

1 ORIGINAL RESEARCH PAPER

2 **Hand and torso pre-cooling does not enhance subsequent high**  
3 **intensity cycling or cognitive performance in heat.**

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# 1 **Hand and torso pre-cooling does not enhance subsequent high** 2 **intensity cycling or cognitive performance in heat.**

3

## 4 **Abstract**

5 The purpose of this study was to compare the separate and combined effects of two practical  
6 cooling methods (hand and torso) used prior to exercise on subsequent high-intensity cycling  
7 performance in heat. Ten trained male cyclists ( $\dot{V}O_{2\text{peak}}$ :  $65.7 \pm 10.7 \text{ ml.kg}^{-1}.\text{min}^{-1}$ ) performed  
8 four experimental trials (randomised within-subjects design) involving 30 min of pre-cooling  
9 (20 min seated; PRE-COOL, 10 min warm-up; PRE-COOL+WUP), while using a: (1) hand  
10 cooling glove (CG); (2) cooling jacket (CJ); (3) both CG and CJ (CG+J); or (4) no-cooling (NC)  
11 control, followed by a cycling race simulation protocol (all performed in  $35.0 \pm 0.6^{\circ}\text{C}$  and  
12  $56.6 \pm 4.5\%$  RH). During the 30 min of pre-cooling, no reductions in core ( $T_c$ ) or mean skin  
13 temperature ( $T_{sk}$ ) occurred, however  $T_{sk}$  remained lower in the CJ and CG+J trials compared  
14 to NC and CG ( $p=0.002-0.040$ ,  $d=0.55-1.01$ ). Thermal sensation ratings also indicated that  
15 participants felt 'hotter' during NC compared to all other trials during both PRE-COOL and  
16 PRE-COOL+WUP ( $p=0.001-0.015$ ,  $d=1.0-2.19$ ), plus the early stages of exercise (sets 1-2;  
17  $p=0.005-0.050$ ,  $d=0.56-1.22$ ). Following cooling, no differences were found for absolute  $T_c$  and  
18  $T_{sk}$  responses between trials over the entire exercise protocol ( $p>0.05$ ). Exercise and cognitive  
19 (working memory) performance also did not differ between trials ( $p=0.843$ ), however cognitive  
20 performance improved over time in all trials ( $p<0.001$ ). In summary, pre-cooling (20 min seated  
21 and 10 min warm-up) in heat did not improve subsequent high-intensity cycling performance,  
22 cognitive responses and associated thermoregulatory strain ( $T_c$  and  $T_{sk}$ ) compared to control.

23

24 **Keywords:** *core temperature, thermoregulation, hand cooling, cooling jacket, thermal*  
25 *sensation, working memory.*

26

27

## 28 **Abbreviations:**

29 BLa – Blood lactate

30 bpm – beats per minute

31 BSA – Body surface area

32 CG – Cooling glove

33 CG+J – Cooling glove and jacket

34 CJ – Cooling jacket

35 CWI – Cold water immersion

36 ES – Effect size

- 1 HR – Heart rate
- 2 NC – No-cooling
- 3 RH – Relative humidity
- 4 RPE – Rating of perceived exertion
- 5 Tc – Core temperature
- 6 TS – Thermal sensation
- 7 Tsk – Skin temperature
- 8 WUP – Warm up
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## 1 Introduction

2 Exercise in heat can limit physical and cognitive performance capacity as a result of a  
3 rise in internal heat load and in particular, core temperatures ( $T_c$ ) [1,2]. Cooling the  
4 body prior to exercise (pre-cooling) is a common strategy used to manage heat related  
5 fatigue as this procedure can create a larger heat storage capacity that is proposed to  
6 enable a greater amount of work to be performed during subsequent exercise [3].  
7 Several pre-cooling techniques applied to the body (cold air, water, ice or cooling  
8 jackets/vests/shirts) or ingested (cold liquid or crushed ice), either separately or in  
9 combination, have resulted in subsequent performance benefits, particularly for  
10 prolonged exercise in heat (see meta-analyses: [4,5]).

11 To date, cold-water immersion (CWI) is recognised as one of the most effective  
12 methods of reducing pre-exercise  $T_c$  and mean skin temperatures ( $T_{sk}$ ), thus increasing  
13 heat storage capacity and improving subsequent prolonged endurance performance in  
14 heat (fixed time or time to exhaustion; [1,6-8]). However, this method requires  
15 extended treatment times (up to 1 h) and is often impractical to implement in the field  
16 (especially outdoors in heat) due to lack of refrigeration and/or suitable water  
17 receptacles. Consequently, less cumbersome pre-cooling methods such as cooling  
18 jackets (CJ) have been trialed. Importantly, wearing a CJ prior to exercise in heat (i.e.  
19 pre-cooling) has been found to improve subsequent endurance performance in heat  
20 (compared to no-cooling: NC) in 5 km running [9] and 16.1 km cycling time-trials [10],  
21 plus run [11] and cycling times to exhaustion [12,13]. These results indicate that  
22 cooling with a CJ prior to exercise can be effective at reducing  $T_c$  and  $T_{sk}$  compared to  
23 NC, therefore blunting the rise in thermoregulatory strain ( $T_c$ , heart rate, perception of  
24 thermal discomfort) during the initial stages of exercise and, in turn, may enable faster  
25 speeds during later stages of an endurance event [9]. However, while CJ represent a  
26 practical and effective method of pre-cooling, their use during race settings can be  
27 difficult due to the need to keep them cold prior to wearing.

28 A recent alternative cooling method that can be applied in the field is a  
29 transportable hand-cooling glove (CG). This device covers the entire hand and utilises  
30 cold circulating water ( $\sim 16^\circ\text{C}$ ) combined with subatmospheric pressures ( $-40\text{ mmHg}$ ) to  
31 increase blood flow to the packed vascular structures underlying the palm (a non-hairy,  
32 glabrous skin surface), thereby extracting heat and cooling venous blood returning to  
33 the core [14]. Used during aerobic exercise (walking uphill at  $5.6\text{ km}\cdot\text{h}^{-1}$ ) in heat ( $40^\circ\text{C}$ ,  
34 20-45% RH), the CG did attenuate the rise in  $T_c$  and significantly extend exercise

1 duration compared to NC ( $2.1 \pm 0.4^\circ\text{C}\cdot\text{h}^{-1}$  and 46.1 min vs.  $2.9 \pm 0.5^\circ\text{C}\cdot\text{h}^{-1}$  and 32.3 min,  
2 respectively [15]). Further, Hsu et al. [16] reported that wearing the CG during 1 h of  
3 submaximal cycling (60%  $\dot{V}\text{O}_2\text{max}$ ) in heat attenuated the rise of  $T_c$ , compared to NC  
4 ( $1.2^\circ\text{C}$  v  $1.8^\circ\text{C}$ ) and improved 30 km cycling time-trial performance (by 6%, compared  
5 to NC). However, participants in these studies wore the CG during exercise, with this  
6 unlikely to be replicated in any sporting scenario. Nevertheless, as the CG is easily  
7 transportable and does not need power (battery operated) or refrigeration, it may be  
8 practical and effective for pre-cooling in the field as recent studies have shown  
9 significant reductions in  $T_c$  and  $T_{sk}$  when used during [17] and post-exercise [18].  
10 However, no studies have assessed the pre-cooling capacity of the CG prior to exercise  
11 whilst resting or during a warm-up (WUP) period (in heat) on subsequent prolonged  
12 performance.

13 Of relevance, prolonged repeated-sprint activity is common in many sports and  
14 has been associated with greater physiological and thermal strain than submaximal  
15 endurance exercise of a matched intensity. This is likely due to the extra metabolic heat  
16 generated by working at a higher intensity when performing repeated-sprints compared  
17 to steady-state continuous exercise [19]. While beneficial effects of pre-cooling with CJ  
18 have been observed for endurance-based activity, their effectiveness prior to prolonged  
19 repeated-sprint exercise remains equivocal. Both Clarke et al. [20] and Duffield et al.  
20 [21] have reported improved (albeit non-significant) effects of pre-cooling using a CJ  
21 on subsequent prolonged (60-90 min) cycling and running repeated-sprint performance  
22 in heat ( $30^\circ\text{C}$ ). Other studies have reported improved subsequent prolonged repeated-  
23 sprint performance (running or cycling for greater than 30 min) in heat associated with  
24 pre-cooling that used a combination of a CJ with other methods (i.e. ice slushy  
25 ingestion, quadriceps ice packs, head and neck ice towels) for 20-30 min [22-24].  
26 Therefore, combining pre-cooling methods (such as CG and CJ) is of interest in that this  
27 may provide a greater benefit for high intensity prolonged repeated-sprint efforts in heat  
28 than using one application alone. However, this premise is yet to be assessed. Further,  
29 practical cooling strategies that can be easily implemented in thermally stressful field  
30 environments (e.g. the upcoming 2020 Tokyo Summer Olympics) should be  
31 investigated, particularly as events such as the men's cycling road race are predicted to  
32 be exposed to very high levels of solar ultraviolet radiation exposure ( $941 \text{ J}\cdot\text{m}^{-2}$  [25]).

33 Specific to cycling, events of 45-60 min duration (e.g. criterium or time-trials)  
34 consist of multiple high-intensity sprints, eliciting greater thermal and physiological

1 strain [26] and mean power output than flat or hilly road races [27]. Moreover, repeated  
2 maximal sprints and short time-trial efforts are required within a continuous effort, with  
3 no opportunity for breaks or cool downs during these particular events. Of relevance,  
4 complex cognitive processes, in particular tactical decision-making, choice reaction  
5 time and working memory are also important considerations for successful sporting  
6 performance [28,29]. Notably, previous studies have reported impairments in attention,  
7 decision-making and working memory following exercise in heat, often associated with  
8 body-mass losses of >2% caused by a high  $T_c$  that resulted in increased sweat output  
9 during these conditions [30-32]. Importantly, neck cooling utilised during running to  
10 exhaustion at 70%  $\dot{V}O_2\text{max}$  improved cognitive tasks of greater complexity compared to  
11 simple cognitive tasks following exercise in heat (30°C, 71% RH) [33]. Therefore, it is  
12 possible that applying cooling prior to exercise in heat may delay an increase in  $T_c$  and  
13 sweat rate compared to NC [34], which in turn may enhance complex cognitive  
14 functions, (such as alertness and decision-making), thereby ultimately improving  
15 cycling race execution.

16 Therefore, the aim of this study was to determine whether cooling applied to the  
17 hand (CG) and torso (CJ), either separately or in combination prior to exercise would  
18 result in improved cycling and cognitive performance in heat. It was hypothesised that  
19 cooling prior-to and during the WUP (in heat) would improve cycling and cognitive  
20 performance due to reduced thermal strain during the early stages of exercise. Further, it  
21 was expected that the combined application of the two cooling methods would enhance  
22 these effects to a greater extent.

23

## 24 **Methods:**

### 25 *Participants*

26 Ten, non-heat acclimatised, competitive male cyclists [mean±SD: age: 21.1±3.3 y;  
27 height: 180.1±7.5 cm; body-mass: 73.9±10.9 kg; body surface area (BSA): 1.9±0.2 m<sup>2</sup>;  
28 sum of seven skinfolds: 45.4±15.3 mm;  $\dot{V}O_2\text{peak}$ : 65.7±10.7 ml.kg<sup>-1</sup>.min<sup>-1</sup>] participated  
29 in this study. All were experienced cyclists (5.1±2.0 y cycling) and maintained a  
30 consistent training volume (~300±113 km of road cycling and ~6±4 h of moderate-high  
31 intensity cross training in other physical activity per week) over the study. Testing was  
32 conducted during the latter winter/early spring months (where average monthly  
33 temperatures in Perth ranged between 18.4-20.3°C; July-September) to ensure that  
34 participants were not heat acclimatised. Using a G-power analysis [35], it was

1 determined that ten participants were needed based on a study by Barr et al. [36] that  
2 used an effect size of 1.4, at an alpha level of 0.05 and power of 0.80. All participants  
3 provided informed consent and ethical approval was granted by the Human Research  
4 Ethics Committee of the University of Western Australia.

### 6 ***Experimental Design***

7 Participants attended a familiarisation session, followed by four randomised  
8 experimental trials performed at the same time of day at least 3 days apart to control for  
9 circadian variability. Trials (all in heat:  $35.0 \pm 0.6^\circ\text{C}$  and  $56.6 \pm 4.5\%$  RH) involved a 30  
10 min pre-cooling period, where participants were first seated for 20 min (PRE-COOL)  
11 and then commenced warming up for 10 min (PRE-COOL+WUP) while using: (1) hand  
12 CG; (2) CJ; (3) both the CG and CJ (CG+J); or (4) NC (control), followed by a cycling  
13 race simulation protocol. In the 24 h prior to testing, participants replicated food and  
14 fluid intake and abstained from vigorous exercise and alcohol.

### 16 ***Familiarisation Session***

17 Anthropometric measurements were first recorded (as described earlier) then a graded  
18 exercise test on a cycle ergometer was performed to determine  $\dot{V}O_{2\text{peak}}$ , commencing  
19 at an intensity of 160 W and increasing by 30 W every 3 min until volitional  
20 exhaustion. Expired air was analysed via a metabolic cart (TrueOne 2400, Parvo  
21 Medics Inc, Utah, USA). Following recovery, participants then completed the first 3  
22 sets of the cycling race simulation (detailed below) to become accustomed to the  
23 format, pacing and procedures used during the subsequent experimental trials. All  
24 testing was performed on a stationary air-braked cycle ergometer (Evolution bicycles,  
25 Geelong, Australia), connected to a customised computer program for determination of  
26 work/power output (Cyclemax, UWA, Australia). This (6 gear) ergometer allows for  
27 individual resistance and cadence choices, with resistance proportional to pedal rate as  
28 air is displaced from fan blades attached to the flywheel when the wheel turns. This  
29 variation in pedal rate and gearing reflects the type of resistance and convective  
30 conditions commonly experienced during road cycling races. Participants were then  
31 familiarised to the cognitive test (Serial Sevens) and all other equipment to be used  
32 during the experimental trials.

### 34 ***Cognitive Task (Serial Sevens)***



1 A modified verbal version, based on the original Serial Sevens subtraction task used by  
2 Hayman [37], was assessed at 4 time points in each trial: baseline and following sets 2,  
3 4 and 6 (end). The Serial Sevens task is a complex cognitive task designed to assess  
4 attention, concentration and working memory [38], with this modified version similar to  
5 that used by Kennedy and Scholey [39]. During this task, participants were presented  
6 with a randomly generated number (between 900-1000) and asked to count backwards  
7 (out loud) by 7 as quickly and as accurately as possible for 60 s. The task was scored as  
8 total number of subtractions made in this time (representing speed) and the number of  
9 incorrect responses (to represent accuracy). Participants were instructed that if they  
10 made a mistake they should carry on subtracting from the new number and subsequent  
11 responses were scored as positive if they were correct in relation to the new number.

12

### 13 ***Preliminary Procedures***

14 Eight hours prior to the experimental trial, participants ingested a radiotelemetry pill  
15 (CorTemp, HQ, Inc., Palmetto, USA) for the measurement of gastrointestinal T<sub>c</sub> and  
16 ingested 600 mL of water at least 1 h prior to arrival for pre-exercise hydration  
17 purposes. Upon arrival, a mid-stream urine sample was collected in a sterile container  
18 and 1 mL placed on the plate of a refractometer (TE-RM10SG, 1.000-1.070, Test  
19 Equip, Dandenong, Australia) to determine urine specific gravity (U<sub>SG</sub>) to check that  
20 cyclists attended each trial in a similar euhydrated state (U<sub>SG</sub><1.020). Nude body-mass  
21 was then recorded on a digital platform scale (Model ED3300; Sauter Multi-Range,  
22 Ebingen, Germany) to the nearest 0.01 kg. A heart-rate (HR) monitor (Polar RS400,  
23 Finland) was fitted across the chest and skin thermistors (Skin Sensor SST-1, Physitemp  
24 Instruments Inc, Clifton, NJ, USA) taped on the sternum, right mid-anterior forearm and  
25 right mid-posterior calf to record T<sub>sk</sub> by a computerised program (DASYLab Light,  
26 National Instruments, Ireland Resources Ltd). Mean T<sub>sk</sub> was then calculated using the  
27 formula = (0.5 x T<sub>sternum</sub>) + (0.14 x T<sub>forearm</sub>) + (0.36 x T<sub>calf</sub>) [40]. A capillary blood  
28 sample (finger prick) was then collected to measure blood lactate (BLa) concentration  
29 (Lactate Pro 2, Arkray KDK Corp., Kyoto, Japan). Baseline T<sub>c</sub> and T<sub>sk</sub>, HR, rating of  
30 perceived exertion (RPE; 6-20 scale) [41] and thermal sensation (TS; 0-8 scale) [42]  
31 were then recorded, and again every 5 min during the 30 min pre-cooling period.

32

### 33 ***Pre-cooling Interventions***

1 Upon entering the climate chamber, participants immediately adopted one of four  
2 conditions (CG, CJ, CG+J or NC) for 30 min (20 min seated immediately followed by  
3 10 min warm-up). The CG (CoreControl™, AVAcore Technologies, Ann Arbor, MI)  
4 was placed on the participant's dominant hand, encapsulating the hand surface area  
5 (wrist to fingertips). The gel CJ (Arctic Heat Products Pty Ltd, Queensland, Australia)  
6 was chosen for this study due to its common use in many Australian sports (e.g.  
7 football, rugby, hockey). The CJ has four anterior and posterior pockets containing  
8 crystals. As per manufacturer's instructions, the jacket was first soaked in water to  
9 activate the crystals to form a gel and then stored in a refrigerator. Prior to the cooling  
10 protocol, the CJ was placed in icy water (0-2°C) for 30 min then wrung out and worn  
11 over the participants cycling bib (participants wore bib shorts only). During the CG+J  
12 trial, participants adopted both cooling methods whereas during the control NC trial, the  
13 participant was seated with no cooling intervention.

14

#### 15 ***Warm-up and Exercise Protocol (Cycling Race Simulation)***

16 The 10 min of self-paced WUP (while still cooling or NC) included 3 x 5 s sprints  
17 performed at 70, 80 and 90% 'perceived' intensity. Then, the cycling protocol,  
18 comprising 6 sets (4 sets of 6 x 15 s sprints with varying recovery durations and 2 sets  
19 of 5 min maximal time trials; see Table 1) was performed. The sprints in sets 1 and 4  
20 were separated by 45 s active recovery, and sets 2 and 5 by 15 s active recovery (all at  
21 100 W). All sets were separated by 3 min of active recovery where participants also  
22 maintained a power output of 100 W. Active recovery was used to simulate a road-race  
23 where there are constant changes of tempo (hills/breakaways/being in the pack and  
24 relatively recovering) while proceeding in the race. Total cycling time was 43 min  
25 (excluding warm-up). This protocol was previously used by Brewer et al. [43] and  
26 modified from the cycling race simulation used by Vaile et al. [44]. During the trial,  
27 participants were only able to see the time left to complete each effort (which counted  
28 down and reset continuously) thus keeping the participant and the researcher blinded to  
29 their power output. Participants ingested 500 ml of water (23°C) throughout the trial.  
30 Performance measures, including total work (kJ) and mean power output (W), were  
31 determined for each individual sprint and time-trial set as well as across the entire trial.  
32 Immediately after each set T<sub>c</sub>, T<sub>sk</sub>, HR, RPE and TS were assessed, with the Serial  
33 Sevens and BLa only measured at the end of sets 2, 4 and 6. Participants then exited the

1 chamber, were towel dried and nude body-mass was again measured to determine sweat  
 2 loss (pre – post nude body-mass + fluid ingested).

3

4 **Table 1:** Cycling race simulation protocol (TT = time-trial).

Set	Activity	*Recovery	Time (min)
1	6 x 15 s sprints	45 s active recovery	6
2	6 x 15 s sprints	15 s active recovery	12
3	5 min TT	-	20
4	6 x 15 s sprints	45 s active recovery	29
5	6 x 15 s sprints	15 s active recovery	35
6	5 min TT	-	43

\*3 min active recovery (100W) separated each set

5

### 6 **Statistical Analysis**

7 All data was analysed using SPSS Statistics Version 25.0 (IBM, Inc., New York, NY)  
 8 and p-values  $p < 0.05$  were considered statistically significant. The effect of the four  
 9 interventions on performance (cycling or cognitive) and physiological/perceptual  
 10 variables ( $T_c$ ,  $T_{sk}$ , HR, RPE, TS) were analysed using two-way (trial x time) repeated-  
 11 measures ANOVAs across all time points, while one-way repeated-measures ANOVAs  
 12 assessed baseline variables, performance trial totals,  $U_{SG}$ , sweat loss and environmental  
 13 conditions. Where main or interaction effects occurred, follow-up post hoc comparisons  
 14 using Bonferroni adjustments and paired sample t-tests were used to determine the  
 15 location of any differences. In addition, inferential statistical analysis using Cohen's  $d$   
 16 effect sizes (ES) was calculated to determine the magnitude of these differences [45],  
 17 with only moderate (0.50-0.80) to large ( $>0.80$ ) ES reported. All values are expressed  
 18 as mean  $\pm$  standard deviation.

19

### 20 **Results:**

21 There was no difference in environmental conditions between trials or at any time point  
 22 during all trials ( $35.0 \pm 0.6^\circ\text{C}$ ,  $p=0.693$ ,  $56.6 \pm 4.5\%$  RH,  $p=0.319$ ). Prior to exercise,  
 23 participants' average  $U_{SG}$  status was  $1.018 \pm 0.01$ , with this value being similar between

1 trials ( $p=0.109$ ). Blood lactate levels were also similar between trials at baseline  
2 ( $1.7\pm 0.8$  mmol.L<sup>-1</sup>;  $p=0.296$ ).

3

#### 4 ***Pre-Cooling Period***

5 For all trials, T<sub>c</sub> was similar at baseline ( $\sim 37.0\pm 0.4^\circ\text{C}$ ,  $p=0.685$ ; Figure 1) and remained  
6 relatively unchanged for the 20 min PRE-COOL period, with no significant differences  
7 or moderate-large ES recorded between trials at any time point ( $p=0.959$ ). Once WUP  
8 commenced, a main effect for time ( $p<0.001$ ) was seen for T<sub>c</sub>, as values gradually rose  
9 in all trials to an average of  $37.3\pm 0.4^\circ\text{C}$ ; however, there were no significant differences  
10 or moderate to large ES between trials from 20-30 min ( $p=0.346$ ).

11 In respect to T<sub>sk</sub>, baseline values in all trials were similar ( $33.3\text{-}33.7^\circ\text{C}$ ,  
12  $p=0.544$ ; see Figure 2) with an interaction effect ( $p=0.001$ ) seen as T<sub>sk</sub> increased every  
13 5 min across the PRE-COOL period in all trials (main effect for time  $p<0.001$  and trial  
14  $p=0.008$ ). Specifically, over this 20 min period, T<sub>sk</sub> was significantly lower for CJ and  
15 CG+J compared to CG at each 5 min time point from 5-20 min ( $p=0.002\text{-}0.022$ ,  $d=0.77\text{-}$   
16  $1.01$ ). Furthermore, moderate to large ES suggested a tendency for T<sub>sk</sub> to be lower for  
17 the CJ compared to NC at every 5 min interval of the 20 min PRE-COOL period, with  
18 these values supported by significant p values recorded at the 10 and 15 min marks (CJ  
19 versus NC:  $d=0.67\text{-}0.85$ ,  $p=0.033\text{-}0.056$ ; 10 min  $p=0.040$ , 15 min  $p=0.033$ ). Similarly  
20 for the CG+J trial, T<sub>sk</sub> values tended to be lower than NC over the 20 min PRE-COOL  
21 period, with values being significant at 15 and 20 min (CG+J versus NC:  $d=0.51\text{-}0.97$ ,  
22  $p=0.005\text{-}0.120$ ; 15 min  $p=0.026$ , 20 min  $p=0.005$ ). Once the 10 min WUP commenced,  
23 T<sub>sk</sub> continued to increased over time ( $p<0.001$ ) and differ between conditions  
24 ( $p=0.003$ ). After the first 5 min of PRE-COOL+WUP (25 min mark of overall cooling,  
25 see Figure 2), T<sub>sk</sub> values remained lower in CJ and CG+J compared to CG ( $p=0.054$ ,  
26  $d=0.66$  and  $p=0.021$ ,  $d=0.79$ , respectively) and NC ( $p=0.052$ ,  $d=0.81$  and  $p=0.004$ ,  
27  $d=1.02$ , respectively). At the end of the 10 min PRE-COOL+WUP period, T<sub>sk</sub>  
28 remained significantly lower for CJ and CG+J compared to NC ( $p=0.014$ ,  $d=0.77$  and  
29  $p=0.015$ ,  $d=0.64$ , respectively), while T<sub>sk</sub> for CJ tended to be lower than CG ( $p=0.076$ ,  
30  $d=0.55$ ).

31 Additionally, HR at baseline averaged  $68\pm 14$  bpm across all trials ( $p=0.905$ ) and  
32 remained relatively unchanged between trials at the end of the 20 min PRE-COOL  
33 period ( $72\pm 15$  bpm,  $p=0.580$ ). Heart rate then increased over the PRE-COOL+WUP to  
34 an average of  $124\pm 20$  bpm ( $p<0.001$ ) at 30 min, but no significant differences occurred

1 between trials ( $p=0.275$ ). Ratings of TS at baseline were the same for all trials ('4 =  
2 comfortable',  $p=1.000$ ). Once cooling (or NC) was applied, a significant interaction  
3 ( $p<0.001$ ) and main effect for trial ( $p<0.001$ ) indicated higher ('hotter') TS ratings for  
4 NC compared to all other trials at each 5 min interval over the 20 min PRE-COOL  
5 period ( $p=0.001-0.013$ ,  $d=1.0-2.19$ ; Figure 3), with TS ratings for CG also tending to be  
6 higher compared to CJ ( $p=0.070-0.217$ ,  $d=0.68-0.99$ ) and CG+J ( $p=0.024-0.070$ ,  
7  $d=0.79-1.12$ ) across the same period. Thermal sensation then increased over the PRE-  
8 COOL+WUP period ( $p<0.001$ ), remaining higher in NC compared to all other trials  
9 ( $p=0.003-0.015$ ,  $d=0.1.26-1.85$ ), while TS was higher in CG compared to CJ and CG+J;  
10  $p=0.024-0.037$ ,  $d=0.85-1.11$ ).

11

### 12 ***Exercise Period***

13 No significant differences or moderate-large ES were found between the four trials at  
14 any time point assessed (sets 1-6) for exercise performance (total work:  $p=0.345$  or  
15 mean power:  $p=0.940$ ; Table 2). Further, similar work and power outputs were  
16 maintained over the entire protocol, as no significant differences existed between trials  
17 for 'like' sets (1 vs. 4, work:  $p=0.897$ , power:  $p=0.965$ ; 2 vs. 5, work:  $p=0.832$ , power:  
18  $p=0.857$ ; 3 vs. 6, work:  $p=0.558$ , power:  $p=0.626$ ). Additionally, no significant  
19 difference was found between trials for the overall trial total work ( $p=0.103$ ) or power  
20 ( $p=0.164$ ).

21 Once exercise began,  $T_c$  continued to increase over the 6 sets (main effect for  
22 time  $p<0.001$ ), peaking at an average of  $38.8\pm 0.4^\circ\text{C}$ . This  $\sim 1.5^\circ\text{C}$  rise occurred over 43  
23 min, however no significant differences were seen between trials ( $p=0.082$ ) following  
24 any of the 6 sets. However, moderate ES indicated that  $T_c$  in the CG+J trial tended to  
25 be lower after set 5 ( $38.4\pm 0.3^\circ\text{C}$ ) compared to all other trials ( $\sim 38.6^\circ\text{C}$ ;  $p=0.071-0.179$ ,  
26  $d=0.5-0.56$ ), and lower than CJ following set 6 at trial completion ( $38.6\pm 0.3^\circ\text{C}$  v  
27  $38.9\pm 0.4^\circ\text{C}$ ;  $p=0.080$ ,  $d=0.58$ ). Further, mean  $T_{sk}$  increased slightly by  $\sim 0.4^\circ\text{C}$  (to  
28  $35.9\pm 0.5^\circ\text{C}$ ) from the end of PRE-COOL+WUP to trial completion (set 6). No  
29 significant interaction ( $p=0.140$ ) or main effects for time ( $p=0.061$ ) or trial ( $p=0.814$ )  
30 were found for  $T_{sk}$ , but moderate ES did show that  $T_{sk}$  tended to be higher for CJ  
31 compared to CG+J in sets 4 ( $p=0.197$ ,  $d=0.56$ ) and 5 ( $p=0.154$ ,  $d=0.55$ ) and compared  
32 to CG in sets 5 ( $p=0.132$ ,  $d=0.61$ ) and 6 ( $p=0.071$ ,  $d=0.64$ ).

33 Heart rate increased over each successive set of the exercise protocol, peaking  
34 after the time-trials (sets 1-3:  $\sim 158$  to  $\sim 174$  bpm, sets 4-6:  $\sim 165$  to  $\sim 180$  bpm; main

1 effect for time  $p < 0.001$ ), although no significant differences in HR were found between  
2 trials after each set ( $p = 0.610$ ). Ratings of TS also increased over the exercise protocol,  
3 from '5 = warm' to '7 = very hot' ( $p < 0.001$ ); with a main effect for trial ( $p = 0.002$ ),  
4 which specifically saw higher values for NC compared to CG ( $p = 0.025-0.050$ ,  $d = 0.56-$   
5  $0.58$ ), CJ ( $p = 0.007-0.053$ ,  $d = 0.58-1.04$ ) and CG+J ( $p = 0.005-0.006$ ,  $d = 1.20-1.22$ )  
6 following the first two sets. Furthermore, RPE values also increased in a steady manner  
7 from the commencement of exercise to the end of the exercise protocol (8 to 19;  
8  $p < 0.001$ ), with no significant differences found between trials upon exercise completion  
9 (RPE:  $19 \pm 1 =$  'extremely hard';  $p = 0.224$ ). Blood lactate levels increased rapidly with  
10 exercise ( $p < 0.001$ ), however responses were not significantly different between trials at  
11 any time point ( $p = 0.652$ ) with final BLa values reaching  $18.7 \pm 4.7$  mmol.L<sup>-1</sup>. Finally,  
12 moderate-large ES indicated that a greater sweat loss occurred for NC ( $1.79 \pm 0.33$  kg,  
13 2.42% body-mass loss) compared to all other trials (1.53-1.60 kg, 2.07-2.16% body-  
14 mass loss;  $p = 0.085$ ,  $d = 0.55-0.88$ ).

15 For the Serial Sevens cognitive task, only a significant main effect for time  
16 occurred ( $p < 0.001$ ), as performance on the task (total amount of numbers subtracted)  
17 improved from baseline (~20 subtractions) to the end of exercise (~24 subtractions),  
18 with no significant interaction found for trials at any point during the protocol  
19 ( $p = 0.843$ ). Additionally, participants made an average error of ~1 number each time the  
20 task was performed, but this was not different over time or between trials ( $p = 0.999$ ).

21

## 22 **Discussion**

23 The purpose of this study was to assess the effects of practical pre-cooling methods  
24 (hand and torso cooling alone and combined) compared to NC on subsequent cycling  
25 and cognitive performance in heat. While the CJ and CG+J resulted in reduced Tsk and  
26 TS during pre-cooling compared to CG and NC, no significant differences or moderate  
27 to large ES were found between trials for subsequent exercise or cognitive performance.  
28 Overall, these results do not support our hypotheses.

29

### 30 ***Pre-cooling Period***

31 During the 30 min pre-cooling period, the cooling modalities had little effect in either  
32 decreasing Tc or limiting its rise (across WUP) compared to NC. This is similar to  
33 previous findings where no effect of cooling on Tc was seen when pre-cooling was  
34 undertaken with a CJ alone while resting in heat ( $34.3-37.0^\circ\text{C}$ , 41-50% RH) [46,47] or

1 when a CJ was worn during an active WUP in heat (35.0°C, 44% RH) [10]. In our  
2 study it was expected that the addition of WUP during pre-cooling would have resulted  
3 in an increased flow of cooler blood (as a result of using the cooling modalities,  
4 specifically CJ and CG+J) from the skin to core, with this ultimately reducing Tc  
5 compared to NC prior to exercise commencement. Possibly, attempting to reduce Tc  
6 using cooling modalities that only cover sections of the body (as opposed to CWI) may  
7 not be consistently successful when Tc is within a normal resting range (~36.5-37.5°C)  
8 [48] or when exposed to heat.

9         The Tsk values in the current study were lower during the initial 20 min resting  
10 period in the CJ and CG+J trials compared to NC, but then similarly increased over time  
11 in all trials. This outcome is supported by other studies that performed pre-cooling (20-  
12 40 min) with a CJ in heat (34.3-37.0°C, 41-50% RH) whilst resting and reported  
13 significantly lower Tsk for the CJ compared to control, with Tsk increasing slightly  
14 over the duration of the pre-cooling period in all trials [46,47]. Across the 10 min  
15 PRECOOL+WUP period, Tsk values in the current study again increased over time in  
16 all trials, yet remained lower for CJ and CG+J compared to NC, similar to results seen  
17 in previous studies utilising a CJ during an active WUP in heat [9,10,47]. Despite the  
18 use of cooling modalities, the slight increase in Tsk during rest and WUP for all trials  
19 found here most likely reflect the overwhelming effects of a hot environment on the  
20 body surface. Furthermore, it has been suggested that wearing the CJ whilst resting  
21 may result in vasoconstriction (with a concomitant decrease in blood flow),  
22 consequently reducing heat exchange between the CJ and the core but enabling some  
23 heat exchange from the skin to the CJ to occur, thus resulting in a reduction in Tsk (but  
24 not Tc) when compared with control [12]. When worn during the WUP, the two CJ  
25 trials continued to mediate localised skin cooling (heat exchange between the jacket and  
26 the skin) compared to NC, with the expectation that cooled blood would result in a  
27 lower Tc due to an increase in blood flow as a result of the active WUP [9]. However  
28 this did not occur here possibly due to reasons noted earlier. Furthermore, the  
29 significantly lower Tsk found here in the two CJ trials compared to the CG alone may  
30 be due to the greater BSA covered by the CJ compared to the CG (CJ ~17% versus CG  
31 ~1% [17]), as well as the fact that mean Tsk is calculated from measurements at various  
32 sites on the body, with greater emphasis placed on the sternal measurement, an area  
33 directly covered by the CJ.

1           In respect to Tc and Tsk results for the CG, no published studies to date have  
2 assessed the effect of this modality on Tc and Tsk responses during pre-cooling with or  
3 without a WUP in heat. Consequently, the results found here suggest that this cooling  
4 method has no impact on the rise in Tc and Tsk when used prior to exercise or during a  
5 10 min active WUP in heat. Possibly, the combination of the minimal BSA covered by  
6 the CG and a lack of effect of the CG on Tc that is within a normal resting range may  
7 partly explain these results, although further studies are required to confirm or refute  
8 these findings.

9           While not surprising, our results do show that the cooling provided by CJ and  
10 CG+J also improved (reduced) TS, as participants ‘felt’ significantly hotter in NC  
11 during the entire 30 min pre-cooling period in heat. The lower TS scores associated  
12 with CJ and CG are supported by other studies that reported lower TS results associated  
13 with the use of a CJ during a WUP compared to NC [9,10,47], with no previous studies  
14 assessing TS during WUP using a CG.

15

### 16 *Exercise Performance*

17 Previous studies have reported significant improvements in subsequent maximal  
18 running and cycling endurance performance [9-12,47] following pre-exercise reductions  
19 in Tc and/or Tsk as a result of wearing a CJ (compared to NC) during pre-cooling and a  
20 WUP in heat. Our results contrast with the majority of this research, as no  
21 improvements in subsequent exercise performance were found here following pre-  
22 cooling with the CJ or CG (either alone or in combination), compared to NC. This  
23 result is likely due to similar Tc values being found between all trials following pre-  
24 cooling, despite lower Tsk values (for the CJ trials) and improvements in TS (for all  
25 cooling trials) leading into exercise, compared to NC.

26           Of relevance, Schlader et al. [49] proposed that lower Tsk and TS values  
27 (compared to a control) could influence self-selected exercise intensity, resulting in  
28 greater power output during the initial stages of cycling in heat, however no effect was  
29 found here. Although participants did report feeling ‘cooler’ in cooling trials compared  
30 to NC following the first two sets of exercise, the lower TS values were not enough to  
31 translate into performance benefits in these or later sets (likely due to similar Tc and  
32 Tsk). It is also possible that once exercise commenced in our study the airflow  
33 generated from the bike fan could have limited the previous Tsk cooling effects seen  
34 during the pre-cooling period, as no further differences in Tsk were found for the CJ



1 trials (compared to NC) once exercise commenced. The effect of the bike fan replicates  
2 convection conditions that would typically be encountered during outdoor road cycling  
3 (high ecological validity), therefore the pre-cooling interventions used here may be  
4 more beneficial in sporting scenarios where wind doesn't offer the same convective skin  
5 cooling effect as that typically seen with cycling.

6 As the overall work and mean power output did not differ between the cooling  
7 and NC trials here, the magnitude of any cooling effect produced appears insufficient to  
8 promote any change in exercise performance. Our findings are similar to those by Quod  
9 et al. [46] who reported a reduction in Tsk, but not Tc (compared to NC) following CJ  
10 pre-cooling, with no improvement found for subsequent 40 min cycling time-trial  
11 performance. Further, Stannard et al. [50] also reported that pre-cooling with a CJ  
12 (compared to NC) resulted in no significant differences between trials for Tc or  
13 subsequent 10 km running time-trial performance. Overall, these results infer that pre-  
14 exercise Tc needs to be reduced (compared to NC) for subsequent exercise performance  
15 to have the best prospects of improvement. Of further consideration is the type of  
16 exercise used following pre-cooling. Specifically, the effects of pre-cooling on  
17 prolonged activity generally show greater benefit for submaximal (continuous) exercise  
18 than maximal repeated-sprint activity (as summarised in Bongers et al. [51]). For  
19 example, when wearing a CJ (for 5-20 min) prior to prolonged repeated-sprint cycling  
20 and running protocols in heat (30-80 min in duration), no significant improvements in  
21 subsequent performance were reported [21,52-54]. This contrasts to the significant  
22 performance improvements seen during prolonged continuous cycling and running  
23 following pre-cooling compared to no-cooling [9-13]. These differences may be  
24 because prolonged repeated-sprint performance elicits greater thermoregulatory and  
25 physiological strain than submaximal endurance activity [19], which in turn may limit  
26 the effects of pre-cooling.

27 With regard to the CG, this was the first study to assess Tc/Tsk responses in a  
28 pre-cooling capacity (30 min). No effect was found for subsequent exercise  
29 performance when compared to NC, so it is likely that (similar to CJ) pre-exercise Tc  
30 needs to be lower than control for any subsequent performance benefits to occur after  
31 using a CG. Interestingly, wearing the CG during walking [15] and cycling [16]  
32 exercise in heat has been found to attenuate the rise in Tc and extend exercise time  
33 compared to NC, but using this method during exercise is impractical in most sporting  
34 scenarios. Additionally, using the CG for 10 min following 60 min of exercise-induced

1 hyperthermia reduced  $T_c$  by  $0.4^{\circ}\text{C}$  and improved subsequent 3 km time trial  
2 performance by 20 s in heat ( $\sim 31^{\circ}\text{C}$ ) compared to NC in wheelchair tennis athletes [55].  
3 Therefore, while a CG was not beneficial for the population of athletes or repeated-  
4 sprint cycling activity used in this study, whether this form of pre-cooling could provide  
5 a benefit in sporting populations that have impaired thermoregulatory ability [56] and  
6 face logistical challenges (e.g. wheelchair athletes) requires further investigation.

7

### 8 ***Sweat Loss and Cognitive Function***

9 Here, greater sweat loss occurred in NC, indicating a greater degree of dehydration  
10 (2.42% body-mass loss) compared to all other trials (2.07-2.16%), for the same rise in  
11  $T_c$ . The lower sweat loss found in the cooling trials is likely due to the delayed onset of  
12 sweating promoted by pre-cooling [57]. Of relevance, exercise-induced fatigue and  
13 dehydration (decreases in body-mass  $>2\%$ ) following prolonged exercise in heat has  
14 previously shown impairments in complex cognitive ability [30-32]. In regard to our  
15 cognitive performance results (specifically working memory), no decrement on the  
16 Serial Sevens task was seen throughout or at the completion of exercise in all trials,  
17 although participants were moderately dehydrated (as mentioned above) and fatigued  
18 (mean HR: 180 bpm, RPE: 19 = ‘very, very hard’, TS: 7 = ‘very hot’). Specifically,  
19 task performance (speed and accuracy) improved (total number of correct subtractions  
20 with no change in errors made) during and following exercise compared to baseline in  
21 all trials. This contrasts with our hypothesis as it was thought that strenuous exercise in  
22 heat would impair cognitive performance, as an increased heat load (elevated  $T_c$ )  
23 impairs complex task performance at a lower  $T_c$  than simple/less attention demanding  
24 tasks [58]. Small increases in  $T_c$  (up to  $38.2^{\circ}\text{C}$ ) have been linked to improved complex  
25 cognitive performance [33,59,60], possibly due to exercise-induced arousal [61],  
26 coupled with higher levels of blood adrenaline caused by exercise [62]. These factors  
27 have previously been described to explain improvements in complex decisional tasks  
28 following acute exercise [63] and could explain the similar improvements over time  
29 seen here. Of relevance, impairments in complex task performance have been shown to  
30 manifest when  $T_c$  exceeds  $>39.0^{\circ}\text{C}$  [64,65], suggesting that a greater hyperthermic state  
31 during exercise ( $T_c$  of  $38.8^{\circ}\text{C}$  achieved here) would have had to occur before cognitive  
32 performance decrements may have been seen.

33       Importantly, the Serial Sevens task is a complex cognitive test that assesses  
34 attention, working memory maintenance and manipulation [38]. By maintaining or

1 improving working memory capacity (as seen here), it would be expected that attention  
2 would be improved, thus enhancing the ability to block out distractions during sporting  
3 events [28]. The comparable cognitive scores found between all trials here is most  
4 likely a reflection of the similar Tc values recorded at the end of pre-cooling.

## 5 6 **Conclusion**

7 In summary, the combined method of pre-cooling (CG+J) was similar in effect to the CJ  
8 alone in reducing Tsk and TS prior to exercise and during a WUP (in heat); however,  
9 this did not translate into improved subsequent cycling performance, most likely  
10 because Tc was unaffected by use of these cooling modalities. Further, no benefit of the  
11 CG alone was found on cooling rates or subsequent exercise performance. Notably,  
12 working memory performance improved in all trials, indicating complex cognitive  
13 function was not negatively affected during prolonged high intensity exercise in heat.

## 14 15 **Practical Applications:**

16 Based on these findings, when determining pre-cooling strategies to implement prior to  
17 prolonged exercise performance in hot and humid conditions (such as that anticipated of  
18 the 2020 Tokyo Olympic Games), athletes and practitioners could consider the  
19 following:

- 20 • As the aim of pre-cooling is to lower Tc prior to exercise, the use of practical  
21 methods such as a CJ and CG were unable to do this, nor did precooling with  
22 these devices improve subsequent performance in a trained cycling population  
23 prior to high intensity endurance exercise in heat.
- 24 • Use of more effective pre-cooling methods or multiple methods used together to  
25 cover greater body surface area may be required to achieve reductions in Tc,  
26 hence delay the rise during exercise in heat and improve endurance exercise  
27 performance.
- 28 • While reductions in Tsk and TS were evident following pre-cooling with the CJ,  
29 CG and CG+J, this did not improve subsequent repeated-sprint performance.  
30 However, these physiological responses to cooling with a CJ and/or CG may be  
31 beneficial for improving performance in submaximal endurance events.
- 32 • Pre-cooling with the CG, CJ and CG+J did not improve complex cognitive  
33 performance during a simulated cycle road race in heat (35.0°C and 56.6% RH)  
34 compared to a no-cooling trial. However highly trained athletes were able to

1 maintain successful cognitive functions (i.e. decision-making) when in a  
2 markedly hyperthermic state (T<sub>c</sub> of 38.8°C).

#### 4 **Disclosure statement**

5 The authors have no conflict of interest to declare.

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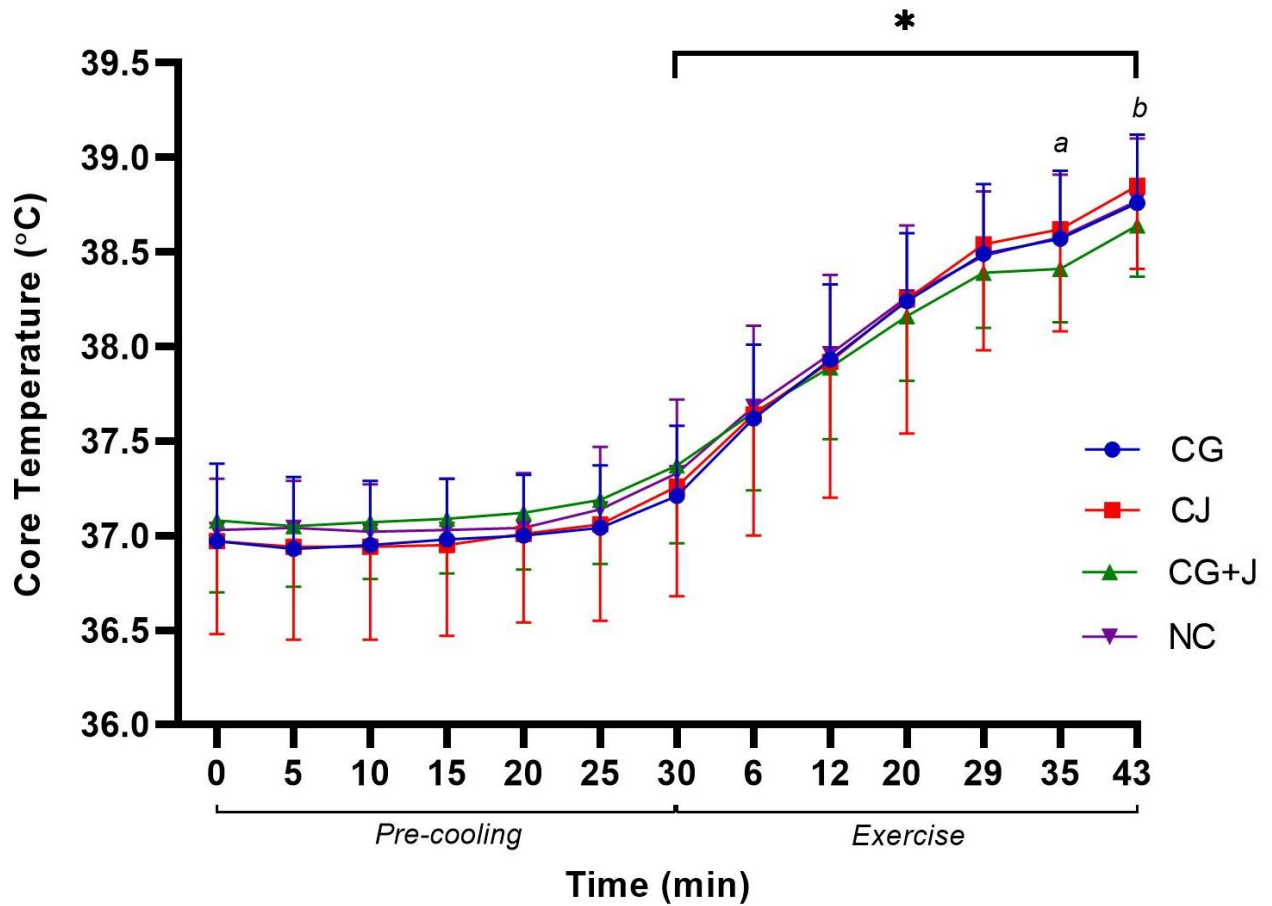
**Table 2.** Total Work (kJ) and Mean Power Output (MPO; Watts) recorded during the simulated cycling race protocol following a 30 min pre-cooling period using a cooling glove (CG), cooling jacket (CJ), cooling glove and jacket (CG+J) or no cooling (NC) (n=10).

	CG		CJ		CG+J		NC	
	Work	MPO	Work	MPO	Work	MPO	Work	MPO
<b>Set 1</b>	51.3 ± 7.9	570.4 ± 88.5	51.9 ± 6.4	577.4 ± 70.9	51.2 ± 6.8	568.9 ± 75.5	51.0 ± 7.7	567.5 ± 85.5
<b>Set 2</b>	47.6 ± 6.4	528.3 ± 69.7	48.1 ± 5.6	533.1 ± 60.1	46.6 ± 6.4	517.1 ± 69.6	46.5 ± 7.5	515.0 ± 80.2
<b>Set 3</b>	95.8 ± 18.2	316.7 ± 55.2	100.8 ± 17.5	333.0 ± 52.7	97.1 ± 17.0	320.6 ± 50.2	98.3 ± 17.5	325.5 ± 53.8
<b>Set 4</b>	51.4 ± 8.2	569.7 ± 88.0	51.9 ± 7.9	575.7 ± 84.5	51.1 ± 7.5	567.9 ± 83.3	50.4 ± 7.9	559.0 ± 85.3
<b>Set 5</b>	45.9 ± 6.8	510.4 ± 77.5	46.8 ± 6.6	520.3 ± 73.4	45.7 ± 6.7	508.2 ± 75.0	45.0 ± 7.4	499.7 ± 82.4
<b>Set 6</b>	96.9 ± 14.5	322.7 ± 47.7	100.4 ± 14.2	339.3 ± 41.7	100.0 ± 17.4	333.2 ± 57.9	97.3 ± 15.9	324.4 ± 82.4
<b>Trial total</b>	388.9 ± 51.0	469.7 ± 60.6	400.1 ± 50.8	479.8 ± 56.4	391.7 ± 51.4	469.3 ± 56.6	388.6 ± 54.3	465.2 ± 63.4

No significant differences ( $p > 0.05$ ) or moderate-large ES were noted for any data.

**Figure 1:** Mean ( $\pm$ SD) core temperature responses ( $^{\circ}$ C) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) and 43 min exercise protocol (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



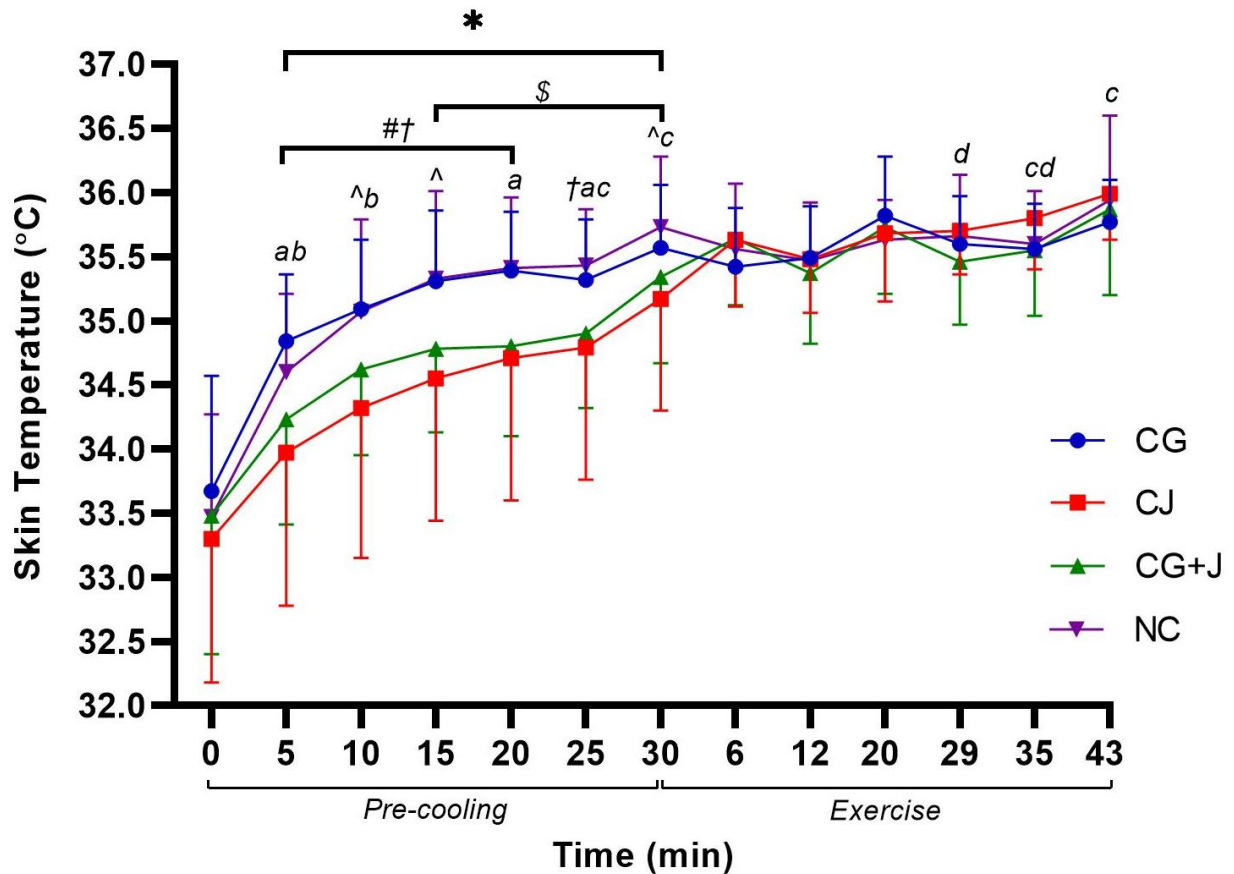
\*Main effect (time); significantly different from preceding time point ( $p < 0.001$ )

<sup>a</sup>Moderate ES for CG+J v all trials ( $d = 0.50-0.56$ )

<sup>b</sup>Moderate ES for CG+J v CJ ( $d = 0.58$ )

**Figure 2:** Mean ( $\pm$ SD) skin temperature responses ( $^{\circ}$ C) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) and 43 min exercise protocol (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



\* Main effect (time); significantly different from preceding time point ( $p < 0.001$ )

# Significant difference for CJ vs. CG ( $p = 0.002-0.022$ )

† Significant difference for CG+J vs. CG ( $p = 0.002-0.022$ )

^ Significant difference for CJ vs. NC ( $p = 0.014-0.040$ )

§ Significant difference for CG+J vs. NC ( $p = 0.004-0.026$ )

<sup>a</sup> Moderate-large ES for CJ vs. NC ( $d = 0.52-0.81$ )

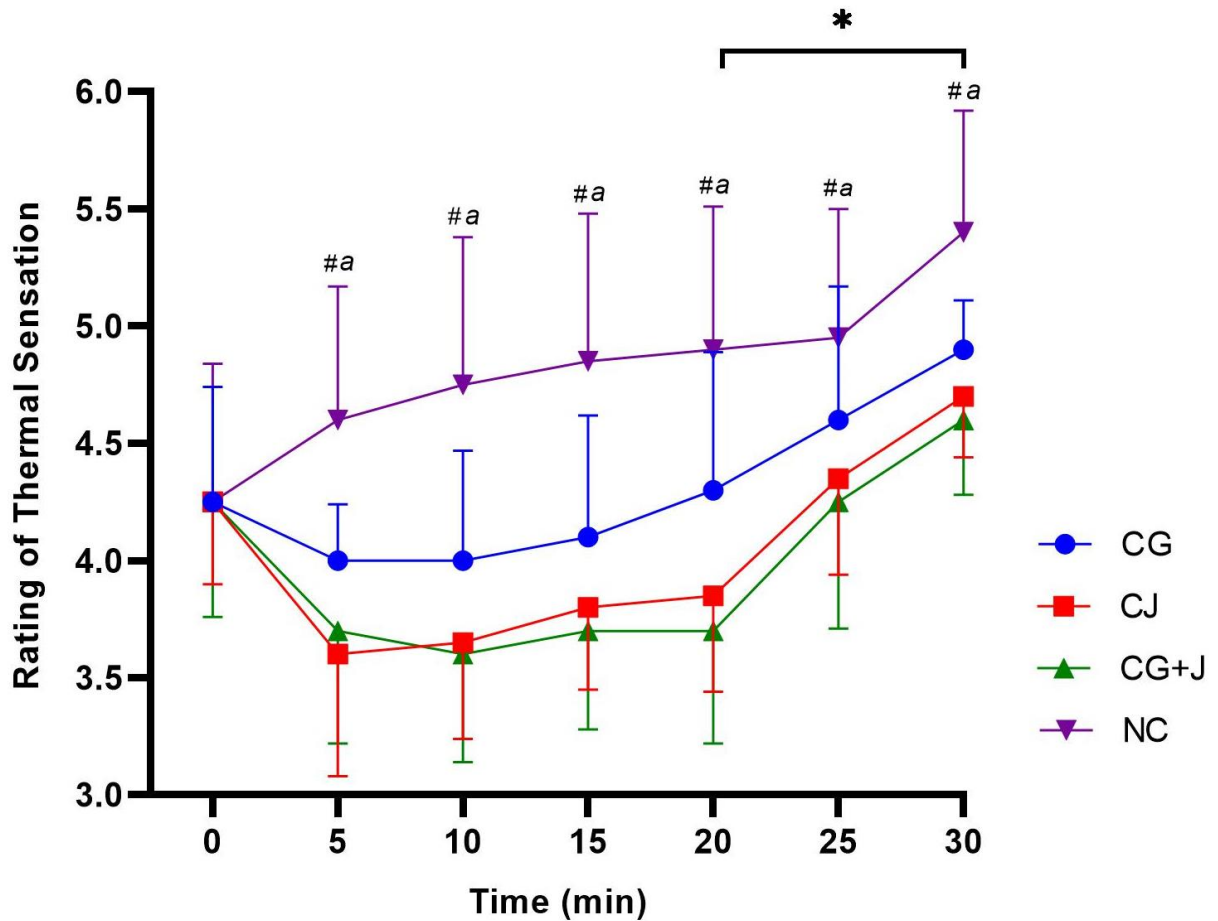
<sup>b</sup> Moderate ES for CG+J vs. NC ( $d = 0.51-0.66$ )

<sup>c</sup> Moderate ES for CJ vs. CG ( $d = 0.55-0.66$ )

<sup>d</sup> Moderate ES for CG+J vs. CJ ( $d = 0.55-0.56$ )

**Figure 3:** Ratings of thermal sensation (mean±SD) during the 30 min pre-cooling period (20 min PRE-COOL, 10 min PRE-COOL+WUP) (n=10).

CG: cooling glove, CJ: cooling jacket, CG+J: cooling glove and jacket, NC: no cooling.



\*Main effect (time); significantly different from preceding time point ( $p < 0.001$ )

# Significant difference for CG, CJ and CG+J vs. NC ( $p = 0.001-0.015$ )

<sup>a</sup> Moderate-large ES for CJ and CG+J vs. CG ( $d = 0.68-1.12$ )