Kempele, Finland) were monitored continuously throughout each trial. $T_{sk}$ was averaged over four sites: (0.3*chest) ± (0.3*shoulder) ± (0.2*thigh) ± (0.2*calf). Participants then donned an ACU (~ 1.8 kg), which was worn for all exercise and rest blocks, and entered the environmental chamber (Cantrol Environmental, Markham, ON, CA).

Each trial began with a 30 min equilibration in which the environmental chamber was set to 36 °C and 30% relative humidity. The exercise protocol consisted of three 50 min bouts of treadmill walking/running at varying percentages of velocity attained at $VO_2$max ($vVO_2$). Specifically, each 50 min bout consisted of 10 min at 40, 70, 40, 60, and 50% of $vVO_2$. Each bout was interspersed with 30 min of cooling (PC, MC, or FC). PC consisted of seated rest following each exercise bout with no external cooling modality. FC was achieved in a seated position by participants rolling up the sleeves of the ACU and immersing the forearms into 20 °C water (First Line Technology, ICE System, Chantilly, VA, USA) for 30 min, while a member of the research team continuously stirred the water. Finally, during MC, participants were seated 2.1 m from a fan providing convective airflow and water mist at 2 m/s.

All data are reported as mean ± standard deviation (SD) unless otherwise stated. Two-way (condition x time, condition x bout) repeated-measures analysis of variance (ANOVA) was used to detect differences in $T_{core}$, HR variables (exercising & resting HR, HRR), $T_{sk}$, and hydration between interventions, with Bonferroni post hoc for adjustment of multiple comparisons. If an interaction was observed, pairwise comparisons were examined.

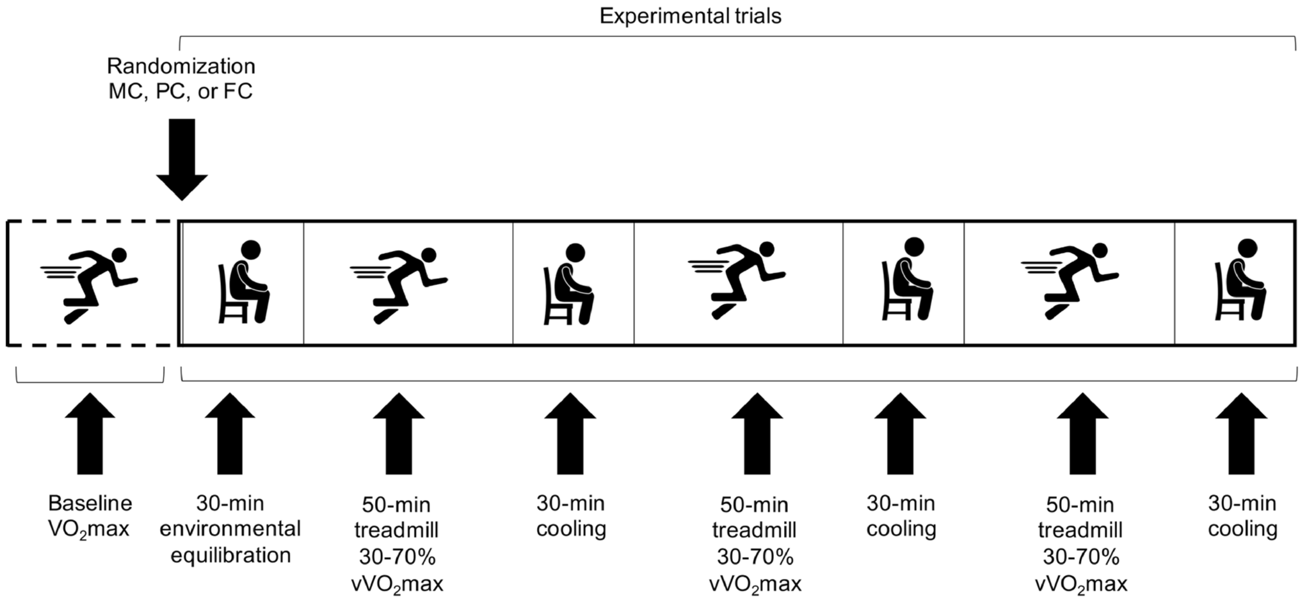


**Fig. 1** Schematic of the study design. MC: fan-mist cooling, PC: passive cooling, FC: forearm cooling

Greenhouse–Geisser correction was used if sphericity was violated. Subjective data (thirst, TS, and RPE) were analyzed with Friedman's test and Wilcoxon Signed-Rank test for post hoc analysis. Alpha level was set at 0.05.

## Results

### Core temperature

Figure 2 shows $T_{core}$ responses over the entire trial duration. The rectal probe of two subjects became displaced during two of the trials which led to missing data points, so

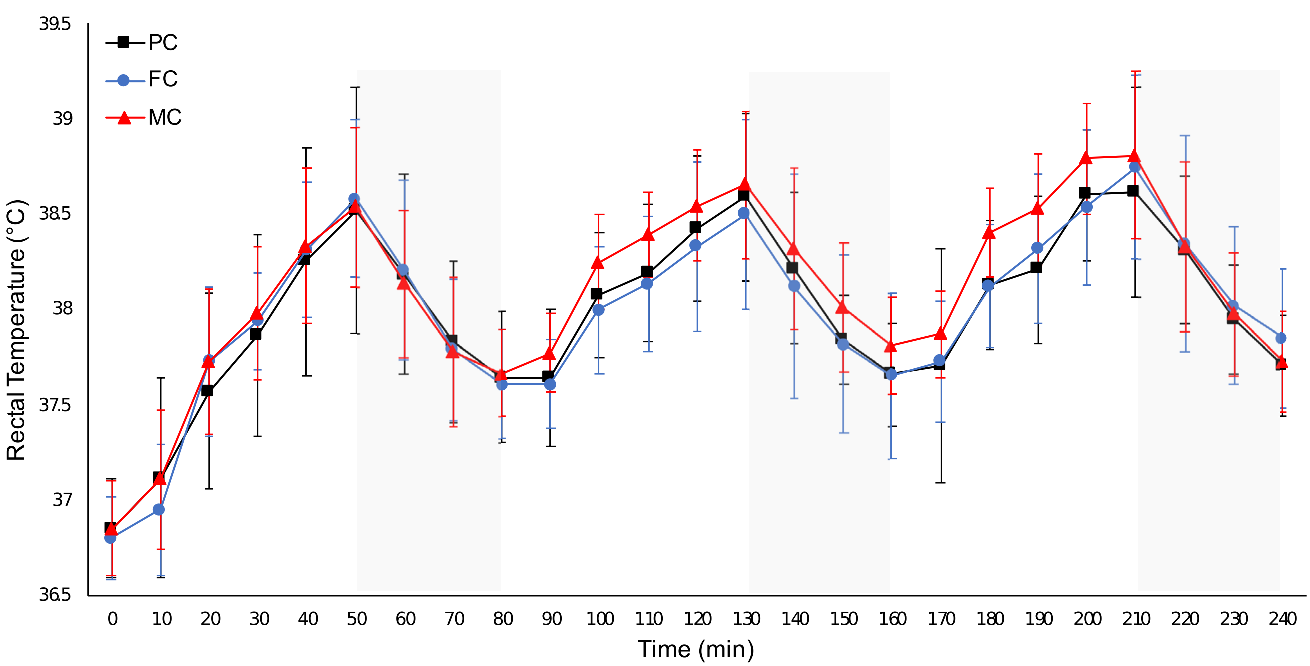


**Fig. 2** Rectal temperature responses over time. Shaded areas represent 30-min cooling bouts. Mean ± SD

$T_{core}$ data were done on a sample of $n = 10$. $T_{core}$ at baseline and throughout the thermal equilibration period were similar ($P > 0.05$). Immediately following bouts one, two, and three, $T_{core}$ reached 38.51 ± 0.40 °C, 38.67 ± 0.34 °C, and 38.65 ± 0.53 °C (PC); 38.63 ± 0.40 °C, 38.52 ± 0.51 °C, and 38.79 ± 0.47 °C (FC); and 38.61 ± 0.36 °C, 38.59 ± 0.55 °C, and 38.88 ± 0.38 °C (MC), respectively. There were no statistically significant differences after any exercise bout in post-exercise $T_{core}$ between groups. The change in $T_{core}$ during rest blocks one, two, and three was −0.63 ± 0.60°C, −0.78 ± 0.80°C, and −0.99 ± 0.35°C (PC); −0.97 ± 0.33°C, −0.91 ± 0.32°C, and −0.92 ± 0.28°C (FC); −0.72 ± 0.64°C, −0.71 ± 0.61°C, and −1.15 ± 0.20°C (MC), respectively, with no statistical difference between groups. Table 1 shows the cooling rates at 10, 20, and 30 min during rest blocks one, two, and three for each group, where we found cooling rates were greater in FC and MC compared to PC in bout one only.

## Heart rate and heart rate recovery

Figure 3 shows HR responses over the trial duration. There were no statistical differences in mean exercising HR or mean resting HR during individual exercise/rest blocks between trials (Table 2). Within conditions, exercise HR was significantly higher in bout two ($P = 0.003$) and bout three ($P = 0.014$) compared to bout one in PC. Exercise HR was significantly higher in bout three ($P = 0.002$) compared to bout one in FC as well as in MC ($P = 0.006$), whereas in bout three, HR was also greater than bout two ($P = 0.038$) in MC. Resting HR between bouts also tended to increase throughout the trial. In PC, bout three resting HR was higher than bout one ($P = 0.017$) as well as in FC ($P = 0.046$), whereas

**Table 1** Cooling rates in ℃/min for 10, 20, and 30 min post-exercise bouts one, two, and three

| | Passive cooling | | | Forearm cooling | | | Fan-mist cooling | | |
|---|---|---|---|---|---|---|---|---|---|
| Time (min) | 10 | 20 | 30 | 10 | 20 | 30 | 10 | 20 | 30 |
| Bout 1 | 0.012 ± 0.016 | 0.024 ± 0.015 | 0.022 ± 0.013 | 0.036 ± 0.027* | 0.039 ± 0.014* | 0.032 ± 0.011* | 0.039 ± 0.025[a] | 0.036 ± 0.015[a] | 0.029 ± 0.012 |
| Bout 2 | 0.041 ± 0.033 | 0.042 ± 0.014 | 0.034 ± 0.011 | 0.042 ± 0.025 | 0.036 ± 0.013 | 0.029 ± 0.011 | 0.038 ± 0.020 | 0.034 ± 0.008 | 0.030 ± 0.006 |
| Bout 3 | 0.018 ± 0.046 | 0.029 ± 0.020 | 0.028 ± 0.014 | 0.043 ± 0.029 | 0.037 ± 0.011 | 0.031 ± 0.009 | 0.047 ± 0.018 | 0.044 ± 0.012 | 0.038 ± 0.006 |

*Data presented as mean ± SD

*Significant difference between FC and PC (all timepoints $P < .001$). [a]Significant difference between MC and PC (10 min: $P = .006$; 20 min: $P = .013$)

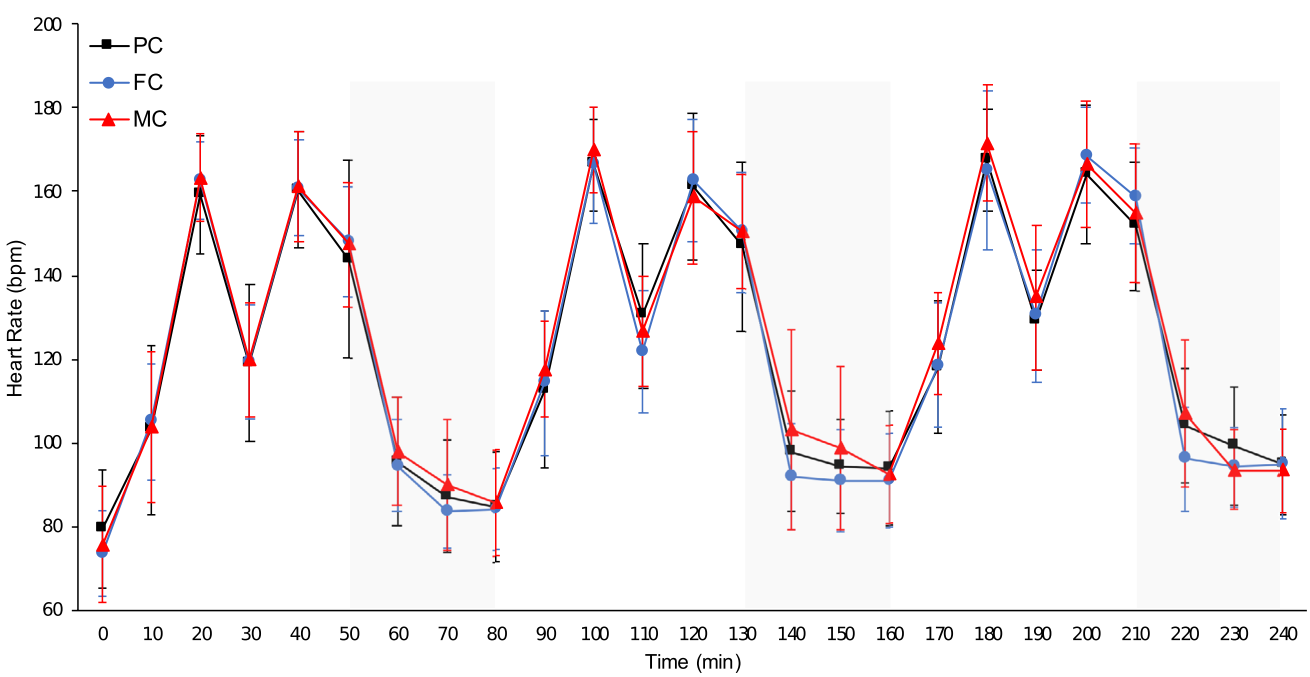


**Fig. 3** Heart rate responses over time. Shaded areas represent 30-min cooling bouts. Mean ± SD

**Table 2** Mean exercise and resting heart rate (bpm) for individual work and recovery bouts

| | Passive cooling | Forearm cooling | Fan-mist cooling |
|---|---|---|---|
| Bout 1 | | | |
| Exercise | $136 \pm 18$*[a] | $139 \pm 11$[a] | $139 \pm 12$[a] |
| Rest | $90 \pm 13$[a] | $87 \pm 7$[a] | $91 \pm 13$ |
| Bout 2 | | | |
| Exercise | $144 \pm 14$ | $144 \pm 13$ | $145 \pm 9$[b] |
| Rest | $95 \pm 12$ | $91 \pm 12$ | $98 \pm 14$ |
| Bout 3 | | | |
| Exercise | $146 \pm 11$ | $148 \pm 11$ | $150 \pm 12$ |
| Rest | $100 \pm 13$ | $95 \pm 11$ | $98 \pm 9$ |

Data presented as mean ± SD

*Significant within condition difference between bouts 1 and 2 (PC, exercise: $P = .003$). [a]Significant within condition difference between bouts 1 and 3 (PC, resting: $P = .017$; FC, exercise: $P = .002$; FC, resting: $P = .046$; MC, exercise: $P = .006$). [b]Significant within condition difference between bouts 2 and 3 (MC, exercise: $P = .038$)

in MC, there were no differences in resting HR between rest bouts. Mean HR during all rest blocks was always lower in FC compared to the other conditions (3–7 bpm) but failed to reach statistical significance.

HRR data were collected at 30 s ($HRR_{30}$), 1 min ($HRR_{60}$), 2 min ($HRR_{120}$) (Macartney et al. 2020), and 10 min post-exercise. We found no statistically significant differences in any of the HRR time points between groups after any of the exercise bouts ($P > 0.05$). However, during blocks two and three, HR exhibited a larger decrease ($P = 0.024$, $P < 0.001$) after 10 min in FC ($-59.0 \pm 12.1$, $-62 \pm 8.4$ bpm) compared to PC ($-49.9 \pm 11.9$, $-48.2 \pm 9.1$ bpm), with no differences ($P = 0.547$, $P = 0.079$) compared to MC ($-47.42 \pm 29.2$, $-47.8 \pm 22.8$ bpm), respectively. After 30 min, in block three only, HR decreased significantly more ($-64.1 \pm 12.9$ bpm) in FC, compared to $-58.1 \pm 11.7$ bpm in PC ($P = 0.021$), with no differences compared to MC ($-61.5 \pm 18.1$ bpm). HRR expressed as a percentage of the end-exercise HR is presented in Fig. 4.

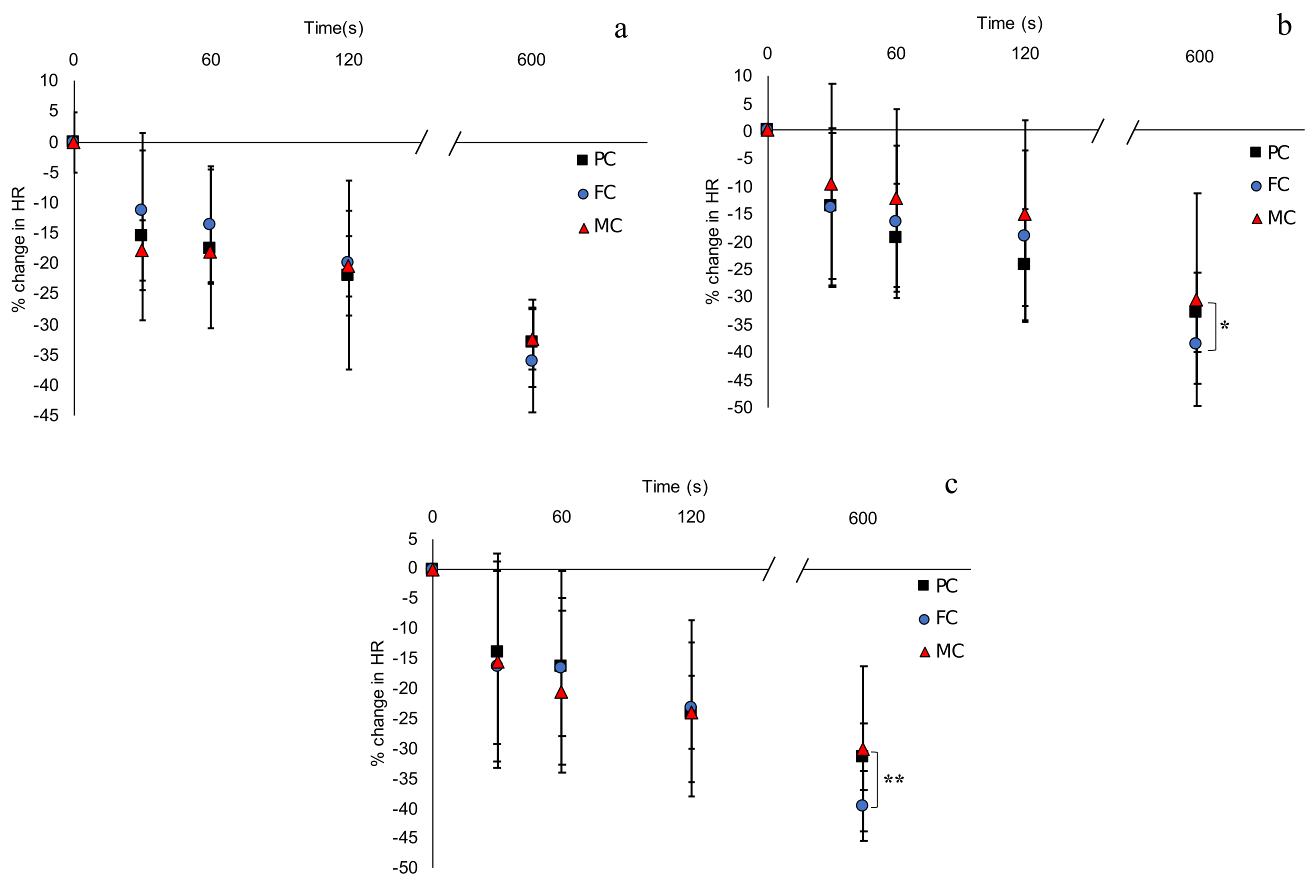


**Fig. 4** Percent decrease in heart rate following end-exercise value (50-min) in each bout. **a**: bout 1; **b**: bout 2; **c**: bout 3; *$P = .011$;**$P < .001$. Mean ± SD

### Skin temperature

$T_{sk}$ throughout the equilibration period did not differ between trials (34.28 ± 0.28 °C; $P > 0.05$). We observed similar responses between groups at the end of bout one (MC: 34.55 ± 0.86 °C, FC: 34.17 ± 0.95 °C, PC: 34.05 ± 0.63 °C), bout two (MC: 34.21 ± 0.62 °C, FC: 33.85 ± 1.17 °C, PC: 34.08 ± 0.56 °C), and bout three (MC: 33.7 ± 1.03 °C, FC: 34.25 ± 1.15 °C, PC: 34.23 ± 1.09 °C) (all $P > 0.05$).

### Hydration

Pre-trial (1.009 ± 0.002) and post-trial USG (1.017 ± 0.002) were similar among trials ($P > 0.05$). Pre-trial nude body mass was 80.16 ± 7.24 kg for PC, 79.99 ± 7.15 kg for FC, and 79.89 ± 7.59 kg for MC ($P > 0.05$). Body mass loss (PC: 2.89 ± 1.4%, FC: 2.75 ± 0.9%, MC: 2.80 ± 1.4%), total fluids consumed (PC: 2245.9 ± 867.1 ml, FC: 2239.8 ± 1189.8 ml, MC: 2432.8 ± 1069.8 ml), and sweat rate (PC: 1.15 ± 0.23 L/hr, FC: 1.07 ± 0.17 L/hr, MC: 1.1 ± 0.24 L/hr) were also similar between trials ($P > 0.05$).

### Subjective measures

TS was not different between groups during exercise block two ($P = 0.439$), but was significantly less ($P = 0.002$) during block three in MC (4.46 ± 0.53) compared to PC (5.75 ± 0.75) and FC (5.63 ± 0.83). During block three, subjective fatigue was significantly lower ($P = 0.041$) in MC (4.49 ± 1.86) compared to FC (5.63 ± 0.83), and tended to be lower compared to PC (5.76 ± 0.75; $P = 0.052$). There were no statistical differences in thirst or rating of perceived exertion (RPE) during any exercise blocks between groups.

## Discussion

In this study, we compared the effect of two intermittent cooling interventions (forearm immersion and fan mist) to control (passive cooling) on thermoregulation, exercising heart rate and heart rate recovery during three, 50 min bouts of treadmill running in the heat with military gear (ACU). Overall, the primary findings from our study revealed: 1 no difference in end-exercise $T_{core}$ between conditions, 2 greater cooling rates in FC (10, 20, & 30 min) and MC (10 & 20 min) vs PC after bout one, 3 ~ 20 °C forearm immersion resulted in a significantly lower HR observed at 10 min of rest in bouts two and three, and 4 subjective TS and fatigue were lower during bout three in MC compared to FC and PC.

Post-exercise $T_{core}$ and the rate of rise during each 50 min bout did not differ between groups. Contrary to our hypothesis, FC did not consistently show faster cooling rates compared to PC and MC, aside from bout one (FC ~ MC > PC). Cooling the hands specifically has been proposed to provide more effective cooling via arteriovenous anastomoses in glabrous skin. Through bypass of capillary transit time and rapidly redirecting blood to the venous system (Walloe 2016), along with a greater surface area/volume ratio compared to other body regions, heat loss is suggested to be augmented (Payne et al. 2018). While a recent meta-analysis found insufficient evidence for rapid cooling using forearm/limb immersion (Zhang et al. 2015), some studies have reported a benefit (Selkirk et al. 2004; Barr et al. 2011). Fan-mist cooling may contribute to lowering skin temperature and widening the core-skin gradient to facilitate heat loss. While pre-cooling studies with fan mist have reported benefit in mitigating $T_{core}$ elevations (Tokizawa et al. 2014; Mitchell et al. 2003), the effect on cooling hyperthermic athletes has been less robust (DeMartini et al. 2011). However, an interesting finding was that while the MC group had the highest post-exercise $T_{core}$, they felt significantly cooler during bout three compared to the PC and MC, possibly due to a 0.53–0.55 °C lower $T_{sk}$. Thus, cooling with fan mist may have a particular benefit in thermal sensation, but may disconnect behavioral and physiological thermoregulation (DeGroot et al. 2015; Barr et al. 2011). This could present a potential safety concern if an unchanging (or rising) $T_{core}$ is accompanied by a lower perception of thermal sensation. As such, an individual could overestimate their ability to perform work in the heat and increase work rate or effort as a result. Since work rate is the strongest driver of change in core temperature, a false perception of cooling effectiveness may accelerate the risk or onset of heat-related illness (Casa et al. 2015).

The most comparable study in the literature is that of Selkirk et al., but we used higher work rates, ad libitum fluid consumption vs replacing ~ 85% fluid losses, and military instead of firefighter gear which stayed on during cooling (Selkirk et al. 2004). Ambient temperature was within 1 °C, but relative humidity was 20% lower in the present study. There are some key differences between Selkirk's findings and ours worth noting: 1) we saw no significant differences in mean HR during rest blocks (Table 2), 2) FC and MC did not result in significantly lower overall rate of $T_{core}$ rise, 3) sweat rates were not different between groups, and 4) $T_{sk}$ did not differ throughout. Importantly, subject characteristics such as age (~ 26 vs ~ 41 years) and fitness level (~ 57 ml/kg/min $VO_2$max vs ~ 45 ml/kg/min $VO_2$peak) were notably different. Ageing is typically associated with decreased thermoregulation but is likely to be secondary to decreased aerobic fitness and other confounding factors rather than ageing per se (Baker 2019; Kenney and Munce 2003). As such, the 23% greater aerobic capacity in our sample may have influenced the smaller rise in $T_{core}$ compared to Selkirk (Selkirk et al. 2004): (final–initial) (PC: 1.70 vs 2.33 °C; FC: 1.86 vs 2.23 °C; MC: 1.97 vs 2.35 °C), but the type of gear worn should also be considered as the resistance to thermoregulation may differ in firefighter turnout gear versus the ACU. In addition, mean $T_{sk}$ was also lower in the present study. Thus, based on the law of initial values, Selkirk's sample may have been more likely to achieve a greater cooling response with the additional effect of gear removal during cooling which will also facilitate greater heat loss.

The lack of a robust response to forearm cooling could also possibly be due to water temperature (~20 °C), since water temperature < 5–10 °C elicits fastest cooling rates (Zhang et al. 2015). Giesbrecht et al. (Giesbrecht et al. 2007) demonstrated that heat loss and decrease in aural temperature was greater with intermittent forearm cooling at 10 °C vs 20 °C. Unfortunately, this precludes a comparison with our data, since aural thermometry is not valid and should not be used in place of rectal temperature for exertional heat stress (Morrissey et al. 2021). However, in firefighters (~40 yr, ~50 ml/kg/min) performing two, 20-min treadmill bouts interspersed with 15 min of cooling, Barr et al. (Barr et al. 2011) reported 0.3 °C lower $T_{core}$ following forearm immersion (~19 °C) vs controls, which led to end-exercise $T_{core}$ following the second 20-min bout to be ~0.4 °C lower. More recently, Nakamura et al. (2020) forearm cooling in 10 °C ice water for 15 min after rectal temperature reached 38.5 °C was shown to result in a ~20 bpm lower HR and ~0.3 °C lower $T_{core}$ compared to control. These contrasting findings can likely be explained by greater body surface area exposure during exercise and/or cooling in previous work, whereas the ACU in the present study only exposes the head and hands and remained on for the duration of the trials. Interestingly, combination of ice slurry ingestion and forearm cooling in the aforementioned study resulted in the fastest cooling rates (significantly lower within 6 min), but was equal to forearm cooling alone by 15 min (Nakamura et al. 2020). Water temperature of 20 °C in our study was chosen as it was expected to be more tolerable for 30 min than ~10 °C, but colder temperatures may be warranted for an optimal response in the presence of protective gear.

Overall, during prolonged physical work in the heat with personal protective gear in young aerobically fit males, forearm immersion (20 °C) and fan mist cooling tend to be more effective than passive cooling in decreasing $T_{core}$ following an initial exercise bout, but this effect waned after subsequent bouts. Although it is important to note that while not reaching statistical significance in bouts two and three, cooling rates at 10 min in bout three were ~0.025 °C/min greater in FC and ~0.029 °C/min greater in MC compared to PC, which could be clinically relevant for mitigating hyperthermia in the field over the course of prolonged periods of physical work. It is not clear why there was not a similar pattern in bout two. As pointed out by Zhang et al. (Zhang et al. 2015), immersion cooling is most effective with $T_{core} \geq 38.6$ °C, water temperature ≤ 10 °C, and immersion duration ≤ 10 min. We expected to observe higher $T_{core}$ based on our protocol, but since maximal levels in all trials were between 38.6 and 38.8 °C, on average, it is possible that the participants did not achieve a requisite level of hyperthermia to benefit from forearm cooling. Indeed, the observed cooling rates were below that observed in a meta-analysis of 29 studies (~0.05 °C/min) (Zhang et al. 2015). A potential confounding effect of the MC trial was that the fan mist may have slightly altered the clothing of the participants (increased wetness) but whether this effect was large enough to alter their heat balance or thermal sensation in subsequent bouts is unclear. Forearm cooling did appear to have a favorable effect on decreasing HR during recovery. Depending on the time scale, the greater decrease in HR post-exercise is reflecting either parasympathetic reactivation (< 1 min) or sympathetic withdrawal (> 1 min) (Imai et al. 1994; Perini et al. 1989; Macartney et al. 2020; Coote 2010), either of which will aid in a faster recovery and preparation for the next bout of physical work. It is important to note that the HR recorded at 30 s post-exercise may not be completely reflective of the cooling modality per se because of the time it took for subjects to get situated for FC and MC. While the acute phase of HRR was not altered, forearm immersion still represents a useful strategy to decrease cardiovascular load if more extended recovery periods are utilized (i.e., > 5 min). These traditional cooling methods should be modified if attempting to optimally attenuate the rise in core temperature while thermally resistive clothing remains on, which could preclude the drop in skin temperature necessary to widen the core-skin temperature gradient. Colder water temperatures and/or the addition of circulating water to maximize convective heat loss (Grahn et al. 2018) with or without sub-atmospheric pressure (Grahn et al. 2009) have shown promise in cooling capability when worn during exercise with PPE and should be explored in future work in military and occupational populations during intermittent activity. Additionally, future work is encouraged that investigates the biophysical properties of different modalities and the associated heat loss in Joules that is required to reach a desired $T_{core}$.

## Conclusion

In our sample of young aerobically fit men, forearm and fan-mist cooling elicited somewhat better cooling rates compared to passive cooling following the first 50 min exercise bout, but had less of an effect following subsequent bouts. While similar studies have seen more robust effects of forearm immersion or fan mist cooling, the major factors differentiating our findings seems to be the lack of profound hyperthermia during exercise and a warmer water temperature (20 °C vs < 10 °C). Whether lack of gear removal during the recovery/cooling period prevented faster cooling rates cannot be completely determined, but could be determined in future research. The faster cooling rates observed following bout one as well as post-exercise HR responses in the cooling trials do suggest they may have clinical utility, but new cooling modalities or methods are thus warranted in a military or occupational setting where intermittent work is performed, but full or partial gear removal is not feasible.

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**Data availability** All data generated or analyzed during this study are included in this published article.

## Declarations

**Conflict of interest** The Korey Stringer Institute focuses on exertional heat illnesses and research aimed at maximizing performance, optimizing safety, and preventing sudden death in athletes, warfighters, and laborers.

**Ethics approval** This study was approved by the University of Connecticut Institutional Review Board and all procedures were in accordance with the Declaration of Helsinki. This study was also reviewed and approved by the U.S. Army Human Research Protections Office (Fort Detrick, MD).

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

## References


Al Haddad H, Laursen PB, Ahmaidi S, Buchheit M (2010) Influence of cold water face immersion on post-exercise parasympathetic reactivation. Eur J Appl Physiol 108(3):599–606. https://doi.org/10.1007/s00421-009-1253-9

Amorim FT, Yamada PM, Robergs RA, Schneider SM (2010) Palm cooling does not reduce heat strain during exercise in a hot, dry environment. Appl Physiol Nutr Metab 35(4):480–489. https://doi.org/10.1139/H10-040

Baker LB (2019) Physiology of sweat gland function: The roles of sweating and sweat composition in human health. Temperature (austin) 6(3):211–259. https://doi.org/10.1080/23328940.2019.1632145

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(6):959–967. https://doi.org/10.1007/s00421-010-1714-1

Buchheit M, Peiffer JJ, Abbiss CR, Laursen PB (2009) Effect of cold water immersion on postexercise parasympathetic reactivation. Am J Physiol Heart Circ Physiol 296(2):H421-427. https://doi.org/10.1152/ajpheart.01017.2008

Casa DJ, McDermott BP, Lee EC, Yeargin SW, Armstrong LE, Maresh CM (2007) Cold water immersion: the gold standard for exertional heatstroke treatment. Exerc Sport Sci Rev 35(3):141–149. https://doi.org/10.1097/jes.0b013e3180a02bec

Casa DJ, DeMartini JK, Bergeron MF, Csillan D, Eichner ER, Lopez RM, Ferrara MS, Miller KC, O'Connor F, Sawka MN, Yeargin SW (2015) National athletic trainers' association position statement: exertional heat illnesses. J Athl Train 50(9):986–1000. https://doi.org/10.4085/1062-6050-50.9.07

Chou TH, Akins JD, Crawford CK, Allen JR, Coyle EF (2019) Low stroke volume during exercise with hot skin is due to elevated heart rate. Med Sci Sports Exerc 51(10):2025–2032. https://doi.org/10.1249/MSS.0000000000002029

Cleary MA, Toy MG, Lopez RM (2014) Thermoregulatory, cardiovascular, and perceptual responses to intermittent cooling during exercise in a hot, humid outdoor environment. J Strength Cond Res 28(3):792–806. https://doi.org/10.1519/JSC.0b013e3182a20f57

Coote JH (2010) Recovery of heart rate following intense dynamic exercise. Exp Physiol 95(3):431–440. https://doi.org/10.1113/expphysiol.2009.047548

DeGroot DW, Kenefick RW, Sawka MN (2015) Impact of arm immersion cooling during ranger training on exertional heat illness and treatment costs. Mil Med 180(11):1178–1183. https://doi.org/10.7205/MILMED-D-14-00727

DeMartini JK, Ranalli GF, Casa DJ, Lopez RM, Ganio MS, Stearns RL, McDermott BP, Armstrong LE, Maresh CM (2011) Comparison of body cooling methods on physiological and perceptual measures of mildly hyperthermic athletes. J Strength Cond Res 25(8):2065–2074. https://doi.org/10.1519/JSC.0b013e3182259b1d

Giesbrecht GG, Jamieson C, Cahill F (2007) Cooling hyperthermic firefighters by immersing forearms and hands in 10 degrees C and 20 degrees C water. Aviat Space Environ Med 78(6):561–567

Gonzalez-Alonso J, Calbet JA, Nielsen B (1998) Muscle blood flow is reduced with dehydration during prolonged exercise in humans. J Physiol 513(Pt 3):895–905. https://doi.org/10.1111/j.1469-7793.1998.895ba.x

Grahn DA, Dillon JL, Heller HC (2009) Heat loss through the glabrous skin surfaces of heavily insulated, heat-stressed individuals. J Biomech Eng 131(7):071005

Grahn D, Makam M, Craig Heller H (2018) A method to reduce heat strain while clad in encapsulating outerwear. J Occup Environ Hyg 15(8):573–579. https://doi.org/10.1080/15459624.2018.1470635

Imai K, Sato H, Hori M, Kusuoka H, Ozaki H, Yokoyama H, Takeda H, Inoue M, Kamada T (1994) Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. J Am Coll Cardiol 24(6):1529–1535. https://doi.org/10.1016/0735-1097(94)90150-3

Kenney WL, Munce TA (2003) Invited review: aging and human temperature regulation. J Appl Physiol (1985) 95(6):2598–2603. https://doi.org/10.1152/japplphysiol.00202.2003

Khomenok GA, Hadid A, Preiss-Bloom O, Yanovich R, Erlich T, Ron-Tal O, Peled A, Epstein Y, Moran DS (2008) Hand immersion in cold water alleviating physiological strain and increasing tolerance to uncompensable heat stress. Eur J Appl Physiol 104(2):303–309. https://doi.org/10.1007/s00421-008-0693-y

Macartney MJ, Meade RD, Notley SR, Herry CL, Seely AJE, Kenny GP (2020) Fluid loss during exercise-heat stress reduces cardiac vagal autonomic modulation. Med Sci Sports Exerc 52(2):362–369. https://doi.org/10.1249/MSS.0000000000002136

Mitchell JB, McFarlin BK, Dugas JP (2003) The effect of pre-exercise cooling on high intensity running performance in the heat. Int J Sports Med 24(2):118–124. https://doi.org/10.1055/s-2003-38203

Morrissey MC, Scarneo-Miller SE, Giersch GEW, Jardine JF, Casa DJ (2021) Assessing the validity of aural thermometry for measuring internal temperature in patients with exertional heat stroke. J Athl Train. https://doi.org/10.4085/1062-6050-0449.19

Nakamura D, Muraishi K, Hasegawa H, Yasumatsu M, Takahashi H (2020) Effect of a cooling strategy combining forearm water immersion and a low dose of ice slurry ingestion on physiological response and subsequent exercise performance in the heat. J Therm Biol 89:102530

Nindl BC, Castellani JW, Warr BJ, Sharp MA, Henning PC, Spiering BA, Scofield DE (2013) Physiological employment standards III: physiological challenges and consequences encountered during international military deployments. Eur J Appl Physiol 113(11):2655–2672. https://doi.org/10.1007/s00421-013-2591-1

Payne S, Macintosh A, Stock J (2018) The thermoregulatory function of the human hand: How do palm and digit proportions affect heat loss? Am J Phys Anthropol 166(4):803–811. https://doi.org/10.1002/ajpa.23469

Perini R, Orizio C, Comande A, Castellano M, Beschi M, Veicsteinas A (1989) Plasma norepinephrine and heart rate dynamics during recovery from submaximal exercise in man. Eur J Appl Physiol Occup Physiol 58(8):879–883. https://doi.org/10.1007/BF02332222

Ranalli GF, Demartini JK, Casa DJ, McDermott BP, Armstrong LE, Maresh CM (2010) Effect of body cooling on subsequent aerobic and anaerobic exercise performance: a systematic review. J Strength Cond Res 24(12):3488–3496. https://doi.org/10.1519/JSC.0b013e3181fb3e15

Rowell LB (1974) Human cardiovascular adjustments to exercise and thermal stress. Physiol Rev 54(1):75–159. https://doi.org/10.1152/physrev.1974.54.1.75

Rowell LB (1990) Hyperthermia: a hyperadrenergic state. Hypertension 15(5):505–507. https://doi.org/10.1161/01.hyp.15.5.505

Sawka MN, Young AJ, Francesconi RP, Muza SR (1985) Pandolf KB (1985) Thermoregulatory and blood responses during exercise at graded hypohydration levels. J Appl Physiol 59(5):1394–1401. https://doi.org/10.1152/jappl.1985.59.5.1394

Sawka MN, Cheuvront SN, Kenefick RW (2012) High skin temperature and hypohydration impair aerobic performance. Exp Physiol 97(3):327–332. https://doi.org/10.1113/expphysiol.2011.061002

Sefton JM, McAdam JS, Pascoe DD, Lohse KR, Banda RL, Henault CB, Cherrington AR, Adams NE (2016) Evaluation of 2 Heat-mitigation methods in army trainees. J Athl Train 51(11):936–945. https://doi.org/10.4085/1062-6050-51.10.13

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(8):521–531. https://doi.org/10.1080/15459620490475216

Tokizawa K, Sawada S, Oka T, Yasuda A, Tai T, Ida H, Nakayama K (2014) Fan-precooling effect on heat strain while wearing protective clothing. Int J Biometeorol 58(9):1919–1925. https://doi.org/10.1007/s00484-014-0794-8

Walloe L (2016) Arterio-venous anastomoses in the human skin and their role in temperature control. Temperature (austin) 3(1):92–103. https://doi.org/10.1080/23328940.2015.1088502

Watanabe K, Stohr EJ, Akiyama K, Watanabe S, Gonzalez-Alonso J (2020) Dehydration reduces stroke volume and cardiac output during exercise because of impaired cardiac filling and venous return, not left ventricular function. Physiol Rep 8(11):e14433

Yeargin S, McKenzie AL, Eberman LE, Kingsley JD, Dziedzicki DJ, Yoder P (2016) Physiological and perceived effects of forearm or head cooling during simulated firefighting activity and rehabilitation. J Athl Train 51(11):927–935. https://doi.org/10.4085/1062-6050-51.10.09

Zhang Y, Davis JK, Casa DJ, Bishop PA (2015) Optimizing cold water immersion for exercise-induced hyperthermia: a meta-analysis. Med Sci Sports Exerc 47(11):2464–2472. https://doi.org/10.1249/MSS.0000000000000693



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