Effect of hand cooling on body temperature, cardiovascular and perceptual responses during recumbent cycling in a hot environment

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Abstract

The purpose of this study was to quantify physiological and perceptual responses to hand immersion in water during recumbent cycling in a hot environment. Seven physically-active males (body mass 79.8 ± 6.3 kg; stature 182 ± 5 cm; age 23 ± 3 years) immersed their hands in 8, 14 and 34°C water whilst cycling at an intensity (W) equivalent to 50% $\dot{V}O_{2peak}$ for 60 min in an environmental chamber (35°C 50% relative humidity). 8 and 14°C water attenuated an increase in body temperature, and lowered cardiorespiratory and skin blood flow demands. These effects were considered to be practically beneficial (standardised effect size > 0.20). There was a tendency for 8 and 14°C to extend exercise duration versus 34°C (>7%). Heart rate, intestinal, mean skin and mean body temperature were less in 8°C compared to 14°C; these differences were considered practically beneficial. Augmented heat loss at the palm-water surface might enable cooler blood to return to the body and limit physiological strain. These findings provide a mechanistic basis for continuous hand cooling and indicate that endurance exercise in hot environments could be improved using this method. Future research should investigate its effectiveness during cycling and running performance.

Key Words: Heat; per-cooling; thermoregulation; body temperature; hyperthermia

Introduction

During fixed intensity and self-paced exercise athletes benefit from artificial heat transfer through protocols that cool the body. These protocols are grouped into pre and-per cooling. Pre-exercise cooling includes cold water immersion (Duffield, Green, Castle, & Maxwell, 2010), iced towels (Minett, Duffield, Marino, & Portus, 2011), ice vests (Duffield & Marino, 2007) and ice slurry ingestion (Siegel et al., 2009). A reduction in body temperature prior to exercise is thought to increase heat storage capacity, core-to-skin gradient and reduce thermal perception enabling exercise at a higher intensity, or for longer before reaching a regulatory limit for performance and body temperature (Marino, 2002). Neck (Tyler, Wild, & Sunderland, 2010), head (Ansley et al., 2008), torso (Kenny et al., 2011) and palm cooling (Grahn, Cao, & Heller, 2005; Hsu, Hagobian, Jacobs, Attallah, & Friedlander, 2005) have been used as per-cooling techniques. These might be applied continuously throughout exercise or at intervals between bouts to attenuate a rise in body temperature, reduce body temperature between bouts and lower perception of heat strain. In a recent meta-analysis on cooling methods (Tyler, Sunderland, & Cheung, 2013) the majority of per-cooling studies were shown to improve exercise performance with similar beneficial effects compared to pre-cooling (d = 0.76; d =

0.73 respectively). These findings were supported by Bongers et al. (2015) who found pre-cooling and per-cooling also had similar beneficial effects on exercise performance (*d* = 0.44; *d* = 0.40, respectively).

Hand or palm cooling has been used as a per-cooling method to attenuate a rise in body temperature (Livingstone, Nolan, & Cattroll, 1989), extend low-intensity cycling, stepping and walking exercise capacity (Allsopp & Pool, 1991; Giesbrecht, Jamieson, & Cahill, 2007; Grahn et al., 2005; House, Holmes, & Allsopp, 1997; Khomenok et al., 2008), improve short-term high intensity wheelchair ergometer (1 km) and cycling performance (3 km) (Goosey-Tolfrey, Swainson, Boyd, Atkinson, & Tolfrey, 2008) and improve endurance cycling performance (30 km) (Hsu et al., 2005) in environmental temperatures greater than 30°C. The hands have a large surface to mass ratio (Taylor, Machado-Moreira, van den Heuvel, & Caldwell, 2014) and low metabolic heat production that suit high rates of conductive heat transfer. Additionally, the glabrous skin of the palms contain dense proportions of arteriovenous anastomoses and retia venosa (Manelli et al., 2005; Sangiorgi et al., 2004) enabling blood flow. A large volume of blood flow through the palm is conducive to heat transfer between warm arterial blood, the palmar surface and cooler contacting media such that heat is conducted and cooler blood returns to the body through venous networks.

In most hand or palm cooling studies the treatment has been applied between bouts of exercise (Allsopp & Pool, 1991; Giesbrecht et al., 2007; Goosey-Tolfrey et al., 2008; Khomenok et al., 2008; Kuennen, Gillum, Amorim, Kwon, & Schneider, 2010; Selkirk, McLellan, & Wong, 2004) or after exercise (House et al., 1997; Livingstone et al., 1989) in hot environments. However, Hsu *et al.* (2005) demonstrated that continuous hand cooling alleviated an increase in tympanic temperature during 60 min of fixed intensity cycling exercise at 60% $\dot{V}O_{2peak}$ in 32°C 25% relative humidity (1.2 ± 0.2°C; 1.8 ± 0.2 °C with and without hand cooling respectively). Similarly, Grahn *et al.* (2005) reported that hand cooling attenuated a rise in oesophageal temperature during walking at 5.7 km·hour^{-1} in 40°C 25% relative humidity (2.1 ± 0.4°C; 2.8 ± 0.5°C (with and without hand cooling respectively). However, only a single-palm was used and the results are only applicable to the vacuum assisted heat extraction device used (RTX CoreControl, AVAcore Inc., CA, USA) which is impractical to use during competition. Moreover, Amorim, Yamada, Robergs, & Schneider (2010) did not report any benefit of the vacuum assisted heat extraction device whilst walking at 6.7 km/h 4% gradient, in 42 ± 1°C, 30 ± 5% relative humidity whilst wearing military uniform and body armour. However this study is limited by several methodological issues. A practical approach to hand cooling was addressed by Scheadler, Saunders, Hanson, & Devor (2013) who secured a gel pack to the non-dominant hand during a running time-trial to exhaustion task at 75% $\dot{V}O_{2peak}$. The rate of change in intestinal temperature was similar between control and gel pack trials and participants ran for longer in the control trial than the gel pack trial (46.7 ± 32.1 min; 41.3 ± 26.3 min respectively). However, the authors only applied the gel to a single palm and did not report its temperature or palm skin temperature, raising doubts as to whether sufficient palm cooling occurred. Furthermore, given the large standard deviation in time to exhaustion it is difficult to make confident interpretations regarding the effectiveness of continuous application of a gel pack during exercise from this study.

Given that the physical properties of the hands are conducive to heat exchange and previous research has identified the potential effectiveness of continuous hand during exercise, alternative methods of should be investigated. Indeed, the ergogenic mechanisms, optimal cooling temperature and whole body physiological and perceptual responses when cooling both hands continuously during exercise are unclear. Therefore, the aim of this study was to provide a mechanistic basis for the development of practical hand cooling techniques by assessing body temperature, cardiovascular and perceptual responses to continuous hand immersion in water during exercise in a hot environment.

METHODS

Participants

A priori sample size calculation based upon finding a 0.20˚C intestinal temperature difference between experimental and control conditions at the end of exercise, a standard deviation of 0.40˚C, β = 0.20 and α = 0.05 suggested a sample size of 6 participants would be adequate. This data was based on findings from a previous study (Hsu et al., 2005). Nine non-heat-acclimated physically active males volunteered for the study that was approved by the local ethics committee and conducted according to the principles of the Declaration of Helsinki. All experimental trials were conducted between the months of August and October where mean ambient temperatures ranged 12 - 22°C. Seven participants (age 24 ± 3 years; body mass 78.3 ± 7.2 kg; stature 180 ± 7 cm) completed all trials; drop-outs were due to illness and one participant being unable to tolerate hand immersion in cold water. All participants provided written informed consent before the study. Participants were told that they were required to place their hands in three different water temperatures whilst exercising but were not told the temperatures or the true purpose of the study. Participants were asked to refrain from strenuous exercise, caffeine and alcohol 24 h before each trial and food 3 h before each trial. Each participant recorded their diet 24 h prior to the first trial and replicated their diet for the remaining trials. Adherence to the standardised diet was verified by the investigator before each trial.

Participants visited the laboratory 4 times, each visit separated by 3 days to 7 days. Trials were performed at least 3 hours after waking and 3 hours before sleep to minimise the circadian rhythm impact on body temperature and gastrointestinal function (Manfredini, Manfredini, Fersini, & Conconi, 1998). Exercise trials were conducted on an externally-verified, electromagnetically-braked ergometer (Lode Angio, Groningen, The Netherlands) positioned for recumbent cycling.

Visit 1: Pre-experimental trial testing and accustomisation

In a temperature controlled laboratory (18°C 60% relative humidity) a continuous 25 $W \cdot min^{-1}$ incremental exercise test to maximal volitional exhaustion was used to determine peak oxygen uptake ($\dot{V}O_{2peak}$) (Ultima, CardiO$_2$, Medgraphics, USA) and peak minute power (W_{peak}). Heart rate was recorded continuously during exercise (RS400, Polar OY, Finland).

After 60 min of rest in a temperate environment, nude body mass (kg) was recorded using beam balance scales (Weylux, UK) before the accustomisation trial. Participants performed 30 min of recumbent cycling within the environmental chamber (28.5°C Wet bulb globe temperature [35°C, 50% relative humidity]) at an intensity of 50% W_{peak} to accustomise to the experimental procedures. During the exercise session heart rate, rating of perceived exertion (RPE) (Borg, 1970) and thermal perception (9 point scale) (Nielsen, Gavhed, & Nilsson, 1989) were assessed every 5 min. Whole body sweat rate (L·hour^{-1}) was estimated from the change in body mass adjusted for fluid intake and urine output.

Experimental trials

An ingestible temperature pill was used to assess intestinal core temperature (CorTemp, HQinc, USA). The validity of temperature measurement of each pill was verified according to recommended guidelines (Hunt & Stewart, 2008). Participants ingested the pill at the same time of day, 6 h prior to each visit (Byrne & Lim, 2007), a procedure demonstrated to provide reliable responses under similar conditions (Ruddock, Tew, & Purvis, 2014).

On arrival, participants voided and nude body mass (kg) and urine osmolality (mOsmol·kg^{-1} H_2O) (Advanced Model 3320 Micro-Osmometer, Advanced Instruments, Inc., USA) were assessed. A urine osmolality of ≤700 mOsmol·kg^{-1} H_2O was used to verify pre and post-trial euhydration status (Sawka et al., 2007). Participants rested for 60 min in the environmental chamber set at 28.5°C WBGT. Participants wore the same clothing (shorts, socks and running shoes) for all trials. Air currents from the environmental chamber fans were ≈0.5 m·s^{-1}, no cooling fans were used.

Thirty minutes before the start of exercise, participants were fitted with a chest strap for the measurement of heart rate, and skin thermistors (Grant Instruments, Cambridge, UK) were attached to the left side of the body at the medial calf, anterior mid-thigh, anterior mid-forearm, chest and index finger using acrylic dressing (Tegaderm, 3M Healthcare, USA), secured in place using hypoallergenic surgical tape (Transpore, 3M Healthcare, USA). A 7-point integrating laser Doppler flowmeter probe (Probe 413, Perimed AB) was positioned on the volar aspect of the upper left forearm and on the left middle fingertip within a housing disc surrounding the probe (Model 455, Perimed AB) for measurement of arbitrary perfusion units (APU). The position of the site was standardised for each participant. Blood pressure (mmHg) was assessed using auscultation and an aneroid sphygmomanometer.

APU (mean of last 60 s for each 5 min period), rating of perceived exertion and whole body, right hand and left hand thermal perception were recorded at -10, -5 min and immediately before exercise (0 min) and then at 5-min intervals throughout the exercise trial. Expired air was assessed breath-by-breath every 15 min for 3 min. Participants were asked to cycle for 60 min within the environmental chamber (28.5°C Wet bulb globe temperature [35°C, 50% relative humidity]) at an intensity of 50% $W_{peak.}$ This intensity and duration was chosen to balance muscular fatigue, due to recumbent cycling, with an ethically acceptable magnitude of heat strain. The exercise test was terminated when one of the following criteria was met: 1) participants voluntarily stopped exercising, 2) when intestinal core temperature reached 39.5 °C or 3) participants completed 60 min of exercise.

Ten minutes before exercise (-10 min) participants immersed their hands up to the ulna head in buckets filled with water controlled at 8, 14 or 34 ± 2˚C. Hands remained immersed in water until the exercise trial was complete. These temperatures were chosen because of the similarity to previous hand cooling research.

Calculations

Weighted mean skin temperature (T_{sk}) was calculated using the equation of Ramanathan (1964). Mean body temperature (T_{body}) was calculated using the equation of Colin, Timbal, Houdas, Boutelier, & Guieu (1971). Mean arterial pressure (MAP) was calculated as using the equation of Razminia et al. (2004). Raw cutaneous vascular conductance (CVC), an index of skin blood flow was calculated as: CVC = APU ÷ MAP .

Statistical analysis

INSERT TABLE 1 HERE

Reliability data for measurements in the study are presented in table 1. Normal distribution was assessed using Kolmogorov-Smirnov test and homogeneity of variance using Levene's test in IBM SPSS statistics version 20 (IBM Armonk, NY, USA). Data were assessed for meaningful between-trial differences using a magnitude-based approach (Hopkins, Marshall, Batterham, & Hanin, 2009). The analysis was performed using a statistical spreadsheet (Hopkins, 2003) that calculates trial means, standard deviations, standardised effect sizes (Cohen's *d*) using the pooled standard deviation and confidence intervals. Cohen's *d* was assessed according to accepted thresholds; ≤ 0.2 (trivial), > 0.2 - 0.59 (small), 0.60 - 1.19 (moderate), 1.20 - 1.99 (large), > 2.0 - 3.99 (very large) and > 4.0 (extremely large) (Hopkins et al., 2009). 90% confidence intervals were calculated for *d*. The probability (% chance) that the between-trial differences were less than, similar to or greater than the smallest worthwhile difference (calculated as 0.2 × between-trial pooled standard deviation) was assessed using a statistical spreadsheet (Hopkins, 2003). When data violated assumptions of normality the Wilcoxon Signed Rank Test was used to assess between-group differences. Statistical significance was set at $P < 0.05$.

Results

Pre-trial measures

Mean $\dot{V}O_{2peak}$ for the recumbent cycling incremental exercise test was 41 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$. Wet bulb globe temperature was similar between 8 (28.6 ± 0.4°C) and 34°C (28.5 ± 0.2°C) trials; d = 0.16 [0.07 to 0.25], there was a moderate difference between 8 and 14°C (28.3 ± 0.2°C); d = 0.70 [0.42 to 0.97] and a moderate difference between 14 and 34°C trials; d = 0.72 [0.16 to 1.29]. Pre-trial urine osmolality was 257 ± 255; 291 ± 225; 387 ± 259 $mOsmol \cdot kg^{-1}$ H_2O for 8, 14 and 34°C trials respectively and within the limit for euhydration.

Initial physiological responses to hand immersion

Hand immersion at rest had no influence on physiological variables (Table 2). Whole body rating of thermal perception was lower after hand immersion (-5 min), irrespective of water temperature, compared to -10 min (difference in thermal perception -0.4 units; d = 0.52 [0.00 to 1.04]). Rating of right and left hand thermal perception was lower than whole body thermal perception when immersed in water at all temperatures (difference in thermal perception -3.6 units; d = 1.48 [1.06 to 1.98] and corresponded to the qualitative descriptor “cool”.

INSERT TABLE 2 HERE

INSERT FIGURE 1 HERE

Exercise duration and cardiorespiratory responses

Mean intensity of exercise was 148 ± 17 W and the duration was 50:48 ± 16:18 min, 51:30 ± 15:00 min and 47:24 ± 14:24 min for 8, 14 and 34°C conditions. Exercise duration in 14°C was 1.3% longer than 8°C and 8.7% longer than 34°C. Exercise duration in 8°C was 7.3% longer than 34°C. However, there were no statistically significant differences between conditions. Five participants completed 60 min of exercise in 8 and 14°C and 3 participants completed 60 min of exercise in 34°C. Exercise trials were self-terminated by participants due to volitional exhaustion. None of participants reached ethical limit of intestinal temperature and there were no instances of heat illness. Percentage of peak heart rate (figure 1A) was likely (94%) lower in 8°C versus 34°C from 25 min onwards (87 ± 4% and 90 ± 5% respectively); d = 0.69 [0.18 to 1.20]. Percentage of peak heart rate during 8°C was also likely (77%) lower than 14°C (89 ± 10%) from 25 min onwards; d = 0.28 [0.10 to 0.46]. Peak percentage heart rate in 14°C and 34°C were similar (68%) from 25 min onwards; d = 0.13 [-0.09 to 0.36]. Mean $\dot{V}O_2$ during 8°C was possibly (62%) less than 34°C (27.1 ± 3.1 $ml \cdot kg^{-1} \cdot min^{-1}$ and 28.0 ± 1.9 $ml \cdot kg^{-1} \cdot min^{-1}$ respectively); d = 0.37 [-0.55 to 1.28]. Mean $\dot{V}O_2$ during 8°C (27.5 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$) was possibly (50%) less than 34°C; d = 0.18 [-2.62 to 2.99] and possibly similar (49%) to 8°C; d = 0.12 [-0.33 to 0.58].

Perceived exertion and thermal perception

Figure 1B shows RPE responses during exercise. There were no statistically significant differences ($P > 0.05$) in mean RPE between 8°C and 14°C (15.3 ± 2.0 and 15.2 ± 1.7 respectively) and 8°C and 34°C (15.6 ± 1.9). However, mean RPE for 14°C was significantly less ($P < 0.05$) than 34°C. Figure 1C shows responses for thermal perception during exercise. Mean thermal perception for 8°C was statistically (P <0.05) less than 14°C (7.3 ± 0.8, 7.5 ± 0.8 respectively) and 34°C (8.0 ± 0.7). Mean thermal perception for 14°C was statistically less than 34°C. Mean qualitative descriptors for 8, 14 and 34°C corresponded to "warm", "warm-hot" and "hot".

Intestinal temperature

Figure 2A shows intestinal temperature responses during exercise. Intestinal temperature was similar between trials for the first 15 min of exercise but increases were attenuated by hand cooling. From 15 min onwards until the end of exercise the change was likely (77%) less in 8°C compared to 14°C (0.74 ± 0.29˚C and 0.83 ± 0.31 respectively); *d* = 0.35 [-0.01 to 0.69]. There was a very likely (99%) difference for change in intestinal temperature between 8°C and 34°C (1.00 ± 0.38˚C) from 15 min onwards until the end of exercise; *d* = 0.84 [0.42 to 1.25] and a likely (85%) difference between 14°C and 34°C over the same time period; *d* = 0.55 [-0.01 to 1.11]. Figure 3 shows these changes from 0 min until the end of exercise for each participant.

INSERT FIGURE 2 HERE

INSERT FIGURE 3 HERE

Mean skin temperature

Change in mean skin temperature (Figure 2B) was less after 5 min and onwards to cessation of exercise in 8°C compared to 34°C (-0.09 ± 0.72°C and 0.77 ± 0.30°C respectively); *d* = 1.24 [0.45 to 2.03]. Change in mean skin temperature for 8°C was also very likely (98%) less throughout exercise compared to 14°C; *d* = 1.09 [0.43 to 1.76]. Change in mean skin temperature was likely (94%) less in 14°C versus 34°C throughout exercise; *d* = 0.63 [0.17 to 1.10].

INSERT FIGURE 4 HERE

Mean body temperature

Change in mean body temperature (figure 2C) at the end of exercise was likely (82%) lower in 8°C compared to 14°C (0.47 ± 0.33°C and 0.71 ± 0.35°C respectively); *d* = 0.69 [-0.24 to 1.61] and very likely (99%) less than 34°C (1.09 ± 0.38°C); *d* = 1.32 [0.60 to 2.04]. Change in mean body temperature at the end of exercise was likely (93%) lower in 14°C compared to 34°C; *d* = 0.95 [0.09 to 1.81].

Fingertip temperature

During water immersion fingertip temperature (Figure 4) was statistically ($P < 0.05$) less in 8°C than 14°C (15.20 ± 3.46 and 18.50 ± 3.30 respectively) and 34°C (34.93 ± 0.93). 14°C was also statistically ($P < 0.05$) less than 34°C.

Skin blood flow

Figures 5 and 6 show skin blood flow responses during exercise. Mean fingertip CVC was significantly ($P < 0.05$) less in 14°C than 8°C (2.9 ± 1.6 and 3.2 ± 1.7 respectively) and 34°C (3.9 ± 1.4). 8°C was significantly ($P < 0.05$) less than 34°C for mean fingertip CVC during exercise. Mean forearm CVC was very likely (99%) less in 8°C compared to 34°C (1.30 ± 0.39 and 1.75 ± 0.47 respectively); *d* = 0.68 [0.51 to 0.86]. Mean forearm CVC was also very likely less (99%) in 14°C (1.34 ± 0.44) compared 34°C; *d* = 0.69 [0.48 to 0.91]. Mean forearm CVC was similar (86%) for 8°C and 14°C; *d* = 0.12 [0.00 to 0.23].

INSERT FIGURE 5 HERE

INSERT FIGURE 6 HERE

Sweat rate

Post-exercise body mass loss was 1.3 ± 1.2% in 8°C, 0.5 ± 0.8% in 14°C and 0.9 ± 0.9% in 34°C. Sweat rate was similar (45%) between 8°C and 34°C (0.97 ± 0.21 $L \cdot hour^{-1}$ and 0.94 ± $L \cdot hour^{-1}$ respectively); *d* = 0.13 [-1.13 to 0.86]. Sweat rate was likely (94%) lower in 14°C (0.69 ± 0.29 $L \cdot hour^{-1}$) compared to 8°C; *d* = 0.69 [-0.12 to 1.84] and likely lower (88%) compared to 34°C; *d* = 0.81 [0.09 to 1.71].

Discussion

The aim of this study was to assess the body temperature, cardiovascular and perceptual responses to hand cooling during exercise. In general, hand cooling attenuated an increase in body temperature, limited heat storage and lowered cardiorespiratory and skin blood flow demands. These effects were considered to be practically beneficial. There was a tendency for participants to exercise longer with hand cooling, however magnitude-based statistical analysis could not be performed as the data was not normally distributed and differences between groups were not statistically significant.

Previous research has demonstrated that hand immersion in cold water can reduce body temperature between bouts of exercise (Allsopp & Pool, 1991; Giesbrecht et al., 2007; Goosey-Tolfrey et al., 2008; House et al., 1997; Khomenok et al., 2008) and single-palm cooling using a heat extraction device applied continuously during exercise can extend exercise duration and improve cycling performance (Grahn et al., 2005; Hsu et al., 2005).

Heat transfer from warm circulating blood is the likely mechanism responsible for these findings. For effective heat transfer there needs to be a balance between thermal gradient (hand cooling) and blood flow (limited vasoconstriction). In the present investigation fingertip temperature was greater than water temperature for 8 and 14°C trials providing evidence of a thermal gradient. Fingertip temperature was also lower than mean skin temperature, providing evidence that the hands were cooled during the exercise trials. However, cooler temperatures might have limited fingertip blood flow and restricted heat transfer as cutaneous vascular conductance was lower in 8°C and 14°C than during 34°C trials.

At the onset of water immersion vasoconstriction occurred at the fingertip but not at the forearm (Figure 5 and 6). This is likely because of an increase in local sympathetic noradrenergic vasoconstrictor activity in response to cold stress (Ekenvall, Lindblad, Norbeck, & Etzell, 1988). Fingertip skin blood flow remained similar in 34°C before and after hand immersion but was lower at the onset of exercise. This probably occurred because of increased sympathetic vasoconstrictor activity at the onset of exercise (Johnson & Park, 1982; Johnson, 1992). After 10 min of exercise fingertip skin blood flow began to increase in all conditions, probably because of vasoconstrictor withdrawal as autonomic heat loss mechanisms were activated (Roddie, Shepherd, & Whelan, 1957). Thereafter, dilation of arteriovenous anastomoses, dense microvascular networks and poor insulative properties of the hand (Manelli et al., 2005; Sangiorgi et al., 2004; Taylor et al., 2014) allowed heat from the blood to be conducted to the water down a thermal gradient. Thus cooler blood returned to the central circulation and presumably less body heat was stored. Therefore, the rate at which intestinal temperature increased during exercise was attenuated in 8 and 14°C (Figure 2A). This was likely because of; 1) cooler blood returning directly from the hands; and 2) relatively cooler blood returning from the active muscles.

Mean skin temperature increase was also attenuated in 8°C and 14°C trials (Figure 2B). Whether this resulted from cooler blood returning to the central circulation through venous structures close to the skin, cold conductance from the hand to forearm, lower-temperature arterial blood circulated to the skin or less skin blood flow is unclear. However, forearm cutaneous vascular conductance was less in 8°C and 14°C compared to 34°C suggesting there was less demand for skin blood flow to aid thermoregulation. This was evident up to 40 min, thereafter CVC in the control trial decreased and was similar to 8°C and 14°C. This likely occurred due to a combination of participant attrition and poor test-retest reliability. Less demand for skin blood flow also attenuated the demands on the cardiovascular system as evidenced by lower heart rates from 25 min onwards in the 8°C condition compared to 14°C and 34°C.

Sweat rate was less in 14°C than 8°C and 34°C but similar between 8°C and 34°C. The reason for the difference in sweat rate between 14°C and 8°C is unclear. However, the similarity between 8°C and 34°C sweat rate suggests that evaporative cooling was not impaired by hand cooling at this temperature. These results indicate that heat transfer via the hands was responsible for limiting body heat storage rather than evaporative cooling mechanisms.

However, despite associations between RPE and cardiovascular demand (Borg, 1982), there were no statistically significant differences in mean RPE (Figure 1B) between trials. This might have been a consequence of the difficulty of the exercise trials where perceived exertion reached near maximal ratings towards the end. However, whole body thermal perception scores were statistically less during the cooling trials with 8°C statistically less than 14°C.

Hsu et al. (2005) used a cooling device (RTX CoreControl, AVAcore Inc., CA, USA) that circulated 22°C water over one palm during fixed intensity (60% $\dot{V}O_{2peak}$) cycling in a hot environment (32°C 25% RH). Similar to the present investigation core temperature change from baseline, measured at the tympanic membrane was less with palm cooling compared to no cooling (1.2 ± 0.2°C; 1.8 ± 0.2 °C with and without hand cooling respectively). Using the same device during exercise in 40°C 25% RH, Grahn et al. (2005) reported an improved exercise tolerance (57.0 ± 6.4 min; 34.1 ± 3.0 min with and without hand cooling respectively) and attenuated rise in oesophageal temperature when compared to no cooling (2.1 ± 0.4°C; 2.8 ± 0.5°C with and without hand cooling respectively) . The authors attributed these benefits to the vacuum induced negative pressure because hand cooling alone had little benefit over no cooling, however, the temperature of the water was 22°C and much warmer than the 8 and 14°C used in the present study. Even so, hand cooling prolonged exercise time compared to 34°C by approximately 4 min, similar to Grahn et al. (2005) even without negative pressure. However, the application of negative pressure at cooler temperatures might compromise heat transfer. Amorim, Yamada, Robergs, & Schneider, (2010) used the same negative pressure cooling device during walking at 6.7 km/h 4% gradient, in 42 ± 1°C, 30 ± 5% relative humidity whilst wearing military uniform and body armour. The authors reported ‘negative’ results for water temperatures of 15°C (n = 3) and 18°C (n = 3) yet assessed a further 4 participants at 22°C and grouped all the data as a single condition. This approach is misleading since each of these temperatures would have led to differing magnitudes of fingertip vasoconstriction, heat transfer and physiological responses, however these responses were not assessed or reported nor were the magnitudes of any of the basic physiological, thermoregulatory or perceptual responses. Unsurprisingly the authors reported no statistically significant effects of hand cooling and concluded that palm cooling did not reduce heat strain during exercise in hot environments. This conclusion was also reached by Scheadler et al., (2013) who reported that participants performed better in the control trial versus the palm cooling trial. However, it is unclear as to whether palm cooling actually occurred since neither Amorim et al. (2010) or Scheadler et al. (2013) reported fingertip or palm temperature or the magnitude of vasoconstriction so the mechanisms responsible for these findings are unclear. Unlike previous studies, we are confident that hand cooling occurred because fingertip temperature was less than mean skin temperature. We also aware that hand cooling caused vasoconstriction which was alluded to, but not investigated by previous research. However, despite this vasoconstriction, which was not maximal; and because we cooled the whole hand and not just the palm, it is likely that cooler blood returned to the central circulation resulting in our observed beneficial effects.

Practical implications

In the present study hand cooling tended to increase exercise duration and lessened the perception of heat strain. These effects were the result of an attenuated rise in body temperature. Heat strain is the principle cause of physiological strain and subsequent termination of exercise in fixed intensity trials in hot environments (González-Alonso & Calbet, 2003; González-Alonso et al., 1999; Nybo & Nielsen, 2001). Therefore, it is important that athletic, military and occupational populations have practical methods available to reduce physiological strain in hot environments. However, unlike pre-cooling the majority of per-cooling methods have little influence on body temperature and performance improvements might be attributed to a lower perception of heat strain. This has practical implications because a mismatch between thermal perception and thermal strain might impair pacing during self-paced trials and as exercise continues accelerate hyperthermia-mediated fatigue. In the present investigation both thermal perception and body temperature were less during hand cooling, alleviating concerns expressed by Tyler et al. (2010) relating to a potentially detrimental mismatch.

Limitations

Our method provides a theoretical basis for future studies, however at present there are limitations to the practical application of the study. We used water buckets to cool the hands, a method that would be difficult to use outside the laboratory. Recumbent cycling was chosen because it enabled the hands to be cooled whilst minimising upper body movements that might have caused artefacts in laser-Doppler recordings limited the intensity of exercise and potential for heat strain. Mean body temperature at the end-of-exercise for 34°C trial was around 38.5°C and could be considered as moderate heat strain. Therefore, our results might not be applicable to exercise that induces greater heat strain. Finally, we were unable to report the amount of heat transferred by hand immersion because we maintained water temperature throughout the trial.

Conclusion

In this study we demonstrated that hand cooling during exercise had several practically beneficial effects. These included an attenuated rise in body temperature, reduced cardiorespiratory demands and improved thermal perception. These effects were observed because heat was transferred from the hands to the water allowing cooler blood to be circulated back to the body. Although the method we used in the present study has several logistical constraints it provides a mechanistic basis for the development of practical hand cooling methods during exercise in hot environments that might benefit athletic, military, occupational and athletic populations.

References

Allsopp, A. J., & Pool, K. A. (1991). The effect of hand immersion on body temperature when wearing impermeable clothing. *Journal of the Royal Naval Medical Service*, *77*, 41–47.

Amorim, F. T., Yamada, P. M., Robergs, R. a, & Schneider, S. M. (2010). Palm cooling does not reduce heat strain during exercise in a hot, dry environment. *Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquée, Nutrition et Métabolisme*, *35*, 480–9. doi:10.1139/H10-040

Ansley, L., Marvin, G., Sharma, A., Kendall, M. J., Jones, D. a, & Bridge, M. W. (2008). The effects of head cooling on endurance and neuroendocrine responses to exercise in warm conditions. *Physiological Research*, *57*, 863–72. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18052690

Bongers, C. C. W. G., Thijssen, D. H. J., Veltmeijer, M. T. W., Hopman, M. T. E., & Eijsvogels, T. M. H. (2015). Precooling and percooling (cooling during exercise) both improve performance in the heat: a meta-analytical review. *British Journal of Sports Medicine*, *49*, 377–384. doi:10.1136/bjsports-2013-092928

Borg, G. A. V. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine*, *2*, 92–98.

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise Science in Sports & Exercise*, *14*, 377–381.

Byrne, C., & Lim, C. L. (2007). The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *British Journal of Sports Medicine*, *41*, 126–33. doi:10.1136/bjsm.2006.026344

Colin, J., Timbal, J., Houdas, Y., Boutelier, C., & Guieu, J. D. (1971). Computation of mean body temperature from rectal and skin temperatures. *Journal of Applied Physiology, 31*, 484–489.

Duffield, R., Green, R., Castle, P., & Maxwell, N. (2010). Precooling can prevent the reduction of self-paced exercise intensity in the heat. *Medicine and Science in Sports and Exercise*, *42*, 577–84. doi:10.1249/MSS.0b013e3181b675da

Duffield, R., & Marino, F. E. (2007). Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions. *European Journal of Applied Physiology*, *100*, 727–35. doi:10.1007/s00421-007-0468-x

Ekenvall, L., Lindblad, L. E., Norbeck, O., & Etzell, B. M. (1988). alpha-Adrenoceptors and cold-induced vasoconstriction in human finger skin. *American Journal of Physiology. Heart and Circulatory Physiology.*, *255,* H1000–1003.

Giesbrecht, G. G., Jamieson, C., & Cahill, F. (2007). Cooling Hyperthermic Firefighters by Immersing Forearms and Hands in 10°C and 20°C Water. *Aviation Space and Environmental Medicine, 78,* 561–567.

González-Alonso, J., & Calbet, J. A. (2003). Reductions in Systemic and Skeletal Muscle Blood Flow and Oxygen Delivery Limit Maximal Aerobic Capacity in Humans. *Circulation*, *107*, 824–830. doi:10.1161/01.CIR.0000049746.29175.3F

González-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology*, *86*, 1032–9. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/10066720

Goosey-Tolfrey, V., Swainson, M., Boyd, C., Atkinson, G., & Tolfrey, K. (2008). The effectiveness of hand cooling at reducing exercise-induced hyperthermia and improving distance-race performance in wheelchair and able-bodied athletes. *Journal of Applied Physiology*, *105*, 37–43. doi:10.1152/japplphysiol.01084.2007

Grahn, D. a, Cao, V. H., & Heller, H. C. (2005). Heat extraction through the palm of one hand improves aerobic exercise endurance in a hot environment. *Journal of Applied Physiology*, *99*, 972–8. doi:10.1152/japplphysiol.00093.2005

Hopkins, W. G. (2003). A spreadsheet for analysis of straightforward controlled trials. *Sportscience*, *7*. doi:10.1119/1.14219

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*, 3–13. doi:10.1249/MSS.0b013e31818cb278

House, J. R., Holmes, C., & Allsopp, A. J. (1997). Prevention of heat strain by immersing the hands and forearms in water. *Journal of the Royal Naval Medical Service*, *83*, 26–30.

Hsu, A. R., Hagobian, T. a, Jacobs, K. a, Attallah, H., & Friedlander, A. L. (2005). Effects of heat removal through the hand on metabolism and performance during cycling exercise in the heat. *Canadian Journal of Applied Physiology*, *30*, 87–104. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15855685

Hunt, A. P., & Stewart, I. B. (2008). Calibration of an ingestible temperature sensor. *Physiological Measurement*, *29*, N71–8. doi:10.1088/0967-3334/29/11/N01

Johnson, J. M. (1992). Exercise and the cutaneous circulation. *Exercise and Sport Science Reviews*, *20*, 59–97.

Johnson, J. M., & Park, M. K. (1982). Effect of heat stress on cutaneous vascular responses to the initiation of exercise. *Journal of Applied Physiology*, *53*, 744–749.

Kenny, G. P., Schissler, A. R., Stapleton, J., Piamonte, M., Binder, K., Lynn, A., … Hardcastle, S. G. (2011). Ice Cooling Vest on Tolerance for Exercise under Uncompensable Heat Stress. *Journal of Occupational and Environmental Hygiene*, *8*, 484–491. doi:10.1080/15459624.2011.596043

Khomenok, G. a, Hadid, A., Preiss-Bloom, O., Yanovich, R., Erlich, T., Ron-Tal, O., … Moran, D. S. (2008). Hand immersion in cold water alleviating physiological strain and increasing tolerance to uncompensable heat stress. *European Journal of Applied Physiology*, *104*, 303–9. doi:10.1007/s00421-008-0693-y

Kuennen, M. R., Gillum, T. L., Amorim, F. T., Kwon, Y. S., & Schneider, S. M. (2010). Palm cooling to reduce heat strain in subjects during simulated armoured vehicle transport. *European Journal of Applied Physiology*, *108*, 1217–23. doi:10.1007/s00421-009-1335-8

Livingstone, S. D., Nolan, R. W., & Cattroll, S. W. (1989). Heat loss caused by immersing the hands in water. *Aviation Space and Environmental Medicine*, *60*, 1166–1171.

Manelli, A., Sangiorgi, S., Ronga, M., Reguzzoni, M., Bini, A., & Raspanti, M. (2005). Plexiform vascular structures in the human digital dermal layer: a SEM - corrosion casting morphological study. *European Journal of Morphology*, *42*, 173–7. doi:10.1080/09243860500359885

Manfredini, R., Manfredini, F., Fersini, C., & Conconi, F. (1998). Circadian rhythms, athletic performance, and jet lag. *British Journal of Sports Medicine*, *32*, 101–6. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1756080&tool=pmcentrez&rendertype=abstract

Marino, F. E. (2002). Methods, advantages, and limitations of body cooling for exercise performance. *British Journal of Sports Medicine*, *36*, 89–94. doi:10.1136/bjsm.36.2.89

Minett, G. M., Duffield, R., Marino, F. E., & Portus, M. (2011). Volume-Dependent Response of Pre-Cooling For Intermittent-Sprint Exercise in the Heat. *Medicine and Science in Sports and Exercise*, 1760–1769. doi:10.1249/MSS.0b013e318211be3e

Nielsen, R., Gavhed, D. C. E., & Nilsson, H. (1989). Thermal function of a clothing ensemble during work: dependency on inner clothing layer fit. *Ergonomics*, *32*, 1581–1594.

Nybo, L., & Nielsen, B. (2001). Hyperthermia and central fatigue during prolonged exercise in humans Hyperthermia and central fatigue during prolonged exercise in humans. *Journal of Applied Physiology*, *91*, 1055–1060.

Ramanathan, N. L. (1964). a New Weighting System for Mean Surface Temperature of the Human Body. *Journal of Applied Physiology*, *19*, 531–3. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14173555

Razminia, M., Trivedi, A., Molnar, J., Elbzour, M., Guerrero, M., Salem, Y., … Lubell, D. L. (2004). Validation of a new formula for mean arterial pressure calculation: the new formula is superior to the standard formula. *Catheterization and Cardiovascular Interventions*, *63*, 419–25. doi:10.1002/ccd.20217

Roddie, I. C., Shepherd, J. T., & Whelan, R. F. (1957). THE CONTRIBUTION OF CONSTRICTOR AND DILATOR. *Journal of Physiology*, *136*, 489–497.

Ruddock, A. D., Tew, G. A., & Purvis, A. J. (2014). Reliability of intestinal temperature using an ingestible telemetry pill system during exercise in a hot environment. *Journal of Strength and Conditioning Research*, *28*, 861–869.

Sangiorgi, S., Manelli, a, Congiu, T., Bini, a, Pilato, G., Reguzzoni, M., & Raspanti, M. (2004). Microvascularization of the human digit as studied by corrosion casting. *Journal of Anatomy*, *204*, 123–31. doi:10.1111/j.1469-7580.2004.00251.x

Sawka, M. N., Burke, L. M., Eichner, E. R., Maughan, R. J., Montain, S. J., & Stachenfeld, N. S. (2007). American College of Sports Medicine position stand. Exercise and fluid replacement. *Medicine and Science in Sports and Exercise*, *39*, 377–90. doi:10.1249/mss.0b013e31802ca597

Scheadler, C. M., Saunders, N. W., Hanson, N. J., & Devor, S. T. (2013). Palm Cooling Does not Improve Running Performance. *International Journal of Sports Medicine*, *34*, 732–735.

Selkirk, G. a, McLellan, T. M., & Wong, J. (2004). Active versus passive cooling during work in warm environments while wearing firefighting protective clothing. *Journal of Occupational and Environmental Hygiene*, *1*, 521–31. doi:10.1080/15459620490475216

Siegel, R., Maté, J., Brearley, M. B., Watson, G., Nosaka, K., & Laursen, P. B. (2009). Ice Slurry Ingestion Increases Core Temperature Capacity and Running Time in the Heat. *Medicine and Science in Sports and Exercise*, *42*, 717–725. doi:10.1249/MSS.0b013e3181bf257a

Taylor, N. a S., Machado-Moreira, C. a, van den Heuvel, A. M. J., & Caldwell, J. N. (2014). Hands and feet: physiological insulators, radiators and evaporators. *European Journal of Applied Physiology*, *114*, 2037–60. doi:10.1007/s00421-014-2940-8

Tyler, C. J., Sunderland, C., & Cheung, S. S. (2013). The effect of cooling prior to and during exercise on exercise performance and capacity in the heat: a meta-analysis. *British Journal of Sports Medicine*, 1–8. doi:10.1136/bjsports-2012-091739

Tyler, C. J., Wild, P., & Sunderland, C. (2010). Practical neck cooling and time-trial running performance in a hot environment. *European Journal of Applied Physiology*, *110*, 1063–74. doi:10.1007/s00421-010-1567-7

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