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Effect of cold water immersion on repeat cycling performance and thermoregulation in the heat

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Abstract

To assess the effect of cold water immersion and active recovery on thermoregulation and repeat cycling performance in the heat, ten well-trained male cyclists completed five trials, each separated by one week. Each trial consisted of a 30-min exercise task, one of five 15-min recoveries (intermittent cold water immersion in 10°C, 15°C and 20°C water, continuous cold water immersion in 20°C water or active recovery), followed by 40 min passive recovery, before repeating the 30-min exercise task. Recovery strategy effectiveness was assessed via changes in total work in the second exercise task compared with that in the first. Following active recovery, a mean 4.1% ($s = 1.8$) less total work ($P = 0.00$) was completed in the second than in the first exercise task. However, no significant differences in total work were observed between any of the cold water immersion protocols. Core and skin temperature, blood lactate concentration, heart rate, rating of thermal sensation, and rating of perceived exertion were recorded. During both exercise tasks there were no significant differences in blood lactate concentration between interventions; however, following active recovery blood lactate concentration was significantly lower ($P < 0.05$; $2.0 \pm 0.8 \text{ mmol} \cdot \text{l}^{-1}$) compared with all cold water immersion protocols. All cold water immersion protocols were effective in reducing thermal strain and were more effective in maintaining subsequent high-intensity cycling performance than active recovery.

Keywords: Recovery, thermal strain, perceived exertion, pre-cooling

Introduction

Cryotherapy is commonly used as a post-exercise recovery strategy in a variety of sports. It is thought to be effective when core temperature is significantly increased (Hadad, Rav-Acha, Heled, Epstein, & Moran, 2004), and for the treatment of inflammation, spasm, and pain (Eston & Peters, 1999; Meeusen & Lievens, 1986; Merrick, Ranin, Andres, & Hinman, 1999). While various forms of cryotherapy, including cold water immersion, have been suggested to be effective treatments to decrease metabolism, inflammation, blood flow, pain, and skin, muscle and intra-articular temperatures, as well as increase tissue stiffness (Merrick *et al.*, 1999), the specific effects of cold water immersion on the recovery profile and subsequent performance of athletes has not been studied thoroughly. Cold water immersion has been used to treat cases of hyperthermia and heat stroke, as it creates a thermal gradient between the skin and the environment, which is 25

times that of air (Hadad *et al.*, 2004). Despite a lack of scientific research and understanding about its effects, performing cold water immersion as a recovery strategy following high-intensity exercise has become increasingly popular.

In addition to the use of cold water immersion as a post-exercise recovery strategy, it has also been investigated as a cooling intervention before physical activity (pre-cooling). Intense exercise in hot environmental conditions can raise core temperature by up to 1°C every 5–7 min of exercise (Kay, Taaffe, & Marino, 1999). When core body temperature exceeds 39°C, the ability to maintain maximal muscle activation may become impaired and eventually result in the premature termination of exercise (Gonzalez-Alonso *et al.*, 1999; Marino, 2002; Nielsen *et al.*, 1993). Additionally, similar muscle and core temperatures have been observed at the point of fatigue, suggesting that fatigue primarily responds to signals initiating in the active muscles and internal organs as well as the central nervous

system (Gonzalez-Alonso *et al.*, 1999). Whole-body pre-cooling is thought to enhance the safe temperature margin between the operating temperature and the critical limiting temperature (Marino, 2002), and therefore may enhance athletic performance in hot environments.

Active recovery is anecdotally reported to be one of the most commonly performed post-exercise recovery strategies; therefore, active recovery serves as an ideal control. While active recovery has been shown to enhance the removal of lactate (Bonen & Belcastro, 1976; Gupta, Goswami, Sadhukhan, & Mathur, 1996; Hayashi *et al.*, 2004; Taoutaou *et al.*, 1996), the effect of active recovery on subsequent performance remains inconclusive, with some studies suggesting active recovery can result in the maintenance of performance (Bogdanis, Nevill, Lakomy, Graham, & Louis, 1996; Monedero and Donne, 2000; Signorile, Ingalls, & Tremblay, 1993; Thiriet *et al.*, 1993), whereas others have suggested that subsequent performance is not maintained or enhanced by active recovery (Watson & Hanley, 1986; Weltman & Regan, 1983). The conflicting findings may be attributed to differences in methodologies, exercise protocols/modalities, and markers of recovery. Whole-body cold water immersion performed between exercise tasks may enhance recovery; however, depending on timing, it may also provide a pre-cooling stimulus for the next exercise performance.

To our knowledge, the effect of whole-body cold water immersion on repeat cycling performance and thermoregulation in the heat has not been researched. Furthermore, the effect of various water temperatures and durations of exposure have not been examined. Cold water immersion appears to be an effective recovery strategy for reducing symptoms associated with muscle soreness (Eston & Peters, 1999) and fatigue (Lane & Wenger, 2004), as well as an effective method of pre-cooling before exercise (Kay *et al.*, 1999; Lee & Haymes, 1995; Marsh & Sleivert, 1999). Therefore, it is appropriate to investigate the effects of various cold water immersion protocols on physiological responses to exercise in the heat and cycling performance repeated within a short time. However, it is important to ensure a comparison of the cold water immersion interventions with the commonly implemented practice of active recovery. While the effect of cooling provides a greater allowance for heat storage during exercise as well as reducing both cardiovascular and thermoregulatory strain (Kay *et al.*, 1999), in a hot environment active recovery may have the opposite effect. Therefore, the purpose of the present study was to investigate the effects of cold water immersion and active recovery on repeated cycling performance and thermoregulation in a hot environment.

Methods

Participants

Ten well-trained male cyclists volunteered to participate in the study. Their mean ($\pm$ standard deviation) age, height, body mass, peak oxygen consumption ($\dot{V}O_{2peak}$), and sum of seven skinfolds were as follows: 32 years ($s=5$), 1.81 m ($s=0.05$), 71.6 kg ($s=5.9$), 70.7 ml $\cdot$ kg⁻¹ $\cdot$ min⁻¹ ($s=7.9$), and 53.6 mm ($s=18.6$), respectively. Participants were informed of any risks and provided written informed consent. The study was approved by the Australian Institute of Sport Research Ethics Committee.

Experimental design

Initially, participants completed a $\dot{V}O_{2peak}$ test on a cycle ergometer (Lode, Groningen, Netherlands) to establish each individual's peak power output and $\dot{V}O_{2peak}$. In addition, as the participants were not heat-acclimatized, each individual completed two familiarization trials before testing began. The participants had access to a fan at all times throughout the study, with self-selected fan settings maintained at those selected in each participant's familiarization sessions. The identical cycle exercise tasks consisted of a 5-min warm-up (60 s at each of the following intensities: 125 W, 150 W, 175 W, 200 W, 75% peak power output), 15 min at a workload equal to 75% peak power output, followed immediately by a 15-min time-trial (Jeukendrup, Saris, Brouns, & Kester, 1996). Participants had access to time information and were required to produce as much work as possible in that time, but no other information or encouragement was provided. Immediately after the first exercise task, a standardized cool down was completed (5 min at 40% $\dot{V}O_{2peak}$) (McAinch *et al.*, 2004) followed by one of five 15-min recovery strategies and 40 min of passive recovery. Passive recovery consisted of the participant remaining seated in a temperature-controlled chamber in an attempt to replicate exposure in athletic settings. One hour after the cessation of the initial exercise task (including 5-min cool down, 15-min recovery strategy, and 40 min passive rest), the participants were required to repeat the initial 30-min exercise task (Figure 1). In a randomized crossover design, the participants completed a total of five trials, each separated by one week. The typical error of measurement for total work completed was relatively consistent throughout treatments (0.9–1.3%). All test sessions were conducted in a temperature-controlled chamber in which ambient temperature and relative humidity were maintained at 34.0°C ($s=0.2$) and 39.4% ($s=1.5$), respectively. During all five trials, a carbohydrate beverage

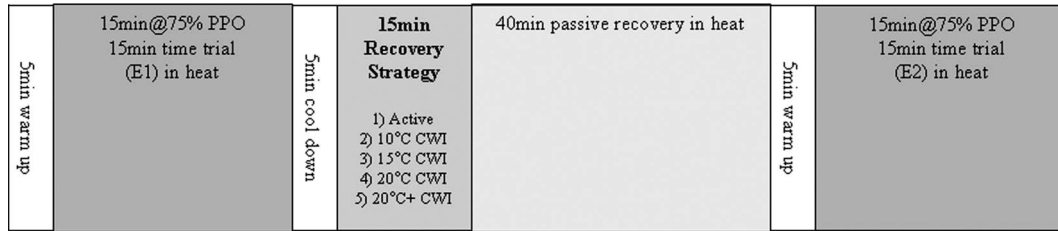


Figure 1. Events of a single test session, including a 5-min warm-up, 30-min exercise task (E1) (15 min fixed intensity at 75% peak power output followed by a 15-min time trial), 5-min warm-down, one of five 15-min recovery strategies, followed by 40 min passive recovery seated in a temperature-controlled chamber before repeating the exercise task (E2).

(Gatorade; 6% carbohydrate content) was consumed ($3 \text{ ml} \cdot \text{kg}^{-1} \text{ body mass}^{-1}$) during the first 15 min of both exercise tasks, as well as $15 \text{ ml} \cdot \text{kg}^{-1}$ during the one-hour recovery between exercise tasks. Participants performed each exercise trial at the same time of day. In addition, body mass was recorded before each trial to ensure body mass was stable throughout the study.

Recovery strategies

Immediately after exercise, participants performed 5 min of cycling at an intensity of 40% $\dot{V}\text{O}_{2\text{peak}}$ (McAinch *et al.*, 2004) followed by one of five recovery strategies:

1. Participants immersed their entire body (excluding the neck and head) while seated in 10°C water in an inflatable bath for 1 min, followed by 2 min out of the bath, repeated five times (five cycles = 15 min). For all cold water immersion protocols, mean air temperature and relative humidity were 29.2°C ($s = 1.4^\circ\text{C}$) and 58.0% ($s = 2.1$), respectively.
2. Participants immersed their entire body (excluding the neck and head) while seated in 15°C water in an inflatable bath for 1 min, followed by 2 min out of the bath, repeated five times (five cycles = 15 min).
3. Participants immersed their entire body (excluding the neck and head) while seated in 20°C water in an inflatable bath for 1 min, followed by 2 min out of the bath, repeated five times (five cycles = 15 min).
4. Participants immersed their entire body (excluding the neck and head) while seated in 20°C water in an inflatable bath for 15 min (continuous exposure).
5. Participants cycled continuously at 40% $\dot{V}\text{O}_{2\text{peak}}$ (McAinch *et al.*, 2004) for 15 min (active recovery). Mean air temperature and relative humidity were 31.1°C ($s = 2.6$) and 48.0% ($s = 4.2$), respectively.

Performance assessment

Total work. The effectiveness of each recovery strategy in maintaining or improving total work during the two 15-min time-trials was assessed by comparing the total work measured during the first and second exercise tasks. Recovery and performance following the cold water immersion and active recovery strategies were also assessed through the measurement of lactate concentration, ratings of perceived exertion, and ratings of perceived thermal comfort.

Mean body temperature ($\bar{T}_b$). Core temperature was monitored with a disposable rectal probe (Mon-a-therm, Mallinckrodt Medical, St. Louis, MO, USA) inserted at least 12 cm beyond the anal sphincter before testing (O'Brien *et al.*, 2000; Zhang & Tokura, 1999). Skin temperatures were monitored with skin thermistors (Grant Instruments Ltd, Cambridgeshire) attached to the left side of the body at four sites (chest, forearm, quadriceps, and calf) using adhesive tape. Rectal and skin temperatures were recorded every 5 min throughout each session (exercise and recovery) from an eight-channel digital thermometer (Zentemp 5000, Zencor Pty Ltd., Australia). Rectal (T_{core}) skin temperatures (T_{Chest} , T_{Forearm} , T_{Thigh} , T_{Calf}) were then used to calculate mean skin temperature ($\bar{T}_{\text{sk}}$) according to the equation established by Ramanathan (1964) (equation 1). Mean body temperature ($\bar{T}_b$) was also calculated by methods described by Schmidt and Bruck (1981) (equation 2).

$$\bar{T}_{\text{sk}} = 0.3 \times (T_{\text{Chest}} + T_{\text{Forearm}}) + 0.2 \times (T_{\text{Thigh}} + T_{\text{Calf}}) \quad (1)$$

$$\bar{T}_b = 0.87 T_{\text{core}} + 0.13 \bar{T}_{\text{sk}} \quad (2)$$

The typical error of measurement for skin temperature was 0.13°C (0.45%). Repeat tests of core

temperature had an intra-class correlation of 0.86, with a typical error of measurement of 0.11°C (0.30%).

Blood lactate concentration. Blood lactate concentration was measured via a capillary earlobe sample and analysed with a Lactate-Pro (Shiga, Japan). During both exercise tasks, blood lactate was measured immediately before exercise, at the end of the 15 min at a fixed (75%) peak power output, and at the end of each of the 30-min exercise tasks. In addition, blood lactate was analysed immediately after the 15-min recovery period (50 min). The typical error of measurement for blood lactate concentration was $0.1 \text{ mmol} \cdot \text{l}^{-1}$ ($< 5 \text{ mmol} \cdot \text{l}^{-1}$) and $0.4 \text{ mmol} \cdot \text{l}^{-1}$ ($5-10 \text{ mmol} \cdot \text{l}^{-1}$).

Rating of perceived exertion. Participants rated their perceived exertion on a scale of 6 ("no exertion at all") to 20 ("maximal exertion") (Noble, Borg, Jacobs, Ceci, & Kaiser, 1983) every 5 min throughout the fixed-intensity phase of the exercise task.

Thermal sensation scale. Participants rated their perceived thermal comfort on a scale of 0 ("unbearably cold") to 8 ("unbearably hot") (Young, Sawka, Epstein, Decristofano, & Pandolf, 1987) every 5 min throughout the entire test session.

Heart rate. A Polar heart rate monitor (Polar Electro Oy, Finland) was fitted to the participant for the duration of the session. Heart rate was recorded every 5 min throughout both exercise tasks, as well as during the one-hour recovery between the exercise tasks.

Statistical analyses

Data are reported as the mean $\pm$ standard deviation unless otherwise stated. A repeated-measures analysis of variance (ANOVA) was used and *post-hoc* pair-wise comparisons conducted to ascertain any significant changes ($P < 0.05$) between selected change scores or means. Percentage change was calculated via log transformation to allow the assessment of changes relative to individual responses rather than absolute values. Also, log transformation applied more uniformity than raw units to all participants. In addition, the 95% confidence interval (CI) (defining the likely range of the true value in the population from which the sample was drawn) for mean scores and differences between means was also calculated and presented where appropriate. Cohen's effect sizes were also calculated to describe any trends in the data. Statistical analyses were conducted using SPSS computer software (Version 12.0, SPSS Inc, Illinois, USA).

Results

Performance

When active recovery was performed between the two exercise tasks, there was a 4.1% ($s = 1.8$) decrease ($P = 0.00$) in total work (kJ) in the second exercise task compared with the first (Figure 2). Absolute values of total work (log transformed) completed are presented in Table I. However, all cold water immersion protocols resulted in the maintenance of performance compared with active recovery, as they achieved significantly lower percentage differences in work completed from the first exercise task to the second ($P < 0.05$). There were no significant differences ($P > 0.05$) among the temperature or temporal variations of cold water immersion, as all four cold water immersion

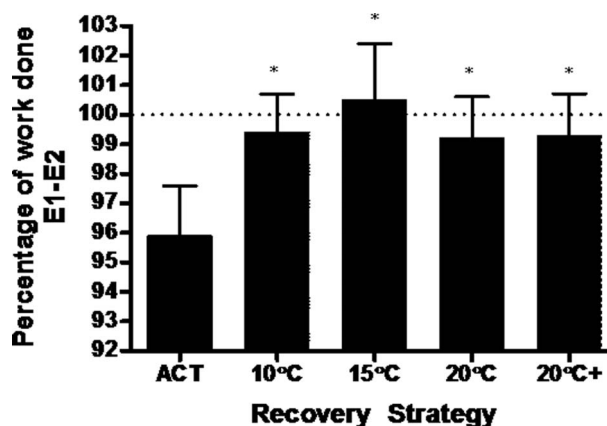


Figure 2. Work done (mean $\pm$ s) in the second exercise task (E2) relative to the first (E1) as a percentage. Dashed line indicates $E1 = E2$. ACT = active recovery; 10°C , 15°C , 20°C = temperature of water in intermittent cold water immersion (CWI) recoveries; $20^{\circ}\text{C}+$ = continuous CWI recovery in water of this temperature. *Significant maintenance/improvement in performance compared with active recovery ($P < 0.05$).

Table I. Log-transformed absolute values of total work (kJ) completed during the first 30-min exercise task and the subsequent 30-min exercise task performed one hour after the first (mean $\pm$ s).

Recovery condition	First exercise task	Second exercise task
Intermittent CWI in 10°C	498 ± 48	495 ± 46
Intermittent CWI in 15°C	498 ± 47	500 ± 46
Intermittent CWI in 20°C	500 ± 44	495 ± 47
Continuous CWI in 20°C	502 ± 47	499 ± 48
Active recovery	503 ± 42	481 ± 38

Note: CWI = cold water immersion.

protocols produced statistically similar improvements compared with active recovery (Figure 2).

Mean body temperature

From the completion of the first exercise task to the end of recovery, there was a significant difference in mean body temperature of 2.6–3.9°C (95% CI) between active recovery and intermittent cold water immersion at 10°C (Figure 3). Additionally, there were significant differences in mean body temperature of 2.2–3.2°C (15°C; 95% CI), 1.6–1.6°C (20°C; 95% CI), and 1.9–1.9°C (20°C+; 95% CI) respectively in the other cold water immersion conditions. Between the first exercise task and the second, there was a difference in mean body temperature of 0.9–1.4°C (10°C; 95% CI), 0.7–1.6°C (15°C; 95% CI), 0.5–1.1°C (20°C; 95% CI), and 0.6–1.3°C (20°C+; 95% CI) between the cold water immersion and active recovery treatments. Additionally, the thermal effect of each recovery intervention was demonstrated immediately after recovery, with mean body temperatures of 34.6°C ($s=0.6$) (10°C intermittent cold water immersion), 35.3°C ($s=0.6$) (15°C intermittent cold water immersion), 36.5°C ($s=0.5$) (20°C intermittent cold water immersion), 36.1°C ($s=0.2$) (20°C+ continuous cold water immersion), and 38.2°C ($s=0.4$) (active recovery). Therefore, a significant reduction in mean body temperature was observed immediately after all cold water immersion recovery interventions. In addition, all cold water immersion protocols resulted in a significant reduction in mean body temperature compared with active recovery.

Blood lactate concentration

There were no significant differences between recovery treatments during the first or second exercise tasks. However, immediately after active recovery, blood lactate concentration was significantly lower ($P < 0.05$) than observed immediately after all cold water immersion treatments (Figure 4).

Rating of perceived exertion

Ratings of perceived exertion at the mid-point of both exercise tasks were significantly lower after intermittent cold water immersion at 10°C (95% CI = 2.4–5.7; $P < 0.05$) and 15°C (95% CI = 0.3–1.4; $P < 0.05$) as well as continuous cold water immersion at 20°C (20°C+) (95% CI = 0.6–2.2; $P < 0.05$) compared with active recovery. However, intermittent cold water immersion at 20°C did not result in a reduced perception of effort compared with active recovery (95% CI = 0.1–1.5; $P > 0.05$). When ratings of perceived exertion were compared at the end-point of both exercise tasks, none of the cold water immersion treatments significantly reduced ($P > 0.05$) perceived exertion compared with active recovery (10°C: 95% CI = –0.3 to 0.8; 15°C: 95% CI = –0.4 to 1.0; 20°C: 95% CI = 0.2 to 1.0; 20°C+: 95% CI = –0.9 to 0.5).

Thermal sensation scale

Following active recovery, the participants' ratings of perceived thermal comfort immediately post-recovery, pre-E2, mid-E2 and at the end of E2 were significantly higher than those following all cold

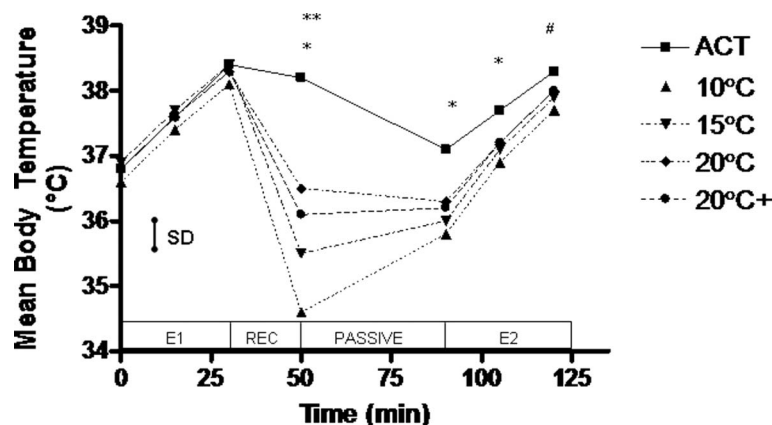


Figure 3. Changes in mean ($\pm s$) body temperature (°C) during the first exercise task (E1), a 5-min active cool down followed by a 15-min recovery strategy (REC), 40 min passive rest, and the second exercise task (E2). ACT=active recovery; 10°C, 15°C, 20°C=temperature of water in intermittent cold water immersion (CWI) recoveries; 20°C+=continuous CWI recovery in water of this temperature. **Significant difference ($P < 0.01$) between active recovery and all four CWI treatments. #Significant difference ($P < 0.05$) between active recovery vs. 10°C, 15°C, and 20°C+ CWI recovery interventions. *Significant difference ($P < 0.05$) between all four CWI recovery interventions.

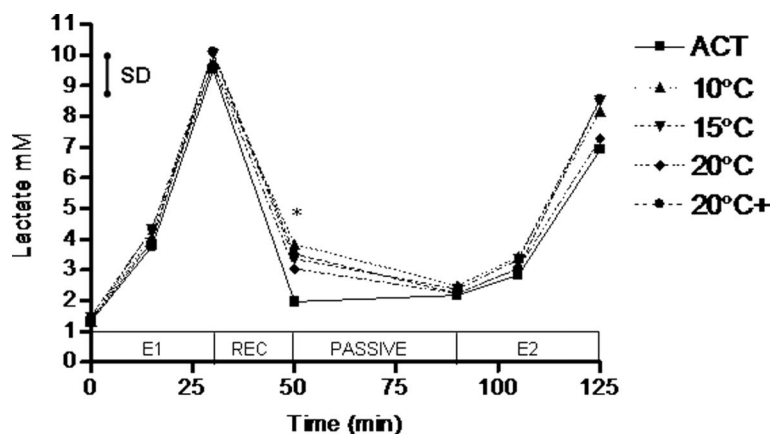


Figure 4. Changes in mean ($\pm s$) blood lactate concentration ($\text{mmol}\cdot\text{l}^{-1}$) during the first exercise task (E1), a 5-min active cool down followed by a 15-min recovery strategy (REC), 40 min passive rest, and the second exercise task (E2). ACT = active recovery; 10°C, 15°C, 20°C = temperature of water in intermittent cold water immersion (CWI) recoveries; 20°C+ = continuous CWI recovery in water of this temperature. *Significant difference ($P < 0.05$) between active recovery and all four CWI treatments.

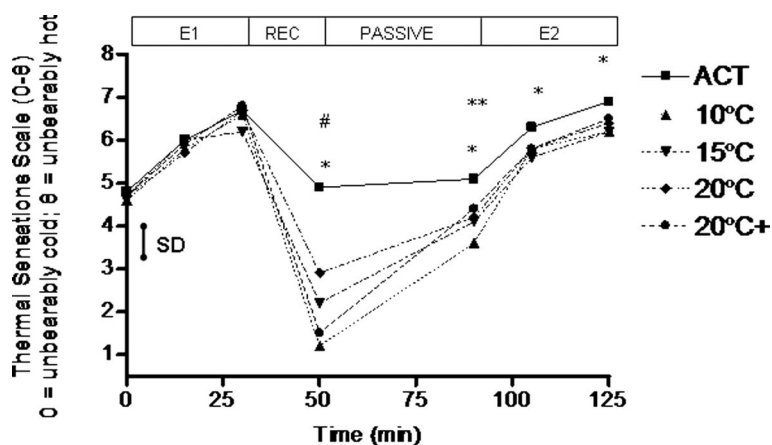


Figure 5. Changes in mean ($\pm s$) perceived thermal comfort during the first exercise task (E1), a 5-min active cool down followed by a 15-min recovery strategy (REC), 40 min passive rest, and the second exercise task (E2). ACT = active recovery; 10°C, 15°C, 20°C = temperature of water in intermittent cold water immersion (CWI) recoveries; 20°C+ = continuous CWI recovery in water of this temperature. *Significant difference ($P < 0.05$) between active recovery and all four CWI treatments. #Significant difference ($P < 0.05$) between CWI protocols 10°C vs. 15°C, 10°C vs. 20°C, and 20°C vs. 20°C+. **Significant difference ($P < 0.01$) between CWI protocols 10°C vs. 15°C, 10°C vs. 20°C, 10°C vs. 20°C+, and 15°C vs. 20°C.

water immersion protocols (Figure 5). Furthermore, immediately after recovery, thermal comfort was rated significantly lower for 10°C versus 15°C and 20°C, as well as for 20°C+ versus 20°C. In addition, immediately before the second exercise task (90 min), thermal comfort ratings were also significantly lower for 10°C versus 15°C, 20°C, and 20°C+, as well as for 15°C versus 20°C+.

Heart rate

During both exercise tasks, there were no significant differences ($P > 0.05$) in heart rate response between any of the recovery interventions. However, immediately after active recovery heart rate was significantly higher ($128 \text{ beats}\cdot\text{min}^{-1}$, $s = 7$; $P < 0.001$) than after all cold water immersion interventions

(10°C: $86 \text{ beats}\cdot\text{min}^{-1}$, $s = 12$; 15°C: $80 \text{ beats}\cdot\text{min}^{-1}$, $s = 7$; 20°C: $81 \text{ beats}\cdot\text{min}^{-1}$, $s = 12$; 20°C+: $81 \text{ beats}\cdot\text{min}^{-1}$, $s = 9$). Interestingly, this significantly reduced heart rate after cold water immersion compared with active recovery ($87 \text{ beats}\cdot\text{min}^{-1}$, $s = 11$) was still evident after 40 min of passive rest in the heat (10°C: $74 \text{ beats}\cdot\text{min}^{-1}$, $s = 13$; 15°C: $69 \text{ beats}\cdot\text{min}^{-1}$, $s = 8$; 20°C+: $71 \text{ beats}\cdot\text{min}^{-1}$, $s = 8$), with the exception of intermittent 20°C cold water immersion ($80 \text{ beats}\cdot\text{min}^{-1}$, $s = 6$).

Discussion

The main finding of the present study was that all cold water immersion protocols were effective in reducing thermal strain and were more effective in

maintaining subsequent high-intensity cycling performance than active recovery. Indeed, no significant differences in total work (second exercise task versus the first) were found between any of the cold water immersion protocols. Additionally, there were no significant differences in blood lactate concentration between interventions or exercise tasks.

The use of cold water immersion as a post-exercise recovery strategy has become increasingly popular and is emerging as an effective post-exercise method of both cooling and enhancing recovery (Eston & Peters, 1999; Lane & Wenger, 2004; Merrick *et al.*, 1999; Yanagisawa, Kudo, Takahashi, & Yoshioka, 2004). Previously, cold water immersion has been used as a method of pre-cooling before exercise in an attempt to improve performance in hot and humid environmental conditions. Various studies have shown cold water immersion (Eston & Peters, 1999; Merrick *et al.*, 1999) and pre-cooling (Hayashi *et al.*, 2004; Kay *et al.*, 1999; Marsh & Sleivert, 1999) to be effective, providing positive results for recovery and/or subsequent performance.

While the effect of pre-cooling has been investigated, we are not aware of any studies that have investigated the effect of such an intervention on a subsequent exercise task. The present study used the cold water immersion intervention as a post-exercise recovery strategy (post-cooling) rather than a pre-exercise (pre-cooling) strategy. The results of this study suggest that the use of cold water immersion of varying temperatures and exposures assisted in an enhanced ability to maintain performance compared with active recovery. Other authors have observed similar findings, reporting various pre-cooling strategies to similarly enhance performance (Armada-da-Silva, Woods, & Jones, 2004; Lee & Haymes, 1995; Marsh & Sleivert, 1999). Lee and Haymes (1995) observed a significantly ($P < 0.01$) longer average exercise duration at 82% $\dot{V}O_{2\max}$ following pre-cooling compared with a control condition. Their pre-cooling protocol consisted of a 30-min exposure to 5°C air (hypothermic) as opposed to 24°C air (thermocomfortable); in addition to a prolonged exercise time, heat storage during the exercise task was greater ($P < 0.01$) following the hypothermic exposure. The authors concluded that pre-cooling resulted in an increased exercise endurance capability, enhanced heat storage capacity, and less strain on both the metabolic and cardiovascular systems (Lee & Haymes, 1995). Similarly, Marsh and Sleivert (1999) found pre-cooling to be effective on a single bout of short-term, high-intensity cycle performance. They reported a significant increase of 3.3% ($s = 2.7$) for a performance test following pre-cooling compared with no pre-cooling. The results of the present study are also in line with those of

Hessemer and colleagues (Hessemer, Langusch, Bruck, Bodeker, & Breidenbach, 1984), who observed a 6.8% increase in mean work rate during a one-hour exercise period compared with a control condition. Therefore, the current findings of an increased ability to produce work following a post-cooling intervention compared with a control are in agreement with previous studies in this area. The findings of this study support cold water immersion as an effective recovery intervention, resulting in the maintenance of subsequent performance significantly greater than that observed after active recovery. It is important to note that this study implemented cold water immersion as a post-exercise recovery strategy (post-cooling) as opposed to a targeted pre-exercise pre-cooling intervention. Therefore, while the aforementioned studies are important in understanding the possible mechanism behind our observed maintenance of performance after cold water immersion, the two cannot be compared directly.

A consistent finding within this study was that there were significant reductions in mean body temperature following all cold water immersion protocols (intermittent cold water immersion in 10°C, 15°C and 20°C water, and continuous cold water immersion in 20°C water), suggesting that changes in blood distribution occurred, likely to be from the peripheral circulation to the central circulation (Marsh & Sleivert, 1999). Indeed, it has been suggested that a critical limiting temperature results in the termination or decline of exercise performance and this is thought to occur due to a reduced efferent command to the skeletal muscles via the central nervous system (Marino, 2004; Nielsen, Savard, Richter, Hargreaves, & Saltin, 1990; Nybo & Nielsen, 2001). In addition, a reduction in core temperature appears to provide a superior capacity for heat storage, which may ordinarily be limited by exercise intensity, body size, metabolic heat production, and also environmental conditions (Marino, 2002). In contrast, however, recent findings (Marino, Lambert, & Noakes, 2004; Tattersson, Hahn, Martin, & Febbraio, 2000) suggest that there may be an anticipatory response that occurs during exercise that allows individuals to ensure the maintenance of homeostasis (Marino, 2004), and that it is this anticipatory response that prevents the attainment of lethal hyperthermia as opposed to the attainment of a critically high core temperature. Whether the effect of lowering core temperature via cooling affects the intensity of pacing due to core temperature at the onset of exercise being reduced and therefore enabling an enhancement and/or maintenance of performance can only be speculated upon at this time. The results of the present study indicate that all cold water immersion

protocols effectively enhanced the maintenance of repeat performance compared with active recovery; suggesting that the reduction in core temperature observed before the second exercise task was beneficial, supporting the notion of an anticipatory regulatory response to exercise in the heat.

A decreased heart rate following pre-cooling strategies has been observed (Hayashi *et al.*, 2004; Marsh & Sleivert, 1999; Olschewski & Bruck, 1988; Wilson *et al.*, 2002) and the results of the present study support such a decrease. In the present study, heart rate was significantly reduced during 40 min of passive rest in the heat following all cold water immersion protocols compared with active recovery of the same duration. No significant differences were observed during the second exercise task; however, it is important to note that more work was completed following all cold water immersion strategies, which may have masked any such effect. Marsh and Sleivert (1999) suggest cooling interventions may result in a decrease in peripheral blood flow, leading to an increase in central blood volume and, therefore, enhanced blood delivery to the working muscles. This increase in central blood flow may be beneficial for subsequent performance and therefore may have played a role in the participants' ability to maintain performance more successfully following cold water immersion versus active recovery. The hydrostatic pressure applied to the body during immersion in water may not only improve the return of fluid from muscle to blood but also increase blood volume, causing an increased stroke volume and cardiac output and thus an increase in blood flow throughout the body (Wilcock, Cronin, & Hing, 2006). Therefore, hydrostatic pressure appears to influence a number of physiological responses that may improve recovery from sustained high-intensity exercise. Marsh and Sleivert (1999) also reported that an increase in central blood volume may provide greater blood availability to the muscle during exercise. In addition, it may increase the clearance of metabolic by-products from the muscle. However, the results of this study do not support this contention, with no significant differences observed in blood lactate concentration between any of the recovery interventions during exercise.

In the present study, there was a significant reduction in perceived exertion during the mid-point of the second exercise task following intermittent cold water immersion at 10°C and 15°C, as well as continuous cold water immersion at 20°C (20°C+). Not surprisingly, no significant differences in ratings of perceived exertion were observed between interventions at the end of the second exercise task, as individuals were near exhaustion at this time and all participants were required to complete as much work as possible in the 15-min time-trial in each of the

exercise tasks. A reduced endurance capability during exercise in the heat has been associated with a higher rating of perceived exertion than similar exercise performed in thermocomfortable conditions (Galloway & Maughan, 1997). Armada-da-Silva *et al.* (2004) reported a significant increase in ratings of perceived exertion at the end of a 14-min cycling exercise following passive heating compared with a control condition. The rating of perceived exertion is thought to be affected via changes in the central nervous system as well as factors such as perception of pain and thermal discomfort (Armada-da-Silva *et al.*, 2004).

We found that a cold water immersion intervention performed between two high-intensity exercise tasks helped to maintain repeat performance in hot environmental conditions compared with active recovery. A reduction in mean body temperature and heart rate following all cold water immersion protocols may have resulted in a decrease in peripheral blood flow and therefore produced a greater volume of blood available centrally or to working muscles (Lee & Haymes, 1995; Marsh & Sleivert, 1999). Indeed, the magnitudes of these temperature reductions were related to the temperature of the cold water used in the protocols (e.g. lower water temperatures resulted in the greatest reductions in mean body temperature). The reductions in mean body temperature may also alter or allow improvements in thermoregulation via greater temperature gradients, producing a greater margin before the previously reported critical temperature is reached. Finally, the neural effects (Meeusen & Lievens, 1986) of cooling and the likely effects of anticipation, pacing ability, and less inhibition of skeletal muscles have all been suggested following cooling.

The findings of the present study support the use of cold water immersion in various sports at times when two training sessions a day may be performed in hot environmental conditions, and during prolonged competitions where opportunities exist for cold water immersion (e.g. half time). Although we did not observe a significant performance enhancement, the maintenance of performance during maximal efforts separated by only one hour may be crucial in many sports (e.g. cycling, rowing).

Future research should attempt to investigate alternative modes of exercise, varying temperatures and durations of cold water immersion, as well as the effect of such an intervention in thermocomfortable conditions.

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