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Conductive and evaporative pre-cooling lowers mean skin temperature and improves time trial performance in the heat.

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Running head: Conductive and evaporative pre-cooling enhances performance

Abstract

Self-paced endurance performance is compromised by moderate to high ambient temperatures which are evident in many competitive settings. It has become common place to implement pre-cooling prior to competition in an attempt to alleviate perceived thermal load and performance decline. The present study aimed to investigate pre-cooling incorporating different cooling avenues via either evaporative cooling alone and/or in combination with conductive cooling on cycling time trial performance. Ten trained male cyclists completed a time trial on three occasions in hot (35˚C) ambient conditions with the cooling garment prepared by i) immersion in water (COOL, evaporative), ii) immersion in water and frozen (COLD, evaporative and conductive) or iii) no pre-cooling (CONT). COLD improved time trial performance by 5.8% and 2.6% vs CONT and COOL, respectively (both $p<0.05$). Power output was 4.5% higher for COLD vs CONT ($p<0.05$). Mean skin temperature was lower at the onset of the time trial following COLD compared to COOL and CONT (both $p<0.05$) and lasted for the first 20% of the time trial. Thermal sensation was perceived cooler following COOL and COLD. The combination of evaporative and conductive cooling (COLD) had the greatest benefit to performance, which is suggested to be driven by reduced skin temperature following cooling.

Keywords

Evaporative cooling, phase change, ice-vest, thermoregulation, heat stress, heat balance

Introduction

Endurance exercise performance progressively deteriorates as the surrounding ambient temperature increases (Galloway and Maughan, 1997), which is further exacerbated when combined with increasing humidity (Watson et al., 2011). It appears that there is a strong link between increases in thermoregulatory strain, due to elevations in both metabolic and ambient heat, and impaired endurance performance. The attainment of a critical core body temperature of approximately 40˚C has been proposed as the main factor limiting endurance performance in hot environments (Gonzalez-Alonso et al., 1999). It is suggested that this critical core temperature ($T_{c)}$ is used as a set point, around which the body bases pace judgment alteration and effort perception in an attempt to complete a given task as quickly as possible without achieving a dangerously high core temperature (Marino, 2004; Schlader et al 2011a). However, recent work on self-paced exercise indicates that a T_c of >40˚C may not be critical in performance determination (Ely et al., 2009), particularly when considering self-paced rather than fixed intensity exercise.

Increases in skin temperature in response to exercise have been suggested to be an important factor in regulating endurance performance in warm ambient conditions (Kenefick et al., 2010; Sawka et al., 2012). In hot conditions, fatigue has been shown to be less reliant on high absolute core temperature, but more dependent on hot skin temperature (>35˚C), as fatigue occurred at relatively low core temperatures of approximately 38.5˚C (Latzka et al., 1998; Montain et al., 1994).

Ways to alleviate the deleterious effect excessive thermal strain has on performance has received wide-ranging focus. One of the most widely adopted practices is that of pre-cooling. Pre-cooling can be applied externally using a variety

of methods (Bogerd et al., 2010; Kay et al., 1999), internally via the use of cold or ice slurry beverages (Ross et al., 2013), or via combinations of pre-cooling methods (Ross et al., 2010). All of these have the aim of reducing core temperature prior to the onset of exercise, thereby increasing the body's ability to store endogenous and exogenous heat and consequently improving exercise performance (Ross et al., 2013).

Several previous studies have demonstrated that pre-cooling prior to exercise has a beneficial effect on performance (for a review see Tyler et al., 2013). However, few studies consider ways in which pre-cooling may be influenced by the type of cooling (e.g. evaporative, conductive, convective) and the effect this may have on performance. Furthermore, we have shown that there are regional differences in heat exchange over the body, with the hands and torso providing a particularly effective location for targeting heat exchange with the surrounding environment (Faulkner, 2012). The effectiveness of hand and forearm cooling at reducing heat strain (Giesbrecht et al., 2007) and performance (Kwon et al., 2010) has been shown previously, however these studies have only used hand/forearm cooling in isolation with devices which are impractical for field use and competition. To our knowledge, no studies combine the use of cooling-vests with hand and forearm cooling to examine the effectiveness at reducing core temperature and improving performance in hot ambient conditions using different combinations of evaporative and conductive cooling. Therefore, it was the aim of this study to investigate the effect of a novel combination of hand, forearm and torso pre-cooling via either mainly evaporative or a combination of evaporative and conductive cooling on subsequent cycling time-trial performance in the heat. We hypothesized that core temperature, skin temperature and the rate of heat storage would be lower following pre-cooling. Furthermore, we hypothesized that these reductions would lead to improved cycling performance,

represented by a faster time trial completion, and that the largest improvement would be seen with the coldest pre-cooling treatment. The garments studied provided cooling via moisture evaporation (held in a special gel) and by conduction to the pre-cooled or frozen (phase change) material.

METHOD

Participants

Ten endurance trained competitive male cyclists and triathletes (25.1 ± 6.1 yrs; height 178.9 ± 6.1 cm; weight 72.5 ± 5.1 kg; $\dot{V}O_2$ max 61.3 ± 4.3 ml/kg/min; body fat 7.2 ± 2.9% body fat) who were familiar with the type of testing involved were recruited for this study. All participants were required to be free from injury. The Loughborough University ethical advisory committee approved all experimental procedures and confirmed to the Declaration of Helsinki. Participants gave their written informed consent.

Experimental Design

Participants visited the laboratory on a total of 5 occasions. Visit 1 consisted of body composition measurement and an incremental exercise test to exhaustion to determine $\dot{V}O_2$ max and maximal power output (W_{max}). Visits 2, 3, 4 and 5 were simulated cycling time trials in which participants were instructed to complete a set amount of work in as short a time as possible. Visit 2 served as a familiarisation trial to ensure that participants were able to complete the required exercise and to minimize any potential learning effect on time trial performance. Visits 3, 4 and 5 constituted the experimental visits where participants underwent i) cold pre-cooling using a cooling garment frozen over night (COLD; evaporative and conductive cooling), ii) moderate

pre-cooling where the cooling garments were saturated in cool (14.2 ± 1.2˚C) water for 30 minutes prior to wearing (COOL; evaporative cooling mainly); or iii) no pre-cooling implemented (CONT). Trials were conducted in a randomized and counterbalanced order, with each visit separated by a minimum of 7 days to minimize acclimation effects.

Visit 1

Participants first had their height (Seca, Birmingham, UK) and weight (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Body composition was determined using skinfold calipers (Harpenden, HaB Intl Ltd, Warwickshire, UK) and the 7 site skinfold method as described by Jackson and Pollock (2004) and weighted for the athletic population. The $\dot{V}O_2$ max test was conducted on an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands), and consisted of 3 minutes at 95W, followed by 35W increments every 3 minutes until the participant reached volitional fatigue.

Visits 3-5

Participants reported to the laboratory in the morning (0600-0900) following an overnight fast and having abstained from caffeine and alcohol ingestion or any strenuous exercise in the preceding 24 hours. Each participant completed their trials at the same time of day to minimize the effects of circadian variation on exercise performance.

Prior to each experimental visit, participants were given an ingestible temperature pill (VitalSense, Mini Mitter, Oregon, USA) to measure core temperature and instructed

to take it 8-10 hours prior to reporting to the laboratory. On arrival the pill was located using a receiver to confirm that it was functioning correctly. Participants then had their nude weight recorded (ID1 Sartorius, Goettingen, DE). They were then instrumented with wireless temperature sensors (iButton, DS1922, Sunnyvale, CA, USA) that were secured in place using Medipore tape (3M, Berkshire, UK). The locations of the iButtons were forehead, scapula, right bicep, left pectoral, left forearm, left hand, right thigh and left calf, to allow for the subsequent calculation of mean skin temperature (ISO 9886 1992). The iButtons recorded at 60 s intervals throughout the duration of each trial. Mean skin temperature ($\overline{T}_{sk}$) was calculated using an area weighted 8-site calculation (ISO 9886 1992). Heart rate was monitored and recorded throughout the trials (RS800, Polar, Finland). In order to minimize differences in clothing insulation, all participants wore a standard athletic shirt during the stabilization, cooling and warm up periods along with their own cycling shorts. This shirt was removed on completion of the warm up prior to the start of the time trial.

Following instrumentation, participants remained in a temperate climate (21.2 ± 0.8˚C) prior to the collection of baseline measures after 30 minutes. Participants were then moved to an environmental chamber maintained at 35.0 ± 0.4˚C and 50.6 ± 1.3 % relative humidity, where they donned the cooling garments for the experimental conditions or remained seated in cycling clothing for a further 30 minutes. On completion of the precooling phase, participants then mounted the cycle ergometer to complete a standardised 9-minute warm up (WUP) which consisted of 3 minute stages of 150W, 200W and 250W. If worn, the cooling garments were removed on

completion of the warm up and participants had 5 minutes to stretch and prepare for the start of the time trial.

For the time trial, participants were given a set amount of work, equivalent to cycling for 1 hour at 75% W_{max} (912.7 ± 131.3 kJ) to complete in as fast a time as possible. The ergometer was set in linear mode so that 75% W_{max} was obtained when participants cycled at their preferred cadence. Participants exercised separately with no performance feedback other than the accumulated work done, target workload and a graphical representation of fluctuations in power output. They had minimal interaction with the investigators.

Heat storage was estimated using the following equation for partitional calorimetry:

$$S\ (W \cdot m^2) = ((C_p\ x\ wt\ x\ (\Delta T_b))/t/\text{BSA}$$

Where S equals heat storage ($W \cdot m^2$), C_p is equal to the specific heat of body tissue (3474 $J \cdot kg^{-1} \cdot °C^{-1}$), wt equals body weight (kg), ΔT_b is equal to the change in body temperature (°C; Hardy and DuBois, 1938), *t* equals the time of observation (min) and BSA equals total body surface area (m^2).

During the time trial, participants were allowed to drink water *ad libitum,* with the total volume consumed recorded to allow for sweat rate calculation. Water was kept at the same temperature as the surrounding environment. At 10% intervals of total work done, T_c was recorded. At 20% intervals, RPE (Borg, 1982), thermal sensation (ASHRAE, 1997) and thermal comfort (Griffiths and Boyce, 1971) were recorded. 20% intervals were chosen to minimize participant/investigator interaction.

Cooling Garments

Figure 1 shows the design and placement of the cooling packs on the anterior side of the vest and sleeves. The vest and sleeves were constructed of a breathable mesh fabric, and pockets of hydrophilic silica gel. During cooling for the COOL trial, cooling was achieved mainly through evaporative cooling from the fabric surface and the gel packs, whereas in the COLD trial, there was a gradual phase change throughout wearing as the ice heated to liquid. Cooling power for the vests in both the COOL and COLD conditions was calculated using a thermal manikin (NEWTON, Measurement Technology Northwest, USA) with a surface temperature of 34°C to mimic skin temperature and a wet surface to represent sweat production. The garments remained in place on the manikin for 60 minutes, with power recorded every 30s. The cooling power of the garments was 190 $W.m^{-2}$ (COLD) and 170 $W.m^{-2}$ (COOL), with forearms having greatest cooling power (COLD: 254 $W.m^{-2}$; COOL 225 $W.m^{-2}$). Assuming that the rate of evaporative cooling between pre-cooling conditions was the same, the calculated difference in heat content between the two vests was 84.9kJ, which equated to a difference in cooling power of 31.5W.

Figure 1 near here

Statistics

Two-way repeated measures analysis of variance (ANOVA) was used to determine main effects of condition and time. Differences in heat storage were analysed using a one-way ANOVA. Where significant differences were identified, *post-hoc* pairwise comparisons with a Bonferonni correction were conducted. Correlations between variables were calculated by Pearson's correlation coefficient. Effect sizes were calculated for time trial completion times, with effect sizes of <0.2 classified as small,

0.4-0.6 as medium and > 0.8 as large (Cohen, 1988). The accepted level of significance was $p<0.05$. All data are presented as mean ± SD unless otherwise stated.

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Results

Time Trial Performance

Time to complete the time trial was significantly faster following COLD ($p<0.05$; d = 0.6, figure 2) compared to CONT, which equated to an improvement of 240 ± 187s, or 5.8%. In addition COLD was faster than COOL (2.6%, *d* = 0.4, $p<0.05$).

Figure 2 near here

Power output

Mean power output throughout the duration of the time trial was higher for COLD (234.4 ± 33.8W) vs CONT (224.4 ± 27.9 W, $p<0.05$, figure 2). This equates to a 10.0 ± 8.4W or 4.3% improvement in mean power output for COLD compared to CONT ($p<0.05$). There were, however, no significant differences in power output between COLD and COOL (227.1 ± 25.7W) or at individual time points.

Mean skin temperature

Conversely, there were significant effects of both pre-cooling conditions ($p<0.05$) and time ($p<0.05$) on mean skin temperature (figure 3). There was a significant interaction for condition and time on $\overline{T}_{sk}$ ($p<0.05$). Mean skin temperature was significantly lower for both COOL and COLD when compared to CONT at T0 (both $p<0.05$) This

effect lasted until 20% of the target workload for COLD. In addition, mean skin temperature was correlated to power output (r^2 = -0.673, $p<0.05$).

Heart rate and core temperature

There was no effect of time or condition on either heart rate throughout each condition. Furthermore, there were no differences in average heart rate between conditions during the time trial (CONT = 166 ± 15 beats·min^{-1}, COOL = 171 ± 11 beats·min^{-1}, COLD 170 ± 10 beats·min^{-1}). There was a main effect of time on core temperature ($p<0.05$) but no effect of condition on core temperature at the start of the time trial (CONT = 36.7 ± 0.4 °C; COOL = 36.7 ± 0.6 °C; COLD = 36.5 ± 0.3 °C) or upon its completion (CONT = 38.6 ± 0.5 °C; COOL = 38.6 ± 0.5 °C; COLD = 38.7 ± 0.4 °C).

Heat Storage

There were no differences in the rate of heat storage between conditions throughout the whole duration of the test. There were differences in the rate of heat storage between conditions following warm up (CONT 41.8 ± 7.5 W·m^2; COOL 62.2 ± 14.6 W·m^2; COLD 79.7 ± 12.3 W·m^{2,} $p<0.05$). There were also differences between conditions at the start of the time trial, with a higher rate of heat storage for both COLD (177.4 ± 49.5 W·m^2) and COOL (122.2 ± 50.7 W·m^2) when compared to CONT (11.3 ± 98.5 W·m^2 both $p<0.05$).

Figure 3 near here

Perceptual measures

There was a significant effect of both time ($p<0.005$) and condition *x* time ($p<0.05$) on thermal sensation (figure 4). An increase in thermal sensation towards feeling "hot" was evident in all conditions throughout the course of the trial. There was a trend for thermal sensation to be less warm for both COOL and COLD compared to CONT, and COLD < COOL throughout. This trend reached significance at T0 (COOL < CONT, $p<0.05$; COLD < CONT $p<0.01$), warm up (WUP; COOL < CONT, $p<0.05$) and recovery (REC; COLD < CONT, $p<0.05$). Pre-cooling application had no effect on either RPE or thermal comfort.

Discussion

The present data demonstrate that using a novel design of a frozen cooling garment which incorporating evaporative and conductive cooling of the torso, hand and forearms resulted in a faster time trial performance (4.8%) in the heat (35˚C) compared to when no pre-cooling was undertaken. This effect was present in the absence of significant changes in $T_{c.}$ Furthermore, the data show that pre-cooling lead to a reduction in $\overline{T}_{sk}$, which was coupled with improvements in thermal sensation at the onset of the time trial. We propose that the observed improvements in performance are due to changes in the peripheral feedback and central regulation of pacing strategies owing to reductions in T_{sk} as we demonstrate improved average power following COLD pre-cooling was associated with lower mean skin temperatures and was independent of any changes in T_c. As these reductions are associated with a concurrent improvement in self-paced time trial performance, it appears likely that $\overline{T}_{sk}$ is important in regulating exercise performance in the heat,

and that T_c may have less of a unique regulatory role than has previously been suggested (Gonzalez-Alonso et al., 1999; Ely et al., 2009).

When comparing conditions COOL and COLD, it is evident that evaporative cooling alone (COOL), though showing an indication of an effect, is not capable of having significant impact on performance. On the other hand, the combination of evaporative and convective cooling within the phase change component in COLD (ice → water) does clearly provide a significant improvement to performance in the heat and is likely due to reductions in T_{sk} and a higher rate of heat storage at the onset of exercise, resulting in improved performance (Tucker et al., 2006; Tucker 2009). However, this view has been challenged, owing to the nature of the relationship between core and skin temperature and the calculation of heat storage (Jay et al., 2007; Jay and Kenny, 2009). This has recently been supported experimentally by Ravanelli et al (2014) who demonstrate that changes in self-paced exercise intensity are not driven by early differences in heat storage following exercise onset. Furthermore, the present data demonstrate that the change in heat storage is primarily driven by a reduction in T_{sk} as there was no change in T_c in response to cooling. Compared to traditional ice vests, the currently tested garment also provides more surface area for cooling, which may also contribute to its effectiveness, particularly if reductions in T_{sk} are important in increasing power output during cycling time trials in the heat.

It was initially believed that one of the primary outcomes of pre-cooling was to cause a reduction in core temperature at the onset of exercise, and that it was this reduction in T_c which resulted in improved endurance performance (Arngrimsson et al., 2004). However, more recently published work has begun to question the importance of core temperature in performance regulation of test protocols which are

self-paced in nature rather than fixed intensity (Ely et al., 2009). Combined with the data presented here, this suggests that in self-paced exercise, the importance of core temperature as a limiting factor is likely to be less important than previously believed. Indeed, it now appears that other feedback mechanisms may be of equal, if not greater importance in regulating pacing than that of T_c.

Evidence has begun to emerge that skin temperatures in excess of 35˚C and resultant high skin blood flow requirements can impair prolonged aerobic exercise (Sawka et al., 2012; Schlader et al., 2011a). In environmental conditions similar to those employed in the present study, exhaustion has been shown to occur at relatively low core temperatures (<38.5˚C) but with skin temperatures in excess of 35˚C (Montain et al., 1994). This points to the potential importance of an ambient temperature threshold above which pre-cooling is likely beneficial, regardless of the rate of heat production. As a result of elevations in T_{sk}, there is an increase in skin blood flow in an attempt to dissipate some of the accumulated heat. The increase in skin blood flow causes redistribution away from the active musculature (Cheuvront et al., 2005) and is likely detrimental to performance. An increase in T_{sk} and cardiovascular strain has been associated with reductions in cycling time trial performance due to reductions in power output and oxygen uptake (Periard et al., 2011). Therefore, following pre-cooling, it is possible that there is a reduction in cardiovascular strain and better maintenance of central blood volume following pre-cooling, which allows for greater skeletal muscle blood flow and oxygen delivery during exercise, thus enhancing performance. Moreover, in situations where T_{sk} is elevated, such as during prolonged endurance exercise and/or in moderate to warm ambient conditions, an individual will work at a greater percentage of $\dot{V}O_2$ max for the same absolute workload, compared to when T_{sk} is lower or when ambient

conditions are more temperate. However, given that the present data do not indicate a reduction in cardiovascular strain following pre-cooling, as evidenced by a lack of change in heart rate, we suggest that the performance improvements appear to be more heavily influenced by reductions in T_{sk}, particularly given the link between reduced T_{sk} and elevated mean power output during the time trial.

Taken together, the aforementioned studies suggest that elevated skin temperatures are capable of impairing aerobic performance. In the present study, pre-cooling had the effect of reducing skin temperature. Furthermore, the point at which a T_{sk} of 35˚C was reached was delayed for between 14 (COOL) and 23 minutes (COLD) of the time trial. Therefore, if T_{sk} at the onset of exercise provides important input into initial self-selected power output and thus overall performance, the improvement in both mean power output and time trial performance may be due to reductions in skin temperature and total cardiovascular strain in response to the intensity the pre-cooling interventions used. This adds to the suggestion that T_{sk} may have an important regulatory function in the fatigue process via a combination of central and peripheral mechanisms in warm ambient conditions.

Reductions in thermal sensation towards feeling less hot may be of importance in the regulation of pacing strategy selection (Schlader et al., 2011b), suggesting thermal perception is an important component of thermoregulatory behaviors which may influence performance. Several authors have reported that perceptual measures are linked to alterations in exercise performance (Bogerd et al., 2005; Tucker, 2009), and that lower thermal sensation following pre-cooling is associated with improved running performance in the heat (Dugas, 2011; Lee et al., 2008). It is possible that perceptual measures may act as a way of regulating pace or effort based on an individual's expectations of a task and how it should "feel" when compared to similar

tasks they have experienced. Several authors have suggested that these comparisons are used by the central nervous system to regulate work rate in order to complete an event as quickly as possible (Noakes et al., 2005; Tucker, 2009). Recently, Levels et al. (2013) suggested that an increased sense of coolness following a pre-cooling procedure resulted in improved pacing in the latter stages of a cycling time trial in the heat. However, the idea of central regulation as an anticipatory controller of exercise performance (Noakes et al., 2005; Tucker et al., 2006) is a current area of much debate and controversy (Perrey et al., 2010) warranting more in-depth investigation.

In conclusion the present study demonstrates that the use of a novel design of ice vest, incorporating torso, forearm and palm cooling is effective at improving cycling time trial performance in the heat by 4.8%. This improvement in performance may be attributable to the method of pre-cooling used being effective at improving heat balance, reducing T_{sk} and thermal sensation, all of which have previously been linked to better endurance performance. The present data support recent evidence questioning the importance of a critical limiting core temperature in determining exercise performance, as it indicates that peripheral changes in skin temperature, coupled with a reduction in body heat content may contribute to improved endurance exercise performance in hot ambient conditions.

Perspectives

Pre-cooling interventions have become common practice in a wide variety of sports before training and competition in the heat in an attempt to improve performance. The present study indicates that a novel pre-cooling intervention combining both evaporative and conductive cooling of the torso, forearms and hands improves cycling time trial performance in the heat more than evaporative cooling alone. This reflects

that the phase change from ice to water adds additional cooling power to that provided by evaporative cooling alone which is important for performance enhancement. Importantly, it appears that skin temperature is a key determinant in improving performance, confirming that core temperature may not be the sole determinant of performance regulation and pacing in the heat. The present data highlights the importance of further evaluating the importance of skin temperature manipulation on pacing strategies and exercise performance in a variety of ambient conditions. Furthermore, the impact of a skin temperature reduction as a result of external pre-cooling, without concurrent core temperature reduction, on the risk of exertional heat illness requires further research.

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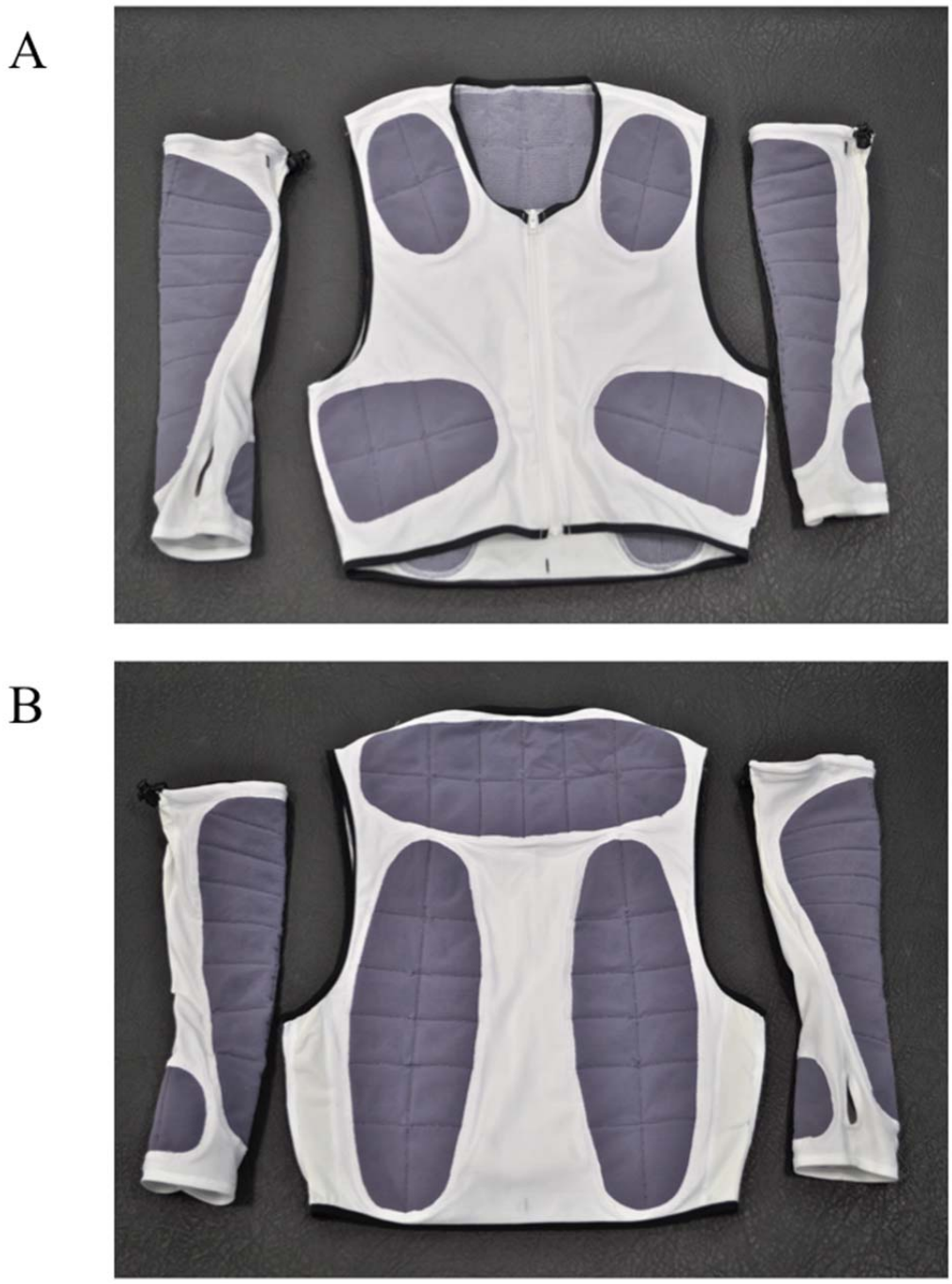

Figure 1: The cooling vest and sleeve ensemble. The vest and sleeves consisted of a breathable mesh body, with hydrophilic silica gel packs (blue regions) that became saturated following water immersion. A) Anterior aspect, B) Posterior aspect. Temperature was manipulated after saturation via cold-water immersion with subsequent storage in a refrigerator (COOL) or a freezer (COLD)

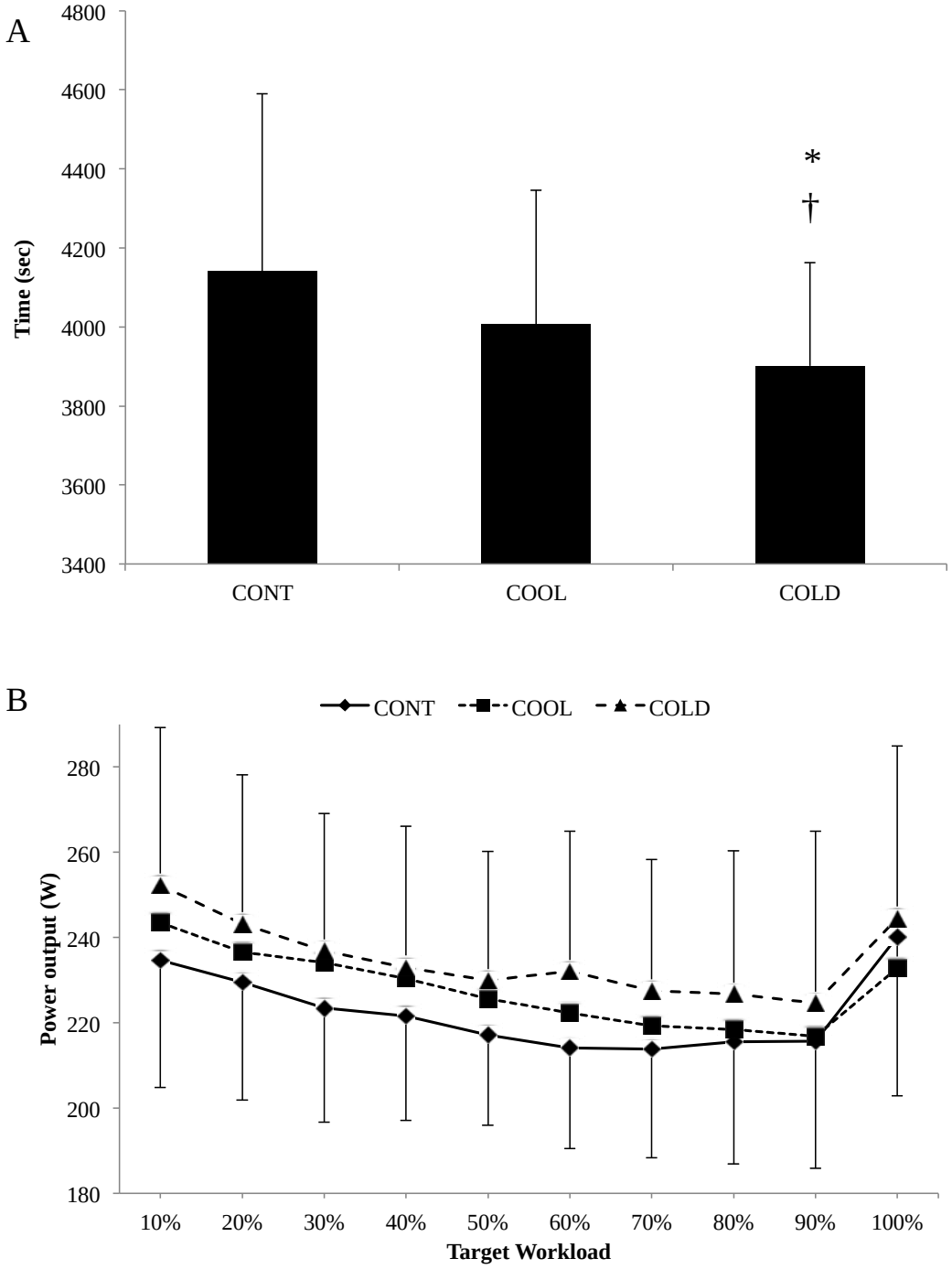

*Figure 2: The temporal relationship between time to complete a set workload time trial and power output A) Time to complete a cycling time trial was significantly improved following the use of an ice vest incorporating both evaporative and conductive cooling compared to the use of no pre-cooling. B) Pre-cooling increased mean power output throughout the course of the time trial for COLD compared to COOL and CONT, with no effect of COOL on CONT. *p<0.05. Data presented as mean ± SD*

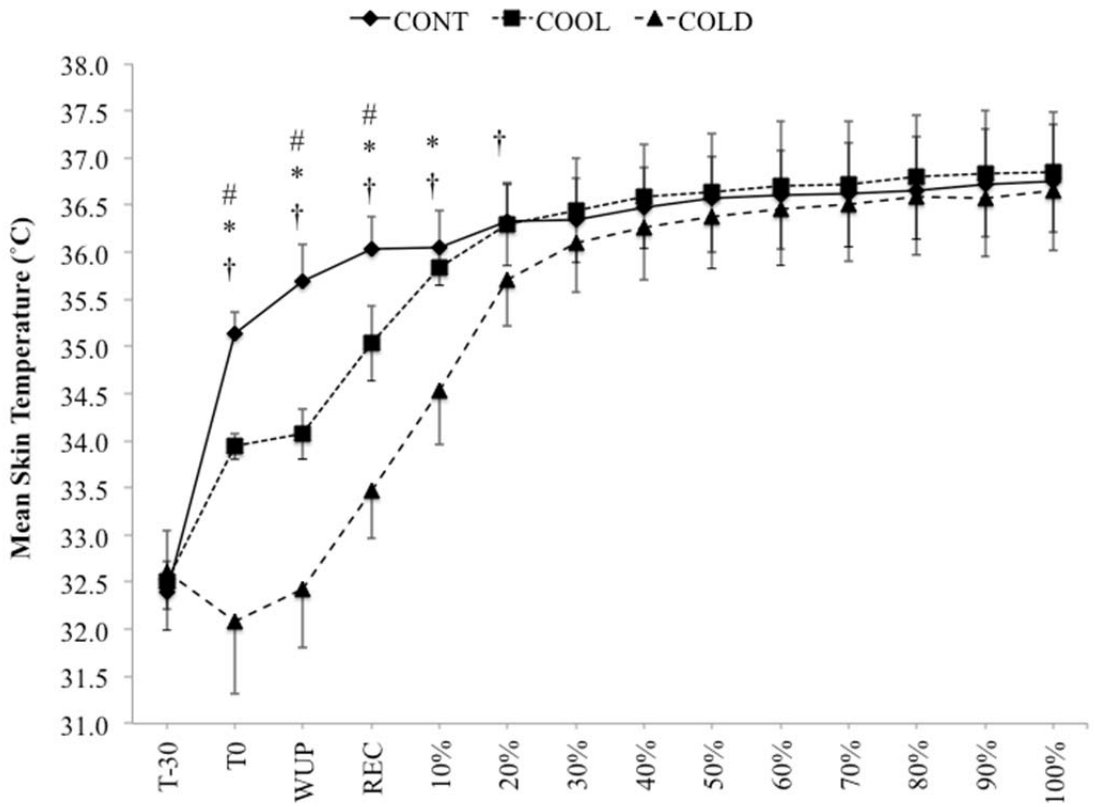

*Figure 3: Pre-cooling had a significant effect on reducing mean skin temperature both during and after cooling application. Cooling reduced skin temperature for both COOL and COLD, with the reduction lasting between 10% (COOL) to 20% (COLD) of the total target workload. *=COLD < CONT p<0.05; # = COOL < CONT p<0.05, †= COLD < COOL p<0.05. Data presented as mean ± SD*