

Mild evaporative cooling applied to the torso provides thermoregulatory benefits during running in the heat

D. Filingeri¹, D. Fournet², S. Hodder¹, G. Havenith¹

¹Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Loughborough, UK, ²Thermal Sciences Laboratory, Oxyane Research, Villeneuve d'Ascq, France

Corresponding author: Davide Filingeri, Environmental Ergonomics Research Centre, Loughborough Design School, Loughborough University, Loughborough LE11 3TU, UK. Tel: +44 (0)1509 223022; E-mail: davidefilingeri@hotmail.it

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We investigated the effects of mild evaporative cooling applied to the torso, before or during running in the heat. Nine male participants performed three trials: control-no cooling (CTR), pre-exercise cooling (PRE-COOL), and during-exercise cooling (COOL). Trials consisted of 10-min neutral exposure and 50-min heat exposure (30 °C; 44% humidity), during which a 30-min running protocol (70% $\dot{V}O_{2\max}$) was performed. An evaporative cooling t-shirt was worn before the heat exposure (PRE-COOL) or 15 min after the exercise was started (COOL). PRE-COOL significantly lowered local skin temperature (T_{sk}) (up to -5.3 ± 0.3 °C) ($P < 0.001$), mean T_{sk} (up to

-2 ± 0.1 °C) ($P < 0.001$), sweat losses (-143 ± 40 g) ($P = 0.002$), and improved thermal comfort ($P = 0.001$). COOL suddenly lowered local T_{sk} (up to -3.8 ± 0.2 °C) ($P < 0.001$), mean T_{sk} (up to -1 ± 0.1 °C) ($P < 0.001$), heart rate (up to -11 ± 2 bpm) ($P = 0.03$), perceived exertion ($P = 0.001$), and improved thermal comfort ($P = 0.001$). We conclude that the mild evaporative cooling provided significant thermoregulatory benefits during exercise in the heat. However, the timing of application was critical in inducing different thermoregulatory responses. These findings provide novel insights on the thermoregulatory role of T_{sk} during exercise in the heat.

Human temperature regulation is challenged during exercise in the heat (Havenith, 2001). The increase in the metabolic heat production (resulting from exercising muscles) and the decrease in the gradient for heat loss to the environment (resulting from high ambient temperatures and humidity) translate into an increased rate of body heat storage (Tikuisis et al., 2002). This results into a quicker obtainment of the “critical” (i.e., ~ 40 °C) core temperature (T_c), which is suggested as one of the main limits to aerobic performance in the heat (González-Alonso & Teller, 1999). Elevated T_c can result in a decreased neural drive to muscle contraction (Nybo & Nielsen, 2001), as well as in cellular perturbations, which could disrupt metabolic and contractile processes within skeletal muscle (Febbraio, 2000). The limit that elevated T_c poses on aerobic performance is particularly evident within conditions of exercise performed at a fixed intensity and to fatigue, as opposed to self-paced exercise, in which behavioral adjustments (i.e., pacing) often prevent the obtainment of such physiological strains (Schlader et al., 2011c).

Pre-cooling strategies (i.e., cold water immersion, ice vests, ice/cold fluids ingestion) have been developed to counterbalance the effects of exercising under heat stress (Tyler et al., 2015). These methods have primarily focused on reducing T_c before exercise in order to increase the margin for metabolic heat production and

thus the time to reach the critical temperature (Marino, 2002). However, emerging evidence suggests that the role of elevated (> 35 °C) skin temperature (T_{sk}) is also critical in impairing aerobic performance under heat stress (Sawka et al., 2012). Elevated T_{sk} narrows the skin to core temperature gradient, thus increasing the skin blood flow requirements, and eventually resulting in an increased level of cardiovascular strain (Sawka et al., 2012). This is exacerbated by the competition for the available cardiac output between the blood flow required by the exercising muscles to meet the oxygen demands and the blood flow required by the skin to meet the demands of temperature regulation (i.e., heat dissipation to the environment) (González-Alonso et al., 2008). Also, heat-induced changes in T_{sk} influence perceptual and cutaneous-sensory feedback such as thermal sensation, comfort, and “sensation of fatigue” (Cheung, 2010), which have been proposed as critical determinants of pacing strategies during performance under heat stress (Tucker & Noakes, 2009; Schlader et al., 2011b). Therefore, in order to preserve performance under heat stress, keeping the skin cool during the exercise might be as important as a pre-exercise reduction in T_c (Schlader et al., 2011c).

Cooling methods, such as air- and water-cooled systems (Stephenson et al., 2007), garments made of phase-change materials (House et al., 2013), as well as

the use of menthol (Gillis et al., 2010), have been developed and shown to be potentially effective in preserving performance in the heat due to their effects on T_{sk} and thermal sensation (Hasegawa et al., 2005). The beneficial effects of these cooling strategies have been shown to vary largely according to the environmental conditions (i.e., the higher the heat load, the more beneficial the cooling), the duration of cooling (i.e., the longer the more beneficial), and most importantly, to the type and duration of exercise performed (i.e., cooling is more beneficial for endurance exercise performed for up to 60 min as opposed to single sprint exercise) (Wegmann et al., 2012). However, due to some specific disadvantages, such as weight of the systems, wearability of the garments, duration of the cooling effect (e.g., garments made of phase-change materials require large quantities of coolant to provide prolonged cooling) (Kenny et al., 2011), or side effects of menthol application (i.e., skin irritation), these methods still present numerous practical limitations (Tyler et al., 2015) and are therefore best suited to specific conditions (e.g., cooling methods with limited capacity are preferable for short-duration exercise under conditions of higher heat loads) (Kenny et al., 2011).

In this respect, evaporative cooling garments have recently received attention, as they could represent a potentially effective alternative to more traditional cooling methods (Webster et al., 2005; Bogerd et al., 2010). These lightweight garments induce mild cooling via the process of water evaporation. These are made of particular hydrophilic fabrics, which, if wetted, allow sustained water evaporation, thereby cooling the garment and the underlying skin. Although using the concept of mild evaporative cooling translates into the possibility to design cooling garments which are lightweight and practical, the limited empirical evidence on their physiological as well as perceptual (i.e., thermal comfort) effects makes any conclusion on these methods difficult to draw (Tyler et al., 2015).

Developing lightweight, thermally comfortable cooling methods, which can be effective in counteracting the thermal strain, has important practical implications not only for elite performance under heat stress but also in the context of amateur and recreational exercise. Individuals who enjoy outdoor sporting activities, such as running or cycling, encounter a variety of environmental conditions, some of which (e.g., heat) can significantly decrease their thermal comfort (Vanos et al., 2010). As the type and amount of physical activity performed has been shown to be influenced by the level of comfort achievable with the surrounding environment (Vanos et al., 2010), developing a practical cooling method, being able to reduce the thermal discomfort experienced while exercising in the heat, might have a positive impact on the activity levels of healthy individuals.

The first aim of this study was to investigate the physiological [i.e., heart rate (HR), T_c , mean and local T_{sk} , and

body sweat loss] and perceptual [thermal, wetness and comfort sensations, and (session) ratings of perceived exertion (RPE)] effects of a lightweight, short-sleeved garment which induced mild evaporative cooling of the torso, with the aim to provide thermoregulatory benefits during submaximal running in the heat [i.e., 30 °C ambient temperature (T_{air}) and 44% relative humidity (RH)]. In this respect, we hypothesized that the mild evaporative cooling applied to the torso would significantly lower local and mean T_{sk} , thus reducing total sweat production and thermal discomfort. The second aim of this study was to investigate the impact of varying the timing of cooling (i.e., wearing the garment before or during exercise) on the above-mentioned physiological and perceptual parameters. We hypothesized that applying the cooling during the exercise (i.e., when participants were already hyperthermic) would significantly lower the HR, the perceived exertion, and the overall level of thermal discomfort. Rapidly cooling the skin has been indeed shown to reduce the cardiovascular strain observed during exercise in the heat due to its effects on skin blood flow (Sawka et al., 2012). When exercising under heat stress, elevated T_c and T_{sk} pose a major challenge to the cardiovascular system due to an increased competition for the available cardiac output between the blood flow required by the exercising muscles to meet the oxygen demands and the blood flow required by the skin for heat dissipation to the environment (González-Alonso et al., 2008). As the increased cardiovascular strain limits aerobic performance (i.e., VO_{2max}) in the heat (i.e., due to a higher fractional VO_{2max} for any given power output) (Kenefick et al., 2010), and as skin blood flow changes as a function of T_{sk} (Cheuvront et al., 2010), rapidly cooling the skin was hypothesized to lower the cardiovascular strain by reducing the skin blood flow requirements for heat dissipation. In terms of performance benefits, reducing the cardiovascular challenge of exercising under heat stress could be beneficial to help maintain the adequate cardiac output required by the exercise, without a concurrent reduction in maximal aerobic power due to increased thermoregulatory demands (Kenefick et al., 2010). Finally, investigating the effects of varying the timing of cooling was considered relevant for its behavioral and perceptual effects. Reductions in T_{sk} during exercise in the heat (and the accompanying thermal sensations) have been previously shown to improve heat tolerance (Hasegawa et al., 2005) and to benefit performance (Schlader et al., 2011a). Also, due to the limited number of studies addressing this concept, cooling during exercise in the heat is an area that receives increasing attention (Tyler et al., 2015).

Materials and methods

Participants

Nine healthy male students [age 21 ± 2 years, height 179 ± 8 cm, body mass 80 ± 9 kg, body fat $8 \pm 3\%$, estimated maximum oxygen consumption (VO_{2max}) 54 ± 5 mL/min/kg] volunteered to

participate in this study. Inclusion criteria for this study were as follows: (1) no history of cardiovascular disease, sensory-related disorders, and muscle-skeletal injuries in the previous 12 months and (2) is physically active (i.e., performing at least 4–6 h of regular exercise per week for at least the last 12 months). All participants gave their informed consent for participation. The test procedure and the conditions were explained to each participant. The study design had been approved by the Loughborough University Ethics Committee and testing procedures were in accordance with the tenets of the Declaration of Helsinki. For a period of 48 h before each trial, the participants were instructed to refrain from strenuous exercise. Furthermore, the participants were asked not to consume caffeine or alcohol 24 h before each trial and to refrain from food 2 h before each trial.

Experimental design

Participants attended one preliminary session to determine their anthropometrical characteristics and aerobic capacity. Each participant's body mass, height and skinfold thickness (seven sites) were measured and recorded. For body composition calculations, American College of Sports Medicine's guidelines for exercise testing and prescription were used (Gordon, 2009). Body density was calculated using the following seven sites (chest, midaxillary, triceps, subscapular, abdomen, suprailiac, and thigh) equation:

$$\begin{aligned} \text{Body density} = & 1.112 - 0.00043499(\text{sum of seven skinfolds}) \\ & + 0.00000055(\text{sum of seven skinfolds})^2 \quad [1] \\ & - 0.00028826(\text{age}) \end{aligned}$$

A submaximal fitness test was performed to estimate individuals' aerobic fitness level (expressed as $\text{VO}_{2\text{max}}$) using the Astrand-Rhyming method (Gordon, 2009). The test was completed on a treadmill (Woodway Pps Med, Woodway Incorporated, Waukesha, Wisconsin, USA) in a thermo-neutral environment (20°C T_{air} , 40% RH) to prevent any thermal strain.

The preliminary session was then followed by three experimental trials, performed in a counterbalanced order: pre-exercise cooling (PRE-COOL), during-exercise cooling (COOL), and control-no cooling (CTR). The cooling trials differed in terms of the timing of applying the cooling: before or during the exercise protocol (i.e., 15 min after the exercise was initiated). All experimental trials consisted of 10-min thermo-neutral exposure (22°C T_{air} , 30% RH; 0.4 m/s environmental chamber's air velocity), followed by 50-min heat exposure (30°C T_{air} , 44% RH; 0.4 m/s environmental chamber's air velocity). During the heat exposure, participants first rested on a chair for 10 min to familiarize with the environmental conditions in which the exercise protocol would be performed and to allow stabilization of physiological values. Then, they performed a 5-min running warm up, at a speed corresponding to 50% of their individual $\text{VO}_{2\text{max}}$. This was followed by 25-min running performed at 70% of their individual $\text{VO}_{2\text{max}}$. During the exercise protocol, participants were exposed to a 2 m/s frontal air velocity. At the end of the exercise protocol, participants were asked to rest on a chair for 10 min before leaving the environmental chamber. A schematic outline of the experimental design is shown in Fig. 1.

Cooling garment

Cooling was applied through an evaporative cooling, short-sleeved, tight fitting t-shirt (Oxylane, Quecha Aquafreeze, Villeneuve d'Ascq, France), which, when worn, covered the torso and shoulders of the participants. The garment induced mild cooling via the process of water evaporation. This was made of a hydrophilic and hydrophobic structure. The outer layer enclosed a hydrophilic fabric and acted as a water reservoir and distributor,

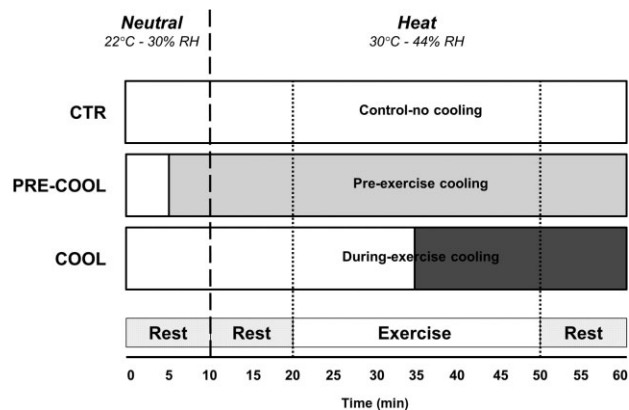


Fig. 1. A summary of the experimental protocol. CTR, no-cooling; PRE-COOL, pre-exercise cooling applied after 5 min of neutral exposure and before the exercise was performed; COOL, during exercise-cooling applied 15 min after the exercise was started. During all trials, participants first rested for 10 min in the neutral environment before moving to the hot environment. Here they rested for the first 10 min, then they started a 5-min running warm up performed at 50% of their $\text{VO}_{2\text{max}}$, followed by a 25-min running protocol performed at 70% of their $\text{VO}_{2\text{max}}$. After the exercise protocol, participants rested in the hot environment for 10 min.

whereas the inner layer, which enclosed a hydrophobic fabric, prevented the wearer from being in contact with the wet outer layer. By wetting the garment, leaving the hydrophilic fabric fully wetted, water starts to evaporate, thereby cooling the garment and the underlying skin. Twenty minutes before the exercise protocol was initiated, the cooling garment was fully dampened in water at ambient temperature ($\sim 22^\circ\text{C}$), then stored in a sealed container to limit evaporation of water to the environment, and maintained in the thermo-neutral environment until it had to be worn by participants. This procedure was repeated for all trials in order to assure consistency. As the dry and fully wet garment weighed 154 and 425 g, respectively, the corresponding water content of the wet garment was 271 g. The insulation value for the cooling garment was $0.041 \text{ m}^2/\text{K}/\text{W}$ (0.26 clo) and was determined using a thermal torso manikin with a uniform skin temperature of 34°C and environmental temperature of 35°C and 30% RH. During the CTR trial (as well as during the first part of the COOL trial), participants wore a reference short sleeved, tight fitting t-shirt (dry mass: 101 g) made of a hydrophilic fabric only (Oxylane, Kalenji Essential, Villeneuve d'Ascq, France). This covered the same areas as the cooling garment (i.e., torso and shoulders) and had an insulation value of $0.031 \text{ m}^2/\text{K}/\text{W}$ (0.20 clo).

Experimental protocol

Participants arrived at the laboratory 30 min before the time scheduled for the test to allow preparation procedures. Before they changed into shorts, socks, and running shoes, the participants were asked to void their bladder, and semi-nude body mass (i.e., only cotton underwear was worn) was recorded on a digital scale (Sartorius Yacoila, Sartorius AG, Gottingen, Germany; precision 0.01 g). Then, they were instructed to self-insert a rectal thermometer (Grant Instruments Ltd., Cambridge, UK) 10 cm beyond the anal sphincter for the measurement of T_{re} .

To estimate mean T_{sk} , five wireless temperature sensors (iButtons, Maxim, San Jose, California, USA) were taped to five skin sites (i.e., cheek, abdomen, upper arm, lower back, and back lower thigh) on the right side of the body to record local T_{sk} (1-min intervals). These five local T_{sk} measurements were used to estimate mean T_{sk} using the Houdas-5W equation (Houdas & Ring, 1982):

$$\begin{aligned} \text{Mean } T_{\text{sk}} = & (\text{check} \times 0.07) + (\text{abdomen} \times 0.175) \\ & + (\text{upper arm} \times 0.19) + (\text{lower back} \times 0.175) \quad [2] \\ & + (\text{back lower thigh} \times 0.39) \end{aligned}$$

To gain additional information on the local skin temperature changes occurring as a result of the cooling garment, the local T_{sk} of four representative skin sites directly exposed to the cooling (i.e., lateral chest, lateral abdomen, lateral upper, and lower back) was recorded with four supplementary skin thermistors (Grant Instruments), which were taped to the left side of the body. The reason for these supplementary local measurements was to gain additional information on the local T_{sk} changes occurring as a direct result of the cooling garment, being these often localized and transient, and thus potentially underestimated when only measurements of whole-body mean T_{sk} are considered (Tyler et al., 2015).

Skin and rectal temperature thermistors were connected to an Elitek/Grant 10 bit, 1000 series data logger (Grant Instruments) recording temperature at 10-s intervals. Finally, each participant wore a Polar HR monitor (Polar Electro Oy, Kempele, Finland), which recorded HR at 10-s intervals.

After preparation, participants (who were wearing only shorts, socks, and running shoes) moved into the thermo-neutral environment, where they rested on a chair for 10 min. As soon as they assumed a seated position, they were asked to rate their thermal, wetness, and comfort sensations, while recording of the physiological parameters was started. Three modified rating scales were used to record individual thermal, wetness, and thermal comfort sensations: a 13-point thermal sensation scale (i.e., -6, very cold; -4, cold; -2, slightly cool; 0, neutral; +2, slightly warm; +4, hot; +6, very hot); a 13-point wetness perception (i.e., -6, dripping wet; -4, wet; -2, slightly wet; 0, neutral; +2, slightly dry; +4, dry; +6, very dry); a 13-point thermal comfort scale (i.e., -6, very uncomfortable; -4, uncomfortable; -2, slightly uncomfortable; 0, neutral; +2, slightly comfortable; +4, comfortable; +6, very comfortable) (Olesen & Brager, 2004). No descriptors were applied to intermediate scores (i.e., -5; -3; -1; +1; +3; +5). The participants familiarized with the scales during the preliminary session.

After 5 min of thermo-neutral exposure, depending on the experimental trial, participants wore the reference garment (CTR and COOL trials) or the evaporative cooling garment (PRE-COOL trial), and thermal, wetness, and comfort sensations were immediately recorded. Upon completion of the 10-min thermo-neutral exposure, the participants moved into the environmental chamber set for the heat exposure. During the first 10-min exposure, the participants rested on a chair to familiarize with the environmental conditions in which the exercise protocol would be performed and to allow stabilization of physiological values. During this time and throughout the rest of the test, individual sensations were recorded every 5 min. Following the acclimation period, the participants moved to the treadmill to perform a 5-min warm up (50% $\text{VO}_{2\text{max}}$), followed by 25 min running (70% $\text{VO}_{2\text{max}}$), while exposed to a 2 m/s frontal air velocity. On average, the 50% and 70% $\text{VO}_{2\text{peak}}$ running speeds corresponded to 7 ± 1 and 10 ± 1 km/h, respectively (these values represent mean $\pm$ standard deviation). During the exercise protocol, the participants were asked to rate their RPE at 5-min intervals using the 6–20 Borg's scale (Borg, 1982). During the COOL trial only, after 15 min from when the exercise was initiated, the participants changed from the reference to the cooling garment, which was then kept on until the end of the trial.

Upon completion of the 30-min running protocol, the participants were asked to move to a chair and rest in the warm environment for 10 min. At the end of the 10-min post-exercise recovery, they were asked to score a session RPE, corresponding to the overall perceived effort the session performed had required (Foster et al., 2001). During all trials, water at room temperature was provided *ad libitum* and the amount consumed was recorded.

Finally, semi-nude body mass (i.e., only cotton underwear was worn) was recorded after each trial and body sweat loss was adjusted for water intake.

Statistical analysis

In the present study, the independent variables were the condition (i.e., CTR, PRE-COOL, and COOL) and time. The dependent variables were HR, T_{c} , mean and local T_{sk} , body sweat loss, thermal sensation and comfort, wetness perception, and RPE. Parametric statistics were used to investigate the main effects and interactions of the variables during the 30-min exercise protocol. Baseline, post-heat adaptation, and post-exercise data were also analyzed and reported. Data were first tested for normality of distribution and homogeneity of variance using Shapiro-Wilk and Levine's tests, respectively. Then data were analyzed by a two-way repeated measures analysis of variance (ANOVA), with condition and time as repeated measures variables. Body mass loss data were analyzed by a one-way repeated measures ANOVA, with condition as repeated measures variable. Huynh-Feldt or Greenhouse-Geisser corrections were undertaken to adjust the degrees of freedom for the averaged tests of significance. When a significant main effect was found, Tukey's post-hoc analyses were performed. In all analyses, $P < 0.05$ was used to establish significant differences. Estimated marginal means and 95% confidence intervals were used to investigate the main effects and interactions of the variables. Observed power was computed using $\alpha = 0.05$. Data are reported as mean $\pm$ standard error. Statistical analysis was performed using IBM SPSS Statistics 19 (IBM, Armonk, New York, USA).

Results

Heart rate

Mean HR values for each trial are shown in Fig. 2(a). A significant main effect of condition ($F = 4.18_{(2, 16)}$, $P = 0.03$; observed power = 0.6) and time ($F = 124_{(1.17, 9.37)}$, $P < 0.001$; observed power = 1) was found on the HR values recorded during the exercise protocol. Overall, the average HR recorded during the COOL and PRE-COOL trials were, respectively, 7 ± 3 and 3 ± 2 bpm lower than in the CTR trial. A significant interaction between condition and time was also found ($F = 3.17_{(10, 80)}$, $P = 0.002$; observed power = 1). Post-hoc analyses indicated that during the COOL trial, 20 min after the exercise protocol was started, the HR was significantly lower than in the CTR (-11 ± 2 bpm, $P = 0.002$) and PRE-COOL trials (-7 ± 2 bpm, $P = 0.004$). Post-exercise HR values were found to differ significantly between conditions, with the values recorded during the COOL trial being 10 ± 3 ($P = 0.004$) and 6 ± 2 bpm ($P = 0.013$) significantly lower than in the CTR and PRE-COOL trials, respectively.

T_{c}

Mean T_{c} values for each trial are shown in Fig. 2(b). No significant main effect of condition was found on the T_{c} values recorded during the exercise protocol ($F = 0.6_{(2, 16)}$, $P = 0.53$; observed power = 0.14). Only a significant main effect of time was observed ($F = 176.5_{(5, 40)}$,

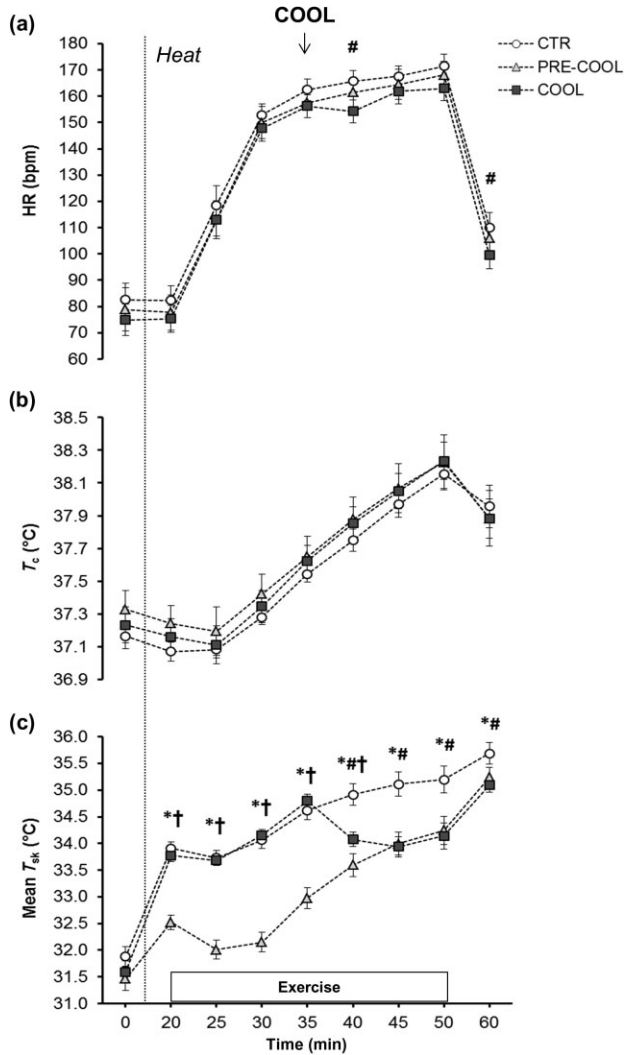


Fig. 2. Mean ($\pm$ standard error) heart rate (HR) (a), T_c (b), and T_{sk} (c) values as recorded during the CTR (no-cooling), PRE-COOL (pre-exercise cooling), and COOL (during-exercise cooling) trials. The application of cooling during exercise (15 min after the exercise was started, COOL trial) is marked by an arrow. * (CTR $\neq$ PRE-COOL), # (CTR $\neq$ COOL), and † (PRE-COOL $\neq$ COOL) refer to significant differences between trials as computed using $P < 0.05$.

$P < 0.001$; observed power = 1), with an average increase in T_c of 1 ± 0.1 °C from a baseline value of 37.2 ± 0.1 °C. No interaction between time and condition was found ($F = 0.84_{(10, 80)}$, $P = 0.58$; observed power = 0.4). Post-exercise T_c values did not differ among conditions ($F = 0.15_{(2, 16)}$, $P = 0.85$; observed power = 0.4).

Mean T_{sk}

Mean T_{sk} values for each trial are shown in Fig. 2(c). A significant main effect of condition ($F = 74.2_{(2, 16)}$, $P < 0.001$; observed power = 1), time ($F = 41.67_{(1.33, 10.65)}$, $P < 0.001$; observed power = 1), and a significant interaction between these two ($F = 67_{(10, 80)}$, $P < 0.001$;

observed power = 1) was found on mean T_{sk} . At the end of the familiarization with the hot environment period, and as a result of the application of the cooling garment, the mean T_{sk} was significantly lower in the PRE-COOL than in the CTR (-1.4 ± 0.1 °C, $P < 0.001$) and COOL trials (-1.2 ± 0.1 °C, $P < 0.001$). No differences were found between CTR and COOL trials (0.13 ± 0.1 °C, $P = 0.22$). During the exercise protocol, the mean T_{sk} was significantly lower in the PRE-COOL than in the CTR trial (from a minimum of -0.9 ± 0.1 to a maximum of -2 ± 0.1 °C). When compared to the COOL trial, PRE-COOL mean T_{sk} was significantly lower up until 20 min from when the exercise was started. From this point, and until the end of the exercise protocol, COOL and PRE-COOL mean T_{sk} values did not differ significantly. These results indicated that the application of the cooling during the exercise (COOL trial) reduced mean T_{sk} to values similar to the ones observed when the cooling was applied prior to start exercising (PRE-COOL trial). Post-exercise mean T_{sk} was found to differ significantly between conditions, with the values recorded during the PRE-COOL and COOL trials being, respectively, 0.4 ± 2 ($P = 0.045$) and 0.6 ± 2 °C ($P = 0.018$) significantly lower than in the CTR trial. No differences were found between PRE-COOL and COOL trials ($P = 0.28$).

Local T_{sk}

Local T_{sk} values for each body region (i.e., chest, abdomen, upper, and lower back) are shown in Fig. 3. Local T_{sk} showed similar trends among all the regions investigated. These patterns were similar to the one observed for the mean T_{sk} . Before starting the exercise protocol, local T_{sk} was significantly lower in the PRE-COOL trial than in the CTR and COOL trials for all the regions investigated. These differences varied in a range of -1.9 ± 0.2 °C (i.e., abdomen) to -5.3 ± 0.3 °C (i.e., chest). During the exercise protocol, local T_{sk} was significantly lower in the PRE-COOL trial than in the CTR and COOL trials up until 15 min from when the exercise was started. Notably, chest local T_{sk} recorded in the PRE-COOL trial showed the greatest regional difference among the regions investigated. Specifically, 10 min after the exercise was started, chest local T_{sk} was 5.3 ± 0.3 °C lower than during the CTR and COOL trials. From 20 min onward and until the end of the exercise protocol, COOL and PRE-COOL local T_{sk} values did not differ significantly. This was observed for all the regions but the chest. Chest local T_{sk} was significantly lower in the COOL than in the PRE-COOL from 25 min after the exercise was started until the end of the test. Post-exercise PRE-COOL and COOL local T_{sk} values were found to be significantly lower than CTR only for the chest and abdomen regions.

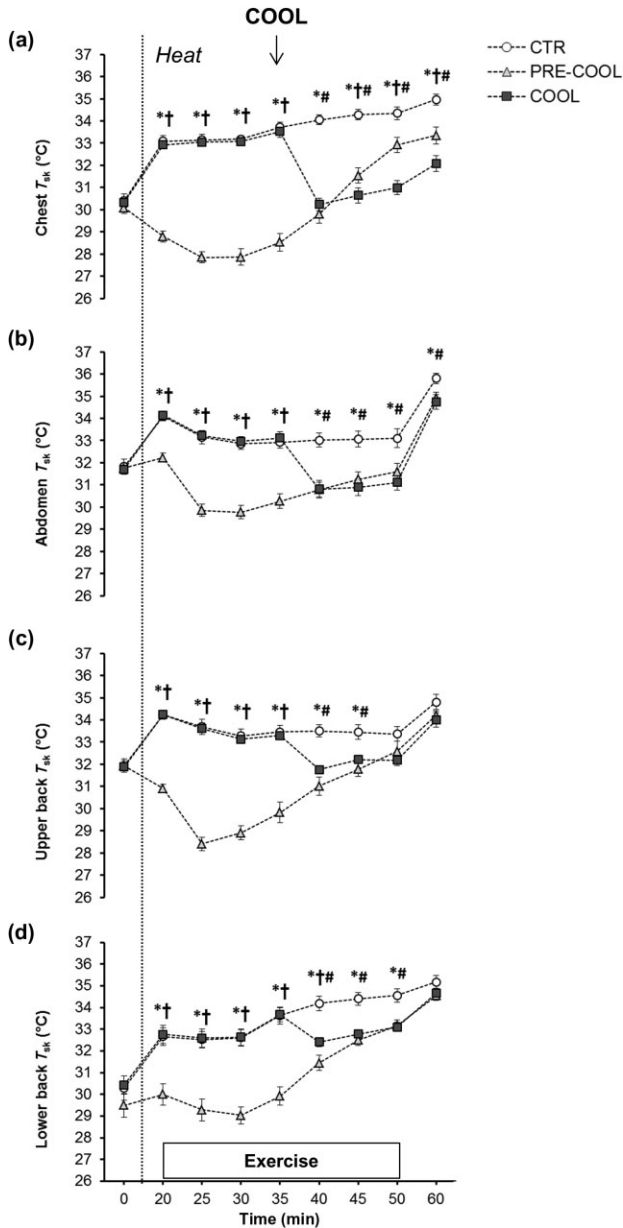


Fig. 3. Mean ($\pm$ standard error) local T_{sk} values for chest (a), abdomen (b), upper (c), and lower back (d) as recorded during the CTR (no-cooling), PRE-COOL (pre-exercise cooling), and COOL (during-exercise cooling) trials. The application of cooling during exercise (15 min after the exercise was started, COOL trial) is marked by an arrow. * (CTR $\neq$ PRE-COOL), # (CTR $\neq$ COOL), and † (PRE-COOL $\neq$ COOL) refer to significant differences between trials as computed using $P < 0.05$.

Body sweat loss

Water ingestion during the exercise protocol did not differ between CTR (226 ± 30 g), PRE-COOL (213 ± 42 g), and COOL trials (181 ± 32 g) ($F = 0.9_{(2, 16)}$, $P = 0.4$; observed power = 0.2). A significant main effect of condition was found on body sweat loss ($F = 2.5_{(2, 16)}$, $P = 0.025$; observed power = 0.7). Post-hoc analysis indicated that the body sweat loss was significantly lower ($P = 0.018$) in the PRE-COOL (630 ± 100 g) than

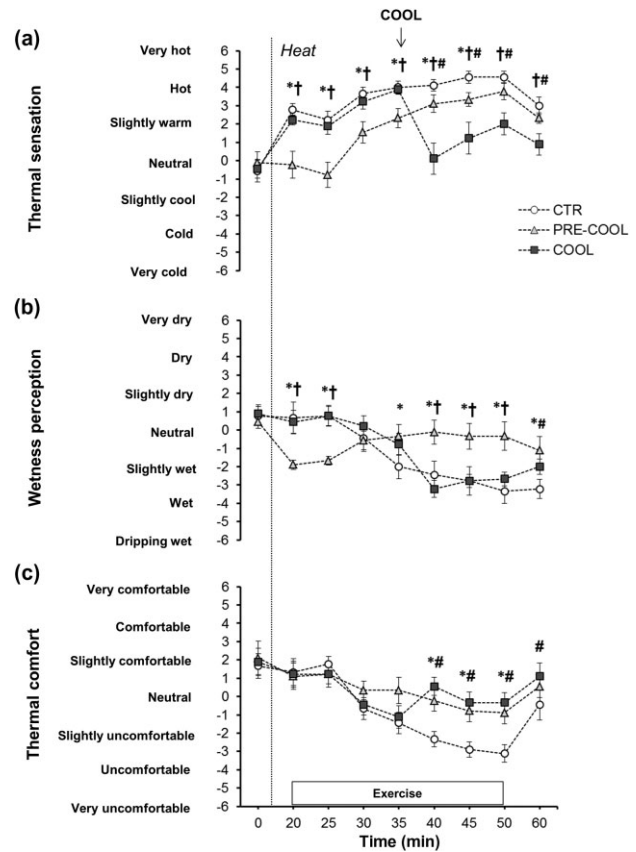


Fig. 4. Mean ($\pm$ standard error) thermal sensation (a), wetness perception (b), and thermal comfort (c) values as recorded during the CTR (no-cooling), PRE-COOL (pre-exercise cooling), and COOL (during-exercise cooling) trials. The application of cooling during exercise (15 min after the exercise was started, COOL trial) is marked by an arrow. * (CTR $\neq$ PRE-COOL), # (CTR $\neq$ COOL), and † (PRE-COOL $\neq$ COOL) refer to significant differences between trials as computed using $P < 0.05$.

in the CTR condition (775 ± 90 g). No significant differences ($P = 0.4$) were found between PRE-COOL and COOL trials (768 ± 85 g).

Thermal sensation

Mean thermal sensation scores for each trial are shown in Fig. 4(a). A significant main effect of condition ($F = 9.8_{(2, 16)}$, $P = 0.002$; observed power = 0.9) and time ($F = 26.92_{(5, 40)}$, $P < 0.001$; observed power = 1) was found on the thermal sensations. Overall, the average thermal sensations recorded during the PRE-COOL, COOL, and CTR trials were 2.2 ± 0.4 (i.e., “slightly warm”), 2 ± 0.5 (i.e., “slightly warm”), and 3.8 ± 0.3 (i.e., “hot”), respectively. Also, a significant interaction between condition and time was found ($F = 18.1_{(10, 80)}$, $P < 0.001$; observed power = 1). Post-hoc analyses indicated that thermal sensations were significantly lower in the PRE-COOL than in the CTR and COOL trials up until 15 min from when the exercise was started. From 20 min onward and until the end of the exercise protocol,

COOL thermal sensations were significantly lower than in the PRE-COOL and CTR trials. Post-exercise thermal sensations were found to differ significantly between conditions, with scores recorded during the COOL trial being significantly lower than in the PRE-COOL ($P = 0.048$) and CTR ($P = 0.013$) trials. No differences were found between PRE-COOL and CTR trials ($P = 0.24$). Expressed in terms of semantic labels, COOL thermal sensations corresponded to “neutral” to “slightly warm,” PRE-COOL thermal sensations corresponded to “slightly warm” to “hot,” and CTR thermal sensations corresponded to “hot.”

Wetness perception

Mean wetness perception scores are shown in Fig. 4(b). No significant main effect of condition ($F = 3.15_{(2, 16)}$, $P = 0.07$; observed power = 0.5), a significant effect of time ($F = 13.07_{(2, 19, 17.5)}$, $P < 0.001$; observed power = 1), and a significant interaction between condition and time ($F = 12.35_{(10, 80)}$, $P < 0.001$; observed power = 1) were found on the wetness perceptions. The perceptual scores indicated that during the PRE-COOL trial, wetness perception was initially “slightly wet” when the cooling garment was worn and then “neutral” during the rest of the trial. On the contrary, during the CTR and COOL trials, an opposite trend was observed, with a significant increase in the level of wetness perceived from the beginning until the end of the trials (i.e., from “neutral” to “slightly wet”). Post-exercise wetness perceptions were found to differ significantly between conditions ($P = 0.025$). Expressed in terms of semantic labels, PRE-COOL and COOL wetness perceptions corresponded to “neutral” to “slightly wet,” whereas CTR wetness perceptions corresponded to “slightly wet” to “wet.”

Thermal comfort

Mean thermal comfort scores for each trial are shown in Fig. 4(c). A significant main effect of condition ($F = 11.2_{(2, 16)}$, $P = 0.001$; observed power = 1) and time ($F = 12.05_{(1.9, 15.5)}$, $P < 0.001$; observed power = 1) was found on the thermal comfort. Overall, the average thermal comfort recorded during the PRE-COOL, COOL and CTR trials were 0 ± 0.4 (i.e., “neutral”), -0.7 ± 0.5 (i.e., “neutral” to “slightly uncomfortable”) and -1.4 ± 0.4 (i.e., “neutral” to “slightly uncomfortable”), respectively. Also, a significant interaction between condition and time was found ($F = 6.4_{(10, 80)}$, $P < 0.001$; observed power = 1). Post-hoc analyses indicated that, as compared to the CTR trial, thermal comfort was significantly improved in the PRE-COOL and COOL trials between 20 and 30 min from when the exercise was started. Post-exercise thermal comfort was found to differ significantly between conditions, with participants being more comfortable at the end of the COOL than the CTR trial ($P = 0.01$). Expressed in terms

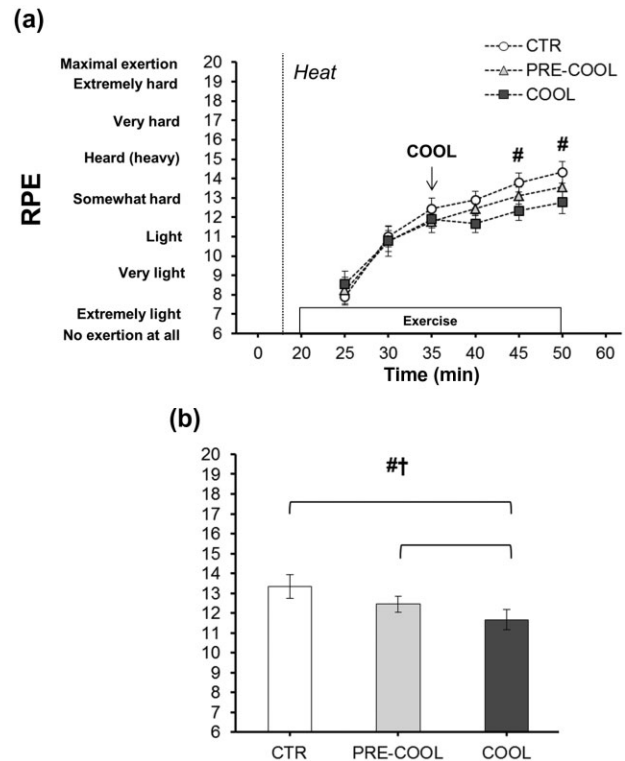


Fig. 5. Mean ($\pm$ standard error) ratings of perceived exertion (RPE) (a) and session RPE values (b) as recorded, respectively, during the exercise phase and 10 min after the exercise was terminated for the CTR (no-cooling), PRE-COOL (pre-exercise cooling), and COOL (during-exercise cooling) trials. In panel (a), the application of cooling during exercise (15 min after the exercise was started, COOL trial) is marked by an arrow. * (CTR $\neq$ PRE-COOL), # (CTR $\neq$ COOL), and † (PRE-COOL $\neq$ COOL) refer to significant differences between trials as computed using $P < 0.05$.

of semantic labels, COOL thermal comfort corresponded to “neutral” to “slightly comfortable,” whereas CTR thermal comfort corresponded to “neutral” to “slightly uncomfortable.”

RPE

Mean ratings of perceived exertion for each trial are shown in Fig. 5(a). No significant main effect of condition ($F = 2.09_{(2, 16)}$, $P = 0.15$; observed power = 0.4), a significant effect of time ($F = 79.32_{(2, 16)}$, $P < 0.001$; observed power = 1), and a significant interaction between condition and time ($F = 3.4_{(10, 80)}$, $P = 0.001$; observed power = 1) were found on ratings of perceived exertion. Post-hoc analyses indicated that, during the COOL trial, RPE scores were significantly lower than during the CTR trial, both after 25 ($P = 0.024$) and 30 min ($P = 0.001$) from when the exercise was started. The analysis of session RPE data indicated a significant effect of condition ($F = 18.2_{(1.2, 9.9)}$, $P < 0.001$; observed power = 1). Post-hoc analyses indicated that session RPE recorded after the COOL trial was significantly

lower than after the PRE-COOL ($P = 0.002$) and CTR ($P = 0.001$) trials (Fig. 5(b)).

Discussion

The aims of this study were to investigate the physiological and perceptual effects of applying mild evaporative cooling to the torso during moderate exercise in the heat, and to investigate whether varying the timing of cooling (i.e., before or during exercise) had an impact on the same physiological and perceptual parameters.

The outcomes of this study indicated that, when applied before exercise (PRE-COOL trial) and when compared to the CTR trial, the evaporation-induced mild cooling of the torso significantly lowered both local (from -1.9 ± 0.2 up to -5.3 ± 0.3 °C) and mean T_{sk} (from -0.9 ± 0.1 up to -2 ± 0.1 °C). This was accompanied by significantly lower body sweat loss. Also, significantly “less hot” thermal sensations and a significant reduction in thermal discomfort were reported during the PRE-COOL trial. Furthermore, this study has shown that when applied during exercise (COOL trial), the evaporation-induced mild cooling significantly decreased local and mean T_{sk} to an extent similar to the one observed during the PRE-COOL trial from the time of application. No effects were observed on body sweat loss in this case. However, when compared to the CTR trial, applying the cooling when participants were already exercising significantly lowered the HR. Although its impact on HR was limited to the initial 10 min of application, on the perceptual side, cooling applied during exercise lowered thermal heat sensations, decreased the thermal discomfort, and also reduced the perceived exertion for up to 25 min from when cooling was initially applied. This resulted in the COOL trial being perceived as the overall least demanding experimental trial.

In summary, the outcomes of this study indicated that, despite its low cooling power (compared to, e.g., ice vests), due to its main effect on mean and local T_{sk} , the mild evaporative cooling method tested in this study provided significant thermoregulatory benefits during exercise in the heat. Furthermore, these findings indicated that varying the timing of cooling had a major impact on the magnitude of the physiological (e.g., HR) as well as perceptual (e.g., RPE) responses. These outcomes have both a fundamental as well as an applied significance.

As no differences in T_c were observed among the experimental conditions, the outcomes of this study provide novel insights on the role played by T_{sk} in influencing the physiological and perceptual responses occurring during exercise in the heat. With regard to pre-cooling, this was observed to significantly improve thermal sensation and comfort during exercise in the heat, regardless of the rate of increase in T_c . T_{sk} seems therefore to have a larger contribution than core, in

characterizing thermal sensation and comfort during exercise in the heat. This is in line with classic studies suggesting skin, more than core temperature, to drive thermal comfort in resting individuals (Gagge et al., 1967). Furthermore, this is aligned to more recent studies, which have shown that sensory feedback arising from changes in T_{sk} can significantly contribute to behavioral adjustments (e.g., pacing strategies) in temperature regulation while exercising (Schlader et al., 2011a, b, c). Thermal sensations arising from variations in T_{sk} seem indeed to initiate behavioral thermoregulation prior to any change in T_c . This is suggested as an anticipatory response to prevent the activation of autonomic thermoregulatory responses (i.e., sweating or shivering) and to maintain heat balance (Schlader et al., 2011a,b,c).

In the present study, it was also found that pre-cooling significantly reduced the body sweat loss (-143 ± 40 g), regardless of the rate of increase in T_c . This result seems to be aligned to the ones reported by Webster et al. (2005) and Hasegawa et al. (2005) who have, respectively, shown that wearing a cooling vest (for 35–50 min) can significantly reduce the total sweat losses (i.e., -100 g when compared to no cooling) during exercise in the heat. A possible explanation to the lower sweat loss could be that the lower rate of increase in body heat content resulting from the pre-cooling intervention translated into lower evaporative requirements for heat balance, thus inducing a significantly lower sweat production (Gagnon et al., 2013). Alongside this change in the central thermoregulatory drive, significant changes in local T_{sk} (such as the ones observed in this study on the chest, abdomen, upper, and lower back) could have also contributed to a significant reduction in local sweat rates. In this respect, evaporation-based local skin cooling has been previously shown to affect local sweating response in the early stages of exercise (Kondo et al., 1997) due to possible changes in the amount of transmitter substance being released at the neuroglandular junction for each nerve impulse (MacIntyre, 1968). As the torso is among the most active body regions in terms of sweat production (Smith & Havenith, 2012), a reduction in the torso sweat production could have contributed significantly to the reduction in the total body sweat loss recorded during the PRE-COOL trial. This hypothesis was perceptually matched by the significantly “less wet” wetness perceptions reported by participants during the exercising phase of the PRE-COOL trial.

From an applied point of view, the fact that pre-cooling significantly reduced body sweat loss is of interest for its potential implications in the context of limiting the amount of fluid loss and thus the rate of dehydration when exercising in the heat. Indeed, although sweating represents the main avenue for heat loss to the environment under heat stress, and should be therefore encouraged to limit core overheating under conditions that permit full evaporation (Bain et al., 2012), when the skin reach sweat saturation (i.e., maximal skin wetness)

(Gagge, 1937) and sweat starts to drip off the skin, any further sweating does not contribute to any further heat loss (i.e., reduced evaporative efficiency of sweating) (Candas et al., 1979), but only to an increase in fluid loss and thus dehydration (Bain et al., 2012). As elevated skin temperature and dehydration have been shown to have a detrimental and interactive effect on aerobic performance (Kenefick et al., 2010), it is therefore clear how a reduction in both T_{sk} and sweat loss (i.e., when this is no longer efficient) is of fundamental importance in order to preserve homeostasis and thus support performance in the heat.

With regard to the application of cooling during exercise in the heat, we observed that suddenly cooling the skin (mean T_{sk} change of $\sim 1^\circ\text{C}$) of exercising individuals resulted in significantly lowered HR, perceived exertion, and the resulting session RPE, regardless of the rate of increase in T_c . The changes in the HR could be explained by the effect of skin cooling in reducing the skin-muscle competition for the available cardiac output (Shaffrath & Adams, 1984). It was indeed hypothesized that by suddenly lowering T_{sk} , the skin blood flow requirements for temperature regulation would be also suddenly lowered (Sawka et al., 2012), thus resulting in a reduced cardiovascular strain. In this respect, by lowering T_{sk} , the resulting increase in the core to skin heat gradient facilitated the heat losses and therefore contributed to further decrease the cardiovascular strain and ultimately the HR. Although the effect on HR was short-lived (i.e., only 10 min from cooling was applied), this outcome confirms the role of T_{sk} as being critical in the modulation of the cardiovascular response during exercise in the heat (Nybo, 2008). Also, this outcome indicates that the manipulation of T_{sk} can be used as a potential method to modulate the cardiovascular challenge of exercising under heat stress, thus helping in preserving maximal aerobic power during exercise under heat stress (Kenefick et al., 2010), at least within short-duration exercise conditions.

It is of interest that the physiological impact of suddenly cooling the skin translated into a significant decrease in the perceived exertion during the exercise, regardless of changes in T_c . This fact was also confirmed by the session perceived effort, which was the lowest when cooling was applied during exercise. This finding highlights the complex nature of RPE and indicates that this conscious perception results from the integration of sensory inputs arising not only from systems such as the cardiovascular and musculoskeletal (Crewe et al., 2008) but also from the skin.

When compared to each other, the PRE-COOL and COOL interventions resulted in different physiological and perceptual responses. This could be due to the overall magnitude and different duration of the two experimental interventions. The PRE-COOL intervention was beneficial in terms of lowering mean T_{sk} (and related thermal sensations and comfort) and the body

sweat loss but it did not have any significant effect on the HR and RPE. The absence of an effect on the HR during the PRE-COOL trial could be due to the mild nature of the cooling used for this study. Previous studies have shown that greater cooling (i.e., able to significantly lower T_c) is indeed needed to result in a significant and prolonged attenuation of the cardiovascular strain resulting from the heat exposure (Marino, 2002; Hasegawa et al., 2005). Based on the linear relationship between RPE and HR (Borg, 1982), the mild effect of this type of cooling on the cardiovascular response could also explain why during the PRE-COOL trial, the RPE was not significantly lowered. The COOL intervention was beneficial in terms of lowering mean T_{sk} (and related thermal sensations and comfort), HR, and RPE, but it did not have any effect on the body sweat loss. As during the COOL trial, the cooling was applied only for the last 25 min of the trial (as opposed to the 55-min application of the PRE-COOL trial), this might have therefore not been sufficient to significantly reduce the sweat production.

In summary, these results indicate that the magnitude as well as the timing (PRE-COOL vs COOL) and duration of the cooling intervention (i.e., 55 min vs 25 min) could have played a role in the different thermoregulatory responses observed during the different experimental trials. Furthermore, these outcomes highlighted the important role of cutaneous thermoreceptors and T_{sk} in body temperature regulation, thermal sensation, and comfort during exercise under heat stress.

We conclude that the mild evaporative cooling method used in this study can provide significant thermoregulatory benefits during exercise in the heat by significantly lowering mean and local T_{sk} as well as thermal discomfort. We have also shown that the timing of application of mild cooling (prior vs during exercise) can significantly change the magnitude of the physiological as well as perceptual benefits occurring during exercise in the heat. Cooling the skin prior to exercise resulted in significantly reduced sweat production and overall thermal discomfort experienced. Suddenly cooling the skin during the exercise resulted in significantly lowered heart rate, as well as the overall thermal discomfort and perceived exertion. These findings provide fundamental insights on the role of skin temperature and thermal comfort in the thermoregulatory processes occurring when exercising under heat stress. Also, these open potential applications of a newly developed and practical mild evaporative cooling method within elite and recreational sport contexts.

In this respect, it has to be highlighted that the practical applications and potential benefits of such mild evaporative cooling garments should be carefully considered in light of the exercise modality performed, the environmental conditions, and the resulting thermal load. As previously reported (see Wegmann et al., 2012), the beneficial effects of external cooling when exercise is

performed in the heat can vary largely, particularly across different exercise modalities. For example, due to the greater thermal stress posed by repeated sprint performance (e.g., intermittent exercise) as opposed to single sprint activities performed in hot conditions, the possibility of investigating the effects of such cooling garment in sports such as e.g., football, could be of interest, as cooling has been already shown to be beneficial for intermittent exercise performed under high thermal loads (Wegmann et al., 2012). From an applied point of view, this seems very relevant in light of the recent 2014 FIFA Football World Cup and of the introduction of cooling breaks, used to reduce the risk of heat-related injuries during those matches performed in high ambient temperatures and humidity (see e.g., BBC SPORT 2014 FIFA WORLD CUP, <http://www.bbc.co.uk/sport/0/football/28075216>). In this context, the practicality of the lightweight cooling method presented in this study, as well as the possibility to change the timing of wetting as well as of re-wetting the garment (e.g., during “cooling breaks”), could represent an advantage in maximizing the performance benefits of such novel method during sport competitions (e.g., football matches) performed under heat stress. Hence, further studies investigating specific performance benefits of this novel method are warranted and recommended.

Perspectives

The mild evaporative cooling method we tested has important practical implications. This method could be integrated with more traditional pre-cooling strategies, which aim to lower T_{c} prior to exercise (e.g., ice slurry ingestion). Also, this method could be used alone to manipulate T_{sk} prior as well as during exercise (e.g., by changing the timing of wetting and of re-wetting the

garment), the latter possible given the low weight of the garment. This could be considered for those sports in which the pacing strategy is essential to maximize performance (e.g., cycling and running). Also, this could be useful for intermittent exercise-based sports (e.g., football) when the environmental conditions pose a greater thermal load than normal. Finally, reducing the sweat loss by cooling the skin (as observed in this study) could attenuate the rate of dehydration during prolonged performance in the heat. This as well as the possibility to lower thermal discomfort during exercise in the heat could contribute to performance benefits in competitive sport, as well as could increase the activity levels of healthy individuals performing in the heat.

Key words: Cooling garment, heat stress, thermoregulation, skin temperature, exercise.

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