

# Cycling time to failure is better maintained by cold than contrast or thermoneutral lower-body water immersion in normothermia

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## Abstract

**Purpose** To examine the effects of four commonly used recovery treatments applied between two bouts of intense endurance cycling on the performance of the second bout in normothermia (~21 °C).

**Methods** Nine trained men completed two submaximal exhaustive cycling bouts (Ex1 and Ex2: 5 min at ~50 %  $\dot{V}O_2$  peak, followed by 5 min at ~60 %  $\dot{V}O_2$  peak and then ~80 %  $\dot{V}O_2$  peak to failure) separated by 30 min of (a) cold water immersion at 15 °C (C15), (b) contrast water therapy alternating 2.5 min at 8 °C and 2.5 min at 40 °C (CT), (c) thermoneutral water immersion at 34 °C (T34) and (d) cycling at ~40 %  $\dot{V}O_2$  peak (AR).

**Results** Exercise performance, cardiovascular and metabolic responses during Ex1 were similar among all trials. However, time to failure (~80 %  $\dot{V}O_2$  peak bout) during Ex2 was significantly ( $P < 0.05$ ) longer in C15 ( $18.0 \pm 1.6$ ) than in CT ( $14.5 \pm 1.5$ ), T34 ( $12.4 \pm 1.4$ ) and AR ( $10.6 \pm 1.0$ ); and it was also longer ( $P < 0.05$ ) in CT than AR. Core temperature and heart rate were significantly ( $P < 0.05$ ) lower during the initial ~15 min of Ex2 during C15 compared with all other conditions but they reached similar levels at the end of Ex2.

**Conclusions** A 30 min period of C15 was more beneficial in maintaining intense submaximal cycling performance than CT, T34 and AR; and CT was also more beneficial than T34 and AR. These effects were not mediated by the effect of water immersion per se, but by the continuous (C15) or intermittent (CT) temperature stimulus (cold) applied throughout the recovery.

**Keywords** Thermotherapy · Exercise recovery · Hydrotherapy · Cold water immersion · Contrast water therapy

## Introduction

Cold water immersion (CWI) and contrast water therapy (CWT), the repeated alternation of cold and hot water immersion, are commonly used for recovery following exercise in an attempt to enhance exercise performance completed on subsequent days (Ingram et al. 2009; Rowsell et al. 2009; Vaile et al. 2008b) and/or on the same day (Bleakley and Davison 2010; Wilcock et al. 2006). Recent investigations have examined these ‘same day’ scenarios, given that many athletic events require intense performance before and after a short break (Dunne et al. 2013; Peiffer et al. 2010a). Examples would include team sports (soccer, basketball, rugby etc.), track cycling, and athletes competing in multiple events separated by short recovery periods. However, the effectiveness of these recovery strategies remain open to question, at least in part, due to methodological variations across studies, including the exercise type employed during subsequent exercise (sprint versus endurance) and/or the immersion level and water temperature used (Yeargin et al. 2006). In addition, long intervals (>1–2 h) are often incorporated between the end of the

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water immersion and the beginning of the subsequent exercise (Stanley et al. 2012; Versey et al. 2011), where influences other than water immersion per se (i.e. warm-down (Barnett 2006; Heyman et al. 2009), stretching (Weerapong et al. 2004) and/or passive rest) could influence subsequent performance. Thus, from an experimental perspective, it is essential to explore scenarios where subsequent exercise is completed immediately after the immersion period to better understand the ergogenic potential and physiological benefits of water immersion on subsequent performance within the same day excluding other influences.

In this context, when subsequent performance is conducted immediately after a CWI recovery treatment, sprint cycling performance is either negatively affected (Crowe et al. 2007; Schniepp et al. 2002) or unaffected (Peiffer et al. 2010b) when compared with passive unimmersed rest. This is most likely due to a reduced contractile speed of the cooled muscles during maximal contractions undertaken following the immersion period (Bergh and Ekblom 1979; Bigland-Ritchie et al. 1992). In contrast, intense submaximal endurance exercise is enhanced when performed soon after CWI compared with passive unimmersed rest both under normothermic (Dunne et al. 2013; Heyman et al. 2009) and hyperthermic (Peiffer et al. 2010a; Yeargin et al. 2006) ambient conditions. This has been proposed to be mediated by factors such as an increase in heat storage capacity due to a reduction in core temperature (Kay et al. 1999; Marsh and Sleivert 1999), a hydrostatic pressure- or temperature-induced increase in venous return (Wilcock et al. 2006) and/or reactivation of cardiac parasympathetic activity (Stanley et al. 2012). The specific contributions of both the temperature stimulus and hydrostatic pressure stimulus of water immersion on subsequent performance have not been extensively studied, and despite some reports showing that cycling and rowing sprint performance are not maintained following warm water immersion (Pournot et al. 2011; Vaile et al. 2008a), to our knowledge the maintenance of intense endurance exercise performed immediately following warm or thermoneutral water immersion (TWI) has not been explored.

We have shown previously that under normothermic conditions CWT enhances subsequent sprint cycling performance when compared with unimmersed passive rest completed immediately after the CWT treatment (Cramp-ton et al. 2011). However, CWT appears to be less effective for the maintenance of high-intensity time trial performance in normothermia, at least when the subsequent time trial is performed ~2 h after the CWT treatment (Versey et al. 2011). To our knowledge, the ergogenic effect of CWT on intense endurance exercise undertaken immediately following the immersion period has also not been explored. While water immersion during recovery is generally passive and is often compared with a passive control

condition, active recovery remains one of the most common recovery interventions used in applied settings. As such, active recovery also serves as an appropriate control. Despite active recovery being well accepted to enhance lactate clearance (Bangsbo et al. 1994), the effects of active recovery on immediate subsequent exercise performance are poorly understood. Recently, active recovery has been shown to be less effective than CWI for maintaining subsequent intense cycling time trial performance (Vaile et al. 2008a, 2011) undertaken ~40 min after the recovery period; but interestingly, active recovery (20 min of light cycling) has been shown to be as effective as CWI for maintaining 'lead' style intense climbing performance when climbing bouts were performed immediately after recovery (Heyman et al. 2009). However, 'lead' climbing involves eccentric exercise that induces some degree of muscle damage and high lactate levels (Morrison and Schoffl 2007; Watts 2004), but it is not known whether active recovery can be beneficial for subsequent performance of a concentric non-damaging intense submaximal exercise performed immediately after the recovery treatment.

We recently reported that intense running performance is improved immediately following post-exercise cold water immersion when compared with passive rest in normothermia (Dunne et al. 2013). As a follow-up, to explore the specific contributions of water temperature and hydrostatic pressure stimuli as well as active recovery within this context, the main aim of the present study was to compare the effects of post-exercise CWI with CWT, TWI and active recovery treatments on intense exhaustive cycling performance when exercise was performed immediately after the immersion period. Due to the clear effect of active recovery on blood lactate (BLa), the effect of water immersion on tissue and core temperature ( $T_{\text{core}}$ ) and the suggestion that any benefit of water immersion is derived via effects on cardiovascular function, these three variables (i.e. BLa,  $T_{\text{core}}$  and HR) were also assessed during the study. It was hypothesised that compared with TWI and active recovery, performance of the subsequent cycling bout would be enhanced following CWI and CWT.

## Methods

### Participants

Nine trained male club-level triathletes (mean  $\pm$  SD; age:  $30 \pm 3$  year; body mass:  $83 \pm 9$  kg; height:  $179 \pm 6$  cm,  $\dot{V}\text{O}_2$  peak:  $55.6 \pm 8.0$  ml.kg<sup>-1</sup>.min<sup>-1</sup>,  $\dot{V}\text{O}_2$  peak:  $4.6 \pm 0.5$  l.min<sup>-1</sup>) volunteered to participate in this study. All participants were non-smokers and regularly undertook vigorous exercise at least 2–3 times per week and their weekly training regimen was maintained throughout the

study. Participants were required to refrain from consuming caffeine and alcohol for 12 h prior to each laboratory session and to arrive to the laboratory well hydrated. In addition, participants were required to complete a 24 h food and fluid recall upon presentation at the first laboratory session, and then instructed to replicate this food and fluid intake as closely as possible in the 24 h prior to all subsequent sessions. Participants were tested at the same time of day for each trial, and did not undertake any heavy exercise for 24 h prior to each laboratory session. Participants gave written informed consent to participate in this study, which was conducted according to the Declaration of Helsinki and approved by the Faculty of Health Sciences Research Ethics Committee, Trinity College Dublin.

### Experimental protocol overview

Following an initial familiarisation and graded incremental cycling test (visit 1), participants were required to complete four separate randomised trials separated by at least 7 days (visits 2–5). All laboratory tests for each participant were completed within 8 weeks. Each trial comprised an exhaustive submaximal cycling exercise bout (Ex1) followed immediately by a randomised 40 min recovery period, followed by a subsequent second identical exhaustive submaximal cycling exercise bout (Ex2) (Fig. 1). All cycling sessions were performed in the exercise laboratory on an electromagnetically braked cycle ergometer controlled via the standard workload programmer (Excalibur Sport, Lode, Groningen, The Netherlands). The bulk of the recovery period was completed within a separate dedicated recovery room. Ambient temperature in both rooms was  $21 \pm 2^\circ\text{C}$ . Participants were instructed to keep a constant cadence of  $80 \text{ rev}\cdot\text{min}^{-1}$  and during all trials (excluding recovery periods) were cooled with a 300-mm diameter fan (Micromark, UK) placed 1 m in front of them that produced an airflow equivalent to  $3 \text{ km}\cdot\text{h}^{-1}$ . Failure for all exercise tests was determined as the point at which a cadence of  $60 \text{ rev}\cdot\text{min}^{-1}$  could no longer be maintained.

### Familiarisation and graded incremental test (visit 1)

A graded incremental cycling test to volitional exhaustion was performed to determine peak oxygen uptake ( $\dot{V}\text{O}_2$ ). Throughout the test oxygen uptake data were measured using an online metabolic system (Metalyser, Cortex, Leipzig, Germany). Following a 5 min resting period, the test began with 3 min cycling at 120 W and increased incrementally by 30 W every 3 min until failure. Peak  $\dot{V}\text{O}_2$  was defined as the highest 30-s mean value recorded before the participant's volitional termination of the test. The peak workload achieved was defined as the highest workload that a participant could sustain for a minimum period of 60 s. Using linear regression analysis the workloads (W) equivalent to 40, 50, 60 and 80 %  $\dot{V}\text{O}_2$  peak for each participant were calculated. These corresponded to the following % peak workloads:  $32 \pm 7$ ,  $44 \pm 3$ ,  $56 \pm 5$  and  $78 \pm 1$  %, respectively. Following the incremental test, participants completed a 10 min passive hip-level CWI at  $8^\circ\text{C}$  to familiarise them with the immersion procedure.

### Experimental trials (visits 2–5)

#### Exercise bouts (Ex1 and Ex2)

Each exercise bout (Ex1 and Ex2) required triathletes to complete 5 min cycling at a workload corresponding to  $\sim 50$  %  $\dot{V}\text{O}_2$  peak, followed by 5 min at a workload corresponding to  $\sim 60$  %  $\dot{V}\text{O}_2$  peak, followed by cycling at a workload corresponding to  $\sim 80$  %  $\dot{V}\text{O}_2$  peak to exhaustion. Participants were not permitted to consume water during Ex1 and Ex2, however, they were allowed to sip tepid water prior to each exercise bout and during the transition periods. During all exercise bouts to failure participants were blinded to their exercise times. The intense exhaustive exercise bouts employed in the present study have been shown to be less reproducible than the time trial based performance tests (Jeukendrup et al. 1996); however, the fixed-workload exhaustive bouts were necessary to accurately

| Exercise 1        |                   |                                                                  | Recovery (40 min) |                                                         |                  | Exercise 2        |                   |                                                                  |
|-------------------|-------------------|------------------------------------------------------------------|-------------------|---------------------------------------------------------|------------------|-------------------|-------------------|------------------------------------------------------------------|
| 5 min $\sim 50\%$ | 5 min $\sim 60\%$ | <b>TTF bout 1</b><br>$\sim 80\%$ to exhaustion<br>(normothermia) | 5 min transition  | 30 min treatment:<br>1) AR<br>2) C15<br>3) CT<br>4) T34 | 5 min transition | 5 min $\sim 50\%$ | 5 min $\sim 60\%$ | <b>TTF bout 2</b><br>$\sim 80\%$ to exhaustion<br>(normothermia) |

**Fig. 1** Timeline of protocol and workloads (%  $\dot{V}\text{O}_2$  peak) for the treatments of active recovery (AR), cold water immersion (C15), contrast water therapy (CT) and thermoneutral water immersion (T34). TTF (time to failure)

quantify the post-immersion  $T_{\text{core}}$  afterdrop effect and HR responses (see below).

### Recovery treatments

The 40 min recovery period comprised a 5 min transition from the exercise laboratory to the recovery room, followed by a 30 min treatment period, and then a further 5 min transition period back to the exercise laboratory. On each testing day one of the following 30 min recovery treatments were performed: (a) active recovery (AR) comprising cycling at 40 %  $\dot{V}\text{O}_2$  peak (McAinch et al. 2004), (b) cold water immersion at 15 °C (C15), (c) contrast water therapy comprising alternating cold water immersion at 8 °C for 2.5 min followed by hot water immersion at 40 °C for 2.5 min (CT) and (d) thermoneutral water immersion at 34 °C (T34). Treatments were administered in a balanced randomised fashion. During all immersion treatments (C15, CT and T34) participants were seated upright in a custom built 330 litre bath (Sturdy Products, Co. Wicklow, Ireland) with knees bent (~90°) so that the feet remained flat on the bottom of the bath. The level of the water during the immersion treatments was approximately to hip level and ranged from 5 to 7 cm above the thigh level (Crampton et al. 2011). Towels were provided following all water immersion treatments so that participants could dry themselves prior to re-dressing for Ex2.

Hip-level immersion was employed to allow a prolonged exposure to temperatures as low as 15 °C, to induce a sufficient muscle (and core) cooling without a drastic effect on core temperature that might occur with deeper (i.e. neck level) immersion (unpublished observations). During CT, 11 transitions were completed between baths. Transitions lasted 5 s each and were not assisted given that both baths were located side by side. In total, there were six cold immersion phases and six hot immersion phases, which is similar to previous investigations (Crampton et al. 2011; King and Duffield 2009). The 15 °C water temperature for CWI, and the cold-to-hot treatment ratio of 1:1 during CT were also chosen because they are widely reported characteristics of water immersion for recovery post-exercise (Crampton et al. 2011; Versey et al. 2011; Wilcock et al. 2006). Similarly, the 30 min recovery treatment was used as it is within the range of those published previously (4–30 min) (Wilcock et al. 2006). This provided eleven immersion transitions that were expected to be sufficient to examine the response of HR with adequate resolution. It was also expected that 30 min would be short enough so that exercise performance would not yet have recovered to baseline levels. No information regarding the expected outcomes of each recovery intervention was given to participants to limit any bias in treatment response. In addition, no

information on the belief effect of each intervention was collected before the study.

### Measurements

#### Core temperature ( $T_{\text{core}}$ )

During each testing session core (intestinal) temperature, was measured continuously using an ingestible temperature sensor and data recorder (CorTemp, HQ, Florida, USA). Participants were required to swallow one sensor with tepid water approximately 3 h before each testing session, and report to the laboratory for testing at least 2 h postprandial as per the manufacturer guidelines. This monitoring system represents a valid index of core temperature when compared with oesophageal and rectal temperature (Byrne and Lim 2007).

#### Blood lactate (BLa)

Blood lactate concentration was measured from finger prick capillary blood samples using a lactate analyser (1500 Sport; YSI, Yellow Springs, OH, USA). During Ex1 and Ex2 and for each testing trial (visits 2–5) blood lactate concentration was assessed at rest, every 5 min thereafter and at the point of failure.

#### Heart rate

HR ( $\text{beats} \cdot \text{min}^{-1}$ ) was continuously monitored and recorded every 5 s during all exercise bouts using a HR monitor (S725x, Polar Electro Oy, Finland).

#### Data presentation and statistical analyses

Unless otherwise indicated, data are expressed as mean  $\pm$  SEM. TTF data were analysed using a two-way repeated measures ANOVA [trial (C15, CT, T34 and AR) by time (Ex1 and Ex2)] and detected differences quantified using a Tukey–Kramer post-hoc test. Effect sizes (ES) were also calculated using Cohen's  $d$  to compare the magnitude of the difference in TTF between the four trials (Cohen 1988). Thresholds for effect sizes were set as the following: <0.19, trivial; 0.20–0.49, small; 0.5–0.79, moderate; >0.8, large; with an effect size of 0.2 being considered as the smallest worthwhile positive effect. Effect size was computed as  $d = [(\text{mean Ex1} - \text{mean Ex2}) / \text{pooled standard deviation}]$ . Recorded HR,  $T_{\text{core}}$  and BLa data were also analysed using two-way repeated measures ANOVA [trial (C15, CT, T34 and AR) by time (all equivalent sampling points)] followed by a Tukey–Kramer post-hoc test. All statistical analyses were performed using SigmaStat (v3.5, Systat Software, Chicago, USA) with the level of significance set to  $P < 0.05$ .

## Results

### Cycling performance (TTF)

TTF for Ex1 was not different ( $P > 0.05$ ) among the four trials (in minutes; C15:  $20.6 \pm 1.1$ ; CT:  $20.9 \pm 1.4$ ; T34:  $22.4 \pm 1.4$ ; AR:  $20.8 \pm 1.8$ ) (Fig. 2). However, TTF for Ex2 was significantly shorter ( $P < 0.05$ , large ES) than Ex1 in CT ( $14.5 \pm 1.5$ ), T34 ( $12.4 \pm 1.4$ ) and AR ( $10.6 \pm 1.0$ ), but not in C15 ( $18 \pm 1.6$ ,  $P > 0.05$ , moderate ES). In addition, TTF for Ex2 was significantly ( $P < 0.05$ , large ES) longer in C15 than in CT, T34 and AR, and it was also longer ( $P < 0.05$ , moderate ES) in CT than AR (Fig. 2). As a consequence, the percentage change in TTF during Ex2 from Ex1 was significantly ( $P < 0.05$ , large ES) smaller in C15 ( $-11.8 \pm 7.8$ ) compared with CT ( $-30.0 \pm 6.4$ ), T34 ( $-43.8 \pm 6.4$ ) and AR ( $-46.3 \pm 6.0$ ); and it was also smaller ( $P < 0.05$ , moderate ES) in CT than T34 and AR.

### Core temperature

The absolute  $T_{\text{core}}$  responses are shown in Fig. 3a. Following the recovery period,  $T_{\text{core}}$  declined during the transition phase and the first 5 min of Ex2 in C15 and T34 before progressively increasing throughout the rest of Ex2 (Fig. 3a). By minute 5 of Ex2 absolute  $T_{\text{core}}$  in C15 was significantly lower than the rest of the conditions, and it remained lower than AR and CT until ~25 % of the time taken to complete the TTF bout in Ex2. At the point of failure in Ex2  $T_{\text{core}}$  was similar for the four conditions (Fig. 3a).

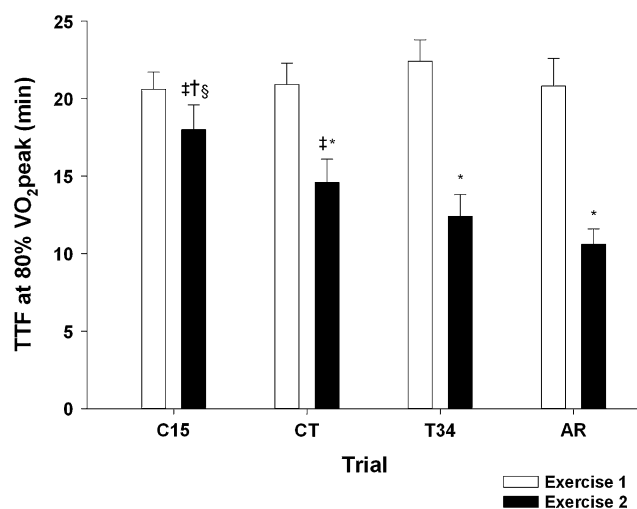


**Fig. 2** Cycling time to failure (min) during the ~80 %  $\dot{V}O_2$  peak bout for Ex1 and Ex2 for the four experimental trials. \*Significantly different from Ex1 ( $P < 0.05$ ); †Significantly different from T34 ( $P < 0.05$ ); ‡Significantly different from AR ( $P < 0.05$ ); §Significantly different from CT ( $P < 0.05$ )

### Blood lactate

Blood lactate was not different among trials while increasing progressively throughout Ex1 (Fig. 3b). At the onset of Ex2, blood lactate tended to be lower for AR when compared with C15 ( $P = 0.06$ ), however, there were no significant differences detected between trials during Ex2 despite again increasing progressively throughout the bout.

### Heart rate

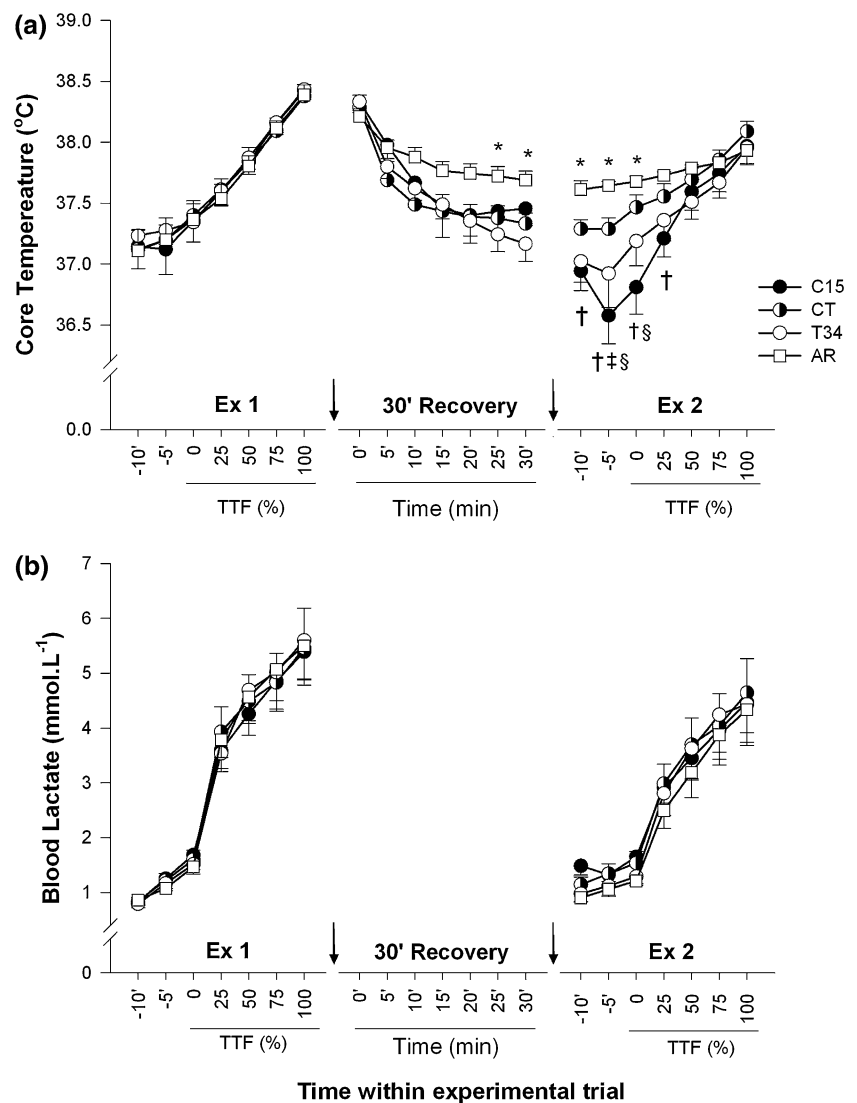
During the 30 min treatment period HR data were significantly higher following every switch between baths in CT when compared with C15 and T34 at similar time points (every ~2.5 min), although the magnitude of the increase in HR tended to be larger when participants moved from warm to cold (Fig. 4). This increase was a short-term response and was not sustained throughout each 2.5 min immersion period in CT. HR responses for C15 were also significantly lower than T34 for most of the time points during the recovery period. During Ex2 HR in C15 was significantly lower than all other trials for the initial 10 min; but during all time points of the TTF bout in Ex2 HR was similar for the four conditions (Fig. 4).

## Discussion

The purpose of the present study was to compare the effect of post-exercise cold water immersion, contrast water therapy, thermoneutral water immersion and active recovery on subsequent intense submaximal cycling performance in normothermic conditions. In contrast to our original hypothesis C15 was the most effective as it was the only treatment that maintained cycling endurance in the subsequent bout, whereas for all other trials cycling endurance during the subsequent bout was significantly reduced when compared with the initial bout. However, overall performance in CT (% change in Ex2 from Ex1) was significantly better when compared with T34 and AR suggesting that C15 and CT recovery interventions are more beneficial than T34 and AR in maintaining subsequent endurance performance.

The performance benefit observed in C15 appeared, at least in part, to be influenced by a reduction in  $T_{\text{core}}$  and, therefore, the associated increase in the available level of heat storage induced by the cold water immersion (Booth et al. 1997; Kay et al. 1999; Lee and Haymes 1995) rather than the water immersion per se, given that in T34 the recovery treatment was not able to maintain subsequent cycling endurance during Ex2. Similarly, previous studies have also reported TWI to be ineffective in maintaining subsequent sprint performance (Pournot et al. 2011; Vaile et al. 2011).

**Fig. 3** Core temperature (a) and blood lactate (b) responses for the four recovery interventions. The mean times of the X-axes are presented in minutes during the initial 10 min (warm-up) of Ex1 and Ex2 as well as the 30 min recovery periods, and then as a percentage of the time achieved during the subsequent TTF tests (i.e. during the ~80 %  $\dot{V}O_2$  peak bouts) of Ex1 and Ex2. The *left arrow* indicates transition to recovery condition, and the *right arrow* transition to cycle ergometer. \*AR significantly different from T34 ( $P < 0.05$ ); <sup>†</sup>C15 significantly different from AR ( $P < 0.05$ ); <sup>‡</sup>C15 significantly different from T34 ( $P < 0.05$ ); <sup>§</sup>C15 significantly different from CT ( $P < 0.05$ )



Upon removal of the cold stimulus there was a significant afterdrop (hypothermic undershoot) effect in C15 reducing  $T_{core}$  by ~0.5 °C by the end of the 5 min transition period and by a further ~0.4 °C by the 5th min of Ex2. This afterdrop effect occurs mostly as a result of the rapid redistribution of blood from the cooled peripheral tissues to the core (Arborelius et al. 1972; Bristow et al. 1994; Mittleman and Mekjavic 1988). As exercise continues a combined effect of an increase in metabolism and restoration of normal muscle temperature results in the distribution of heat from the active musculature to the core, and at this point  $T_{core}$  begins to increase. By the onset of the TTF bout in Ex2 due to this afterdrop effect,  $T_{core}$  for C15 was from ~0.4 to ~0.9 °C lower than for the rest of the trials; while, in turn, the time to reach failure was ~3.5 to ~8 min longer ( $P < 0.05$ ) in C15 when compared with the rest of the trials. This drop in  $T_{core}$  in C15 was accompanied by significantly lower HR responses during the initial 10 min of Ex2 when compared

with the other three treatments, possibly due to a decrease in thermoregulatory strain (Marino 2002; Parkin et al. 1999) as observed under similar normothermic (Dunne et al. 2013) as well as hyperthermic conditions (Peiffer et al. 2010a; Yeargin et al. 2006). Importantly, the end-exercise HR and  $T_{core}$  in Ex2 were almost identical for all four conditions (~166 beats.min<sup>-1</sup> and ~38 °C). Thus, despite participants in the present study not reaching the critical limiting temperature of ~39 °C that has been linked with 'thermal fatigue' (Gonzalez-Alonso et al. 1999), it is possible that cold water immersion somehow delayed the onset of fatigue, at least in part, by maintaining a higher blood flow in previously active muscle, which may coincide with an increase in central blood volume, thereby improving venous return and cardiac efficiency (Vaile et al. 2011). Although it is not clear what caused the failure to continue during Ex1 and Ex2 some participants complained of thermal discomfort and leg muscle fatigue. In this regard, the presumably lower perceived

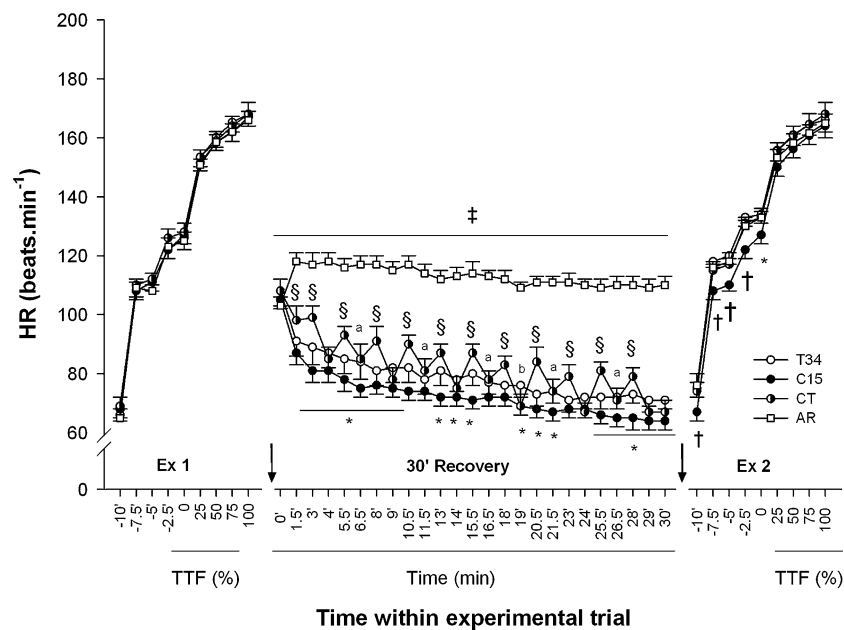


**Fig. 4** Heart rate responses for the four recovery interventions. The mean times of the X-axis are presented in minutes during the initial 10 min (warm-up) of Ex1 and Ex2 as well as the 30 min recovery periods, and then as a percentage of the time achieved during the subsequent TTF tests (i.e. during the ~80 %  $\dot{V}O_2$  peak bouts) of Ex1 and Ex2. The *left arrow* indicates transition to recovery condition, and the

*right arrow* transition to cycle ergometer \*C15 significantly different from T34 ( $P < 0.05$ ); †C15 significantly different from all other trials ( $P < 0.05$ ); ‡AR significantly different from all other trials ( $P < 0.05$ ); §CT significantly different from both C15 and T34 ( $P < 0.05$ ); aCT significantly different from C15 ( $P < 0.05$ ); bT34 significantly different from CT ( $P < 0.05$ )

thermal discomfort and rate of perceive exertion during the initial minutes of the TTF bout in Ex2 during C15 might have affected the performance outcomes.

Despite the significantly different endurance times during Ex2 as a percentage of Ex1 in CT (~70 %) when compared with T34 (~56 %) and AR (~54 %), contrast water therapy did not induce any clear reduction in  $T_{core}$  during the subsequent exercise. However, the relatively brief periods of cold immersion during the contrast protocol may have been responsible for an effect on subsequent performance, possibly by providing a “pumping effect” on the vascular system (Crampton et al. 2011). In the present study, there is evidence for an effect on cardiac function as HR was significantly elevated particularly following the bath transitions, which is somewhat in agreement with recent data from our laboratory (Crampton et al. 2011). Although these data do not provide an explanation of how Ex2 performance was improved in CT when compared with T34 and AR, it is likely that CWT-induced alterations in intra-muscular pressure and blood flow, or the activity of nociceptors in exercised muscles may lead to improved perception of recovery or wellbeing (Stanley et al. 2012; Versey et al. 2011).

Active recovery reduces blood lactate concentration, most likely by maintaining muscle blood flow to allow continued efflux of lactate from active muscle, in conjunction

with uptake by inactive muscle and/or other metabolic sites such as liver (Bangsbo et al. 1995, 1994). In the present study BLA concentrations were numerically lowest in AR at the onset of subsequent endurance exercise, but were not significantly different than the rest of the conditions. However, the present exercise protocol (Ex1) was not designed to induce very high BLA concentrations and thus, it is possible that active recovery might be more effective when more intense exercise protocols are conducted prior to recovery, as shown when employing the modality of intense ‘lead’ style climbing (Heyman et al. 2009).

## Limitations

Given the apparent non-proportional increase in  $\dot{V}O_2$  to power output relationship at exercise intensities exceeding the lactate threshold during step incremental cycling tests (Majerczak et al. 2012; Zoladz et al. 1998, 1995), it is likely that in the present study the assumption of a linear  $\dot{V}O_2$ -workload relationship resulted in overestimation of the load corresponding to 80 %  $\dot{V}O_2$  peak (i.e. 80 %  $\dot{V}O_2$  peak values were underestimated). However, each participant’s loads corresponding to 40, 50, 60 and 80 %  $\dot{V}O_2$  peak were kept the same for all exercise trials, and thus, this factor did not influence the outcomes of the present

study. The hydration status of participants prior to laboratory tests was not quantified, posing a further limitation that may have partly influenced fatigue responses. However, participants were instructed to attend the laboratory tests well hydrated and they were accustomed to attaining an adequate hydration status prior to their competitive races and training sessions. The perceived thermal discomfort or the rates of perceived exertion were not measured in this study and these measurements might have been helpful in shedding some light on the mechanisms whereby exercise performance was superior during C15 and CT.

## Conclusion

In conclusion, the present study supports the use of cold water immersion as a recovery intervention between two bouts of intense submaximal cycling exercise lasting up to ~20 min in moderate ambient conditions (~21 °C). From a practical perspective, cold water immersion could well be applicable for track cyclists competing in multiple events separated by short breaks and/or racing cyclists competing in multiple short duration events such as criterium races. Contrast water therapy appears to be less effective than cold water immersion from our data but still improves subsequent exercise performance when compared with thermoneutral immersion and active recovery. The performance benefits associated with CWI and CWT did not appear to be mediated by the hydrostatic pressure stimulus of water, but more so by the stimulus of the continuous or intermittent application of a cold stimulus, respectively. Our findings are limited to recovery strategies that are not complicated by time and involve hip-level immersions and pre-recovery exercise protocols that do not induce high concentrations of blood lactate; thus, future studies should investigate the effectiveness of water immersion treatments including deeper immersions and more intense exercise protocols. Further studies are also needed to confirm the effectiveness of CWI and CWT using specific recovery times and exercise models that more closely mimic performance of specific team sports. Finally, our findings are likely to be transferable to scenarios under warmer ambient conditions where the effectiveness of CWI and CWT may potentially be magnified due to a greater reliance on thermal factors.

**Conflict of interest** The authors declare they have no conflict of interest.

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