Post-exercise cold water immersion improves intermittent high-intensity exercise performance in normothermia

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Post-exercise cold water immersion improves intermittent high-intensity exercise performance in normothermia

AUTHORS
Avina McCarthy, James Mulligan, Mikel Egaña

CONTACT INFORMATION (corresponding author):
Mikel Egaña
Department of Physiology,
Level 1, Watts Building
Dublin 2, Ireland.
E-mail: megana@tcd.ie
Telephone: +353 1 896 1770
Fax: +353 1 679 3545

AFFILIATIONS & ADDRESSES
Avina McCarthy. Department of Physiology, School of Medicine, Trinity College Dublin, the University of Dublin, Ireland (MCCARTAV@tcd.ie)

James Mulligan. Department of Physiology, School of Medicine, Trinity College Dublin, the University of Dublin, Ireland (jmullig@tcd.ie)

Mikel Egaña: Department of Physiology, School of Medicine, Trinity College Dublin, the University of Dublin, Ireland (megana@tcd.ie)
Abstract

A brief cold water immersion between two continuous high-intensity exercise bouts improves the performance of the latter compared with passive recovery in the heat. We investigated if this effect is apparent in normothermic conditions (~19°C) employing an intermittent high-intensity exercise designed to reflect the work performed at the high-intensity domain in team sports. Fifteen young active men completed two exhaustive cycling protocols (Ex1 and Ex2: 12 min at 85% ventilatory threshold (VT) and then an intermittent exercise alternating 30s at 40% peak power (P_{peak}) and 30s at 90% P_{peak} to exhaustion) separated by 15 min of: a) passive rest, b) 5-min cold water immersion at 8°C and c) 10-min cold water immersion at 8°C. Core temperature, heart rate, rates of perceived exertion and VO_{2} kinetics were not different during Ex1 among conditions. Time to failure during the intermittent exercise was significantly (P<0.05) longer during Ex2 following the 5 and 10 min cold water immersions (7.2±3.5 min and 7.3±3.3 min respectively) compared with passive rest (5.8±3.1 min). Core temperature, heart rate and rates of perceived exertion were significantly (P<0.05) lower during most periods of Ex2 after both cold water immersions compared with passive rest. The time constant of phase II VO_{2} response during the 85% VT bout of Ex2 was not different among the 3 conditions. A post-exercise 5 to 10 min cold water immersion increases subsequent intermittent high-intensity exercise compared with passive rest in normothermia due, at least in part, to reductions in core temperature, circulatory strain and effort perception.

Key words: Exercise recovery, half-time interval, cold-water immersion, hydrotherapy, team sports
Introduction

Intermittent team sports require players to perform short-duration repeated high-intensity efforts separated by brief low-intensity exercise bouts over a prolonged period. Performance of high-intensity exercise has been shown to be significantly reduced during the second half of competitive matches in team sports such as soccer (Reilly 1997; Mohr et al. 2003), handball (Povoas et al. 2012), rugby (King et al. 2009), basketball (Ben Abdelkrim et al. 2007) or futsal (Barbero-Alvarez et al. 2008); thus, for team sport players, an optimal half-time recovery strategy is critical to maximize performance during the second half.

In recent years, cold water immersion (CWI) has received growing attention as a post-exercise recovery intervention to enhance exercise performance completed on subsequent days (Vaile et al. 2008b; Ingram et al. 2009; Rowsell et al. 2009) and/or on the same day (Wilcock et al. 2006; Bleakley and Davison 2010). While recent investigations have examined these ‘same day’ scenarios, their effectiveness is still inconclusive mainly given the methodological variations among studies. These include the type of exercise employed during subsequent exercise (sprint vs. endurance), the water temperature and/or immersion time and level used, or the time interval between the end of the immersion and subsequent exercise bout (sometimes exceeding 1-2 h (Versey et al. 2011; Stanley et al. 2012)).

The vast majority of the previous investigations into the effect of CWI on same-day performance have utilized recovery intervals unsuitable for team sport matches during which players are given ~15 min to recover during half-time. Among studies that most approximate to the ‘half-time’ scenario (i.e. when the CWI/recovery period exceeds 15 min but the post-recovery exercise is performed immediately after the immersion), all-out sprint cycling performance has been shown to be deleteriously affected (Schniepp et al. 2002; Crowe et al. 2007; Crampton et al. 2014). This is most likely due to impaired contractile apparatus of cooled muscles (Bergh and Ekblom 1979; Bigland-Ritchie et al. 1992). Interestingly, a recent study aiming to avoid excessive muscle cooling by maintaining core temperature ($T_{core}$) via upper body exercise during lower-body CWI observed an augmented all-out cycling sprint capacity in subsequent sprinting bouts compared with lower-body CWI without upper body exercise (Crampton et al. 2014); but despite the improvement, active recovery was still superior in maintaining sprint performance compared with both passive and active CWI protocols. On the other hand, high-intensity sustained submaximal endurance exercise appears to be enhanced when performed shortly after CWI compared with passive and/or active recovery in normothermia (Heyman et al. 2009; Crampton et al. 2013; Dunne et al. 2013) and hyperthermia (Yeargin et al. 2006; Peiffer et al. 2010). This has been proposed to be mediated by an
increase in heat storage capacity (Kay et al. 1999; Marsh and Sleivert 1999), an increase in venous return induced by the hydrostatic pressure or cold stimulus of water (Wilcock et al. 2006) and/or reactivation of cardiac parasympathetic activity (Stanley et al. 2012).

To our knowledge only one previous study has investigated the effects of post-exercise CWI carried out within a recovery interval relevant to half time, on subsequent endurance exercise performance carried out immediately after recovery (Peiffer et al. 2010). It was illustrated that a post-exercise 5 min CWI employed within a 15 min recovery interval significantly shortened the completion time of a subsequent 4-km cycling time trial compared with a control (passive rest) condition under hot ambient conditions (35°C). In the study by Peiffer et al (2010) the post-CWI time trial completion time, which was preceded by a fatigue-inducing 25 min moderate intensity bout, was still slower compared with the pre-recovery bout. In order to further explore the use of post-exercise CWI with an applicable immersion protocol to half-time intervals on subsequent exercise performance but under normothermic ambient conditions the aim of the present study was to compare the effects of a short term sternum-level post-exercise CWI (5 min vs. 10 min durations) with a passive rest carried out within a 15 min recovery interval on subsequent intermittent high-intensity exercise performance which was preceded by a fatigue-inducing 12 min moderate exercise bout. As a measure of performance we used an exhaustive exercise protocol which consisted of alternating 30-s of high-intensity with 30-s of low-intensity exercise to reflect the intermittent high-intensity efforts of team sport match play. Due to the effect of cold water immersion on tissue and core temperature and the suggestion that benefits of cold water immersion on concentric non-damaging submaximal exercise are derived via effects on cardiovascular function and/or perception of effort (Peiffer et al. 2010; Crampton et al. 2013; Dunne et al. 2013), to explore the mechanistic basis of any CWI-induced effects on subsequent performance (i.e. time to failure and total work done), $T_{core}$, heart rate (HR) and rates of perceived exertion throughout the entire exercise protocols were assessed. Given that cold exposure (without prior exercise) negatively affects (i.e. slows) the rate of increase in oxygen uptake ($\text{VO}_2$ kinetics) at the onset of subsequent moderate exercise (Shiojiri et al. 1997), to assess whether a brief cold water immersion carried out immediately post-exercise affects subsequent $\text{VO}_2$ kinetics responses, this variable was also measured during the moderate intensity exercise bouts. It was hypothesized that compared with passive rest, both CWI interventions would improve subsequent high-intensity exercise performance.
Materials and methods

Participants
Fifteen young men (mean ± SD; age: 21 ± 1 year; height: 180 ± 5 cm; body mass: 76 ± 8 kg, VO₂ peak: 48.6 ± 7.3 ml.kg⁻¹.min⁻¹, VO₂ peak: 3.8 ± 0.5 l.min⁻¹, Ppeak: 310 ± 32 W) volunteered to take part in this study. All participants were non-smokers with no apparent cardiovascular disease (assessed by medical questionnaire and physical examination) and regularly undertook vigorous exercise at least 2-3 times per week (11 participants were players of an amateur soccer, rugby or Gaelic football team) and their weekly training regimen was maintained throughout the study. All participants were instructed to complete a 24 h food and fluid recall upon presentation to the first laboratory session and to include a meal consisting of approximately 200 g of carbohydrate 3 h prior to this session. They were then instructed to replicate this food and fluid intake as closely as possible in the 24 h prior to their subsequent experimental sessions. Adequate hydration status was ensured at the start of each visit measuring urine specific gravity (accepted euhydration range: 1.000 to 1.020) using an optical refractometer (Bellingham & Stanley, Hants, UK). All participants attended the required laboratory sessions adequately hydrated (i.e. the urine specific gravity was always within the accepted euhydration range). To avoid diurnal fluctuations in Tcore, fatigue and overall exercise capacity, all experimental sessions were held at the same time of day and participants were required to refrain from heavy exercise and caffeine or alcohol consumption for 24 h and 12 h, respectively, before each visit to the laboratory. Each participant 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 Science Research Ethics Committee, Trinity College Dublin.

Experimental Protocol Overview
Following a preliminary incremental cycling test and familiarization (visit 1), participants were required to carry out 3 separate randomized trials (visits 2-4) separated by a minimum of two days. All laboratory sessions were completed within 7 weeks. Each trial required the participants to complete two identical high-intensity cycling bouts (Ex1 and Ex2) separated by a randomized 15 min recovery period (see Fig 1). Each cycling bout consisted of a 3 min warm up period, a 12 min constant load bout followed by repeated intermittent high-intensity exercise bouts to failure. All exercise sessions were performed in the upright position using an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands).
Netherlands). Throughout the incremental test and the 12 min constant load bout participants were instructed to maintain a cadence of 70 rev.min⁻¹ while during the high intensity bouts they cycled at a self-selected cadence and received verbal encouragement in a consistent manner. The ambient temperature of the laboratory in which both the exercise and the recovery protocols were carried out was held constant at a normothermic ambient temperature (19 ± 2°C). During all trials (excluding recovery periods) participants were cooled with a 300-mm diameter fan (Micromark, UK) placed 1 m in front of them that produced an air flow equivalent to 3 km.h⁻¹. Failure for all exercise tests was determined as the point at which a cadence of 60 rev.min⁻¹ could no longer be maintained for more than 3 s.

**Graded Incremental Test and Familiarization (visit 1)**

A graded incremental test to failure was performed to determine the peak power output ($P_{\text{peak}}$), i.e., at VO$_2$ peak, and the ventilatory threshold (VT). After a 3 min period of seated rest, the test began with participants cycling at 30W for 1 min and increased incrementally by 30W every min until task failure. $P_{\text{peak}}$ was defined as the highest workload able to be maintained for a minimum of 30 sec. The VT was determined using the V-slope method (Beaver et al. 1986).

**Experimental Trials (visits 2-4)**

**Exercise bouts (Ex1 and Ex2)**

Each of the experimental sessions involved two identical exercise protocols (Ex1 and Ex2) separated by a 15 min recovery interval. The exercise protocol consisted of a 3 min warm up at 10W followed by a 12 min constant load cycle at a workload evoking 85% VT (204 ± 35 W), a 2 min seated rest period, and finally a series of repeated intermittent high-intensity exercise bouts requiring alternation between 30 s at 40% $P_{\text{peak}}$ (124 ± 13 W) and 30 s at 90% $P_{\text{peak}}$ (279 ± 28 W) until failure. While the present protocol does not specifically mimic the type of match activities of a particular team sport, it was employed to induce failure after participants performing on average ~4 to 8 high-intensity efforts (i.e. total time in the high-intensity domain: ~2 to 4 min), and this reflects the time spent performing high-intensity efforts in many team sports during each half of the match (Mohr et al. 2003; Barbero-Alvarez et al. 2008; King et al. 2009). The 12 min moderate intensity constant-load bouts, which were initiated from a 3 min baseline at 10W, were carried out to 1) assess the VO$_2$ kinetics responses and 2) induce fatigue while still allowing ~4 to 8 high-intensity efforts during the subsequent intermittent high-intensity efforts (a pilot study revealed
that when participants were asked to carry out the moderate constant-load efforts for a longer period of 30 min, they were only able to subsequently complete <4 high-intensity efforts). Participants were allowed to drink small amounts of 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.

**Recovery Interventions**

On each testing day one of the following recovery interventions were performed in a balanced randomized order: (a) passive un-immersed seated rest, (b) 5 min CWI at 8°C (CWI-5) and (c) 10 min CWI at 8°C (CWI-10). During the CWI-5 trial participants were immersed in a custom built bath (Sturdy Products, Co. Wicklow, Ireland) situated next to the cycling ergometer, between min 5 to 10, and were given 5 min to transition from the ergometer to the bath as well as from the bath to the ergometer. The transition times were shortened to 2.5 min to allow for the longer immersion time on the CWI-10 testing trials where participants were immersed between min 2.5 to 12.5. After each immersion period participants dried themselves with towels prior to re-dressing for Ex2 and any surplus time during the transition periods was spent seated passively on a stool. During the recovery treatments participants were seated upright with their back placed against the posterior wall of the bath and their feet against the anterior wall so that their legs were slightly bent (~90°) and fully immersed. During the passive condition participants sat in the same position in the empty bath. During the immersion treatments the level of water was approximately to sternum level while water was fairly stagnant. This level of immersion was employed to induce a significant muscle (and core) cooling without a drastic effect on core temperature that might occur with deeper (i.e. neck level) immersion (unpublished observations). The 8°C water temperature was chosen because it is widely reported characteristic of water immersion for recovery post-exercise (Wilcock et al. 2006) and when compared with passive rest, cold water immersion at 8°C enhances subsequent sustained running performance to a larger extend than cold water immersion at 15°C in similar normothermic conditions (Dunne et al. 2013). The water temperature was monitored with a 6000 series bench thermometer (TM Electronics Ltd., West Sussex, UK) with a type T thermocouple and ice was added to decrease the temperature when needed. 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 (gastrointestinal) temperature was recorded continuously using ingestible body temperature sensors and a hand held data receiver (CorTemp, HQ, Florida, USA). Each participant swallowed the sensor with tepid water approximately 3 h before testing. This method provides a valid index of core temperature in comparison with rectal and oesophageal temperature (Byrne and Lim 2007).

During all cycling tests participants wore a facemask to continuously collect expired air using an online metabolic system (Innocor, Innovision A/S, Odense, Denmark) that measured airflow using a pressure difference pneumotach. Carbon dioxide analysis was performed by using a photoacoustic gas analyzer and oxygen was analyzed using an oxygen sensor (Oxigraf Inc., USA) based on the principle of laser diode absorption spectroscopy. The volume was calibrated with a 3-litre syringe, and the oxygen sensor was calibrated (against room air) prior to each test by the researcher. Both the oxygen sensor and photoacoustic gas analyzer require multi-point calibration performed by the manufacturer periodically (6-12 months). Analysis of expired air allowed determination of pulmonary O\textsubscript{2} uptake (VO\textsubscript{2}), CO\textsubscript{2} output (VCO\textsubscript{2}) and the respiratory exchange ratio breath by breath. HR was recorded second-by-second (S610i, Polar Electro Oy, Finland), rates of perceived exertion were documented using the Borg scale (6 to 20) (Borg 1990) prior to and at the end of each 12-min constant load bout and intermittent high-intensity exercise protocol.

**Data Analysis**

To determine the kinetic parameters of VO\textsubscript{2} at 85% VT, VO\textsubscript{2} responses during the first 6 min of each 12-min bout were linearly interpolated to 1 s intervals, time aligned and smoothed using a 5 s moving average filter. The data were fitted to a biexponential function as follows:

$$VO_2(t) = baseline \ VO_2 + A_c (1 - e^{-(t-TD_c)/\tau_c}) U_c + A_p (1 - e^{-(t-TD_p)/\tau_p}) U_p$$

In this equation, baseline VO\textsubscript{2} is oxygen uptake during cycling at 10 W, and \(A_c\) and \(A_p\), \(\tau_c\) and \(\tau_p\), and TD\textsubscript{c} and TD\textsubscript{p} are the amplitudes, time constants and time delays of the cardiodynamic and primary components, respectively. The conditional expressions (\(U_c\) and \(U_p\)) limit the fitting of a particular phase to the period at and beyond the time delay associated with that phase. Fitting the cardiodynamic phase allowed us to visually determine the transition between the cardiodynamic and primary phase given the large variation observed in the duration of the cardiodynamic phase. However, the cardiodynamic phase cannot be always described by an exponential term (Koga et al. 2005) and thus, only responses of the
primary phase are presented. The VO\textsubscript{2} data were fitted using a weighted least-squares non-linear regression procedure (TableCurve 2D, Systat, USA). Data points lying outside the 95% prediction interval during the initial fit of a model were excluded.

Statistical analysis
Data are presented as mean ± SD. Performance times to failure, number of high-intensity bouts and total work done during the intermittent high-intensity exercise protocol, kinetic parameters of phase II oxygen uptake, HR, \( T_{core} \) and rates of perceived exertion responses were analyzed using a two-way repeated measures ANOVA (trial by time). Differences were detected using Holm-Sidak post-hoc tests. Statistical analyses were performed using SigmaPlot (v. 12, Systat Software, San Jose, USA). Significance was set at \( P \leq 0.05 \). Effect sizes (ES) were also calculated using Cohen’s \( d \) to compare the magnitude of the difference in times to failure, number of high-intensity bouts and total work done between the three 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 \( d = \frac{\text{(mean Ex1} – \text{mean Ex2)} / \text{pooled standard deviation}}{\text{.}} \).

Results

Cycling performance
The time sustained during the intermittent high-intensity exercise protocol in Ex1 was not different \((P > 0.05)\) among the three trials (CWI-5: 8.4 ± 4.7 min; CWI-10: 7.6 ± 3.5 min; passive rest: 8.4 ± 4.4 min) (Fig 2). However, time to failure during Ex2 was significantly longer \((P < 0.05, \text{ moderate ES})\) in CWI-5 (7.2 ± 3.5 min) and CWI-10 (7.3 ± 3.3 min) than the passive rest (5.8 ± 3.1 min) trial. In addition, time to failure during Ex2 was significantly shorter \((P < 0.05, \text{ moderate ES})\) than Ex1 in the passive rest trial while following CWI-5 and CWI-10, performance times were not significantly different between Ex1 and Ex2. Despite not being significantly different, performance times were 1.2 min shorter in Ex2 than Ex1 following CWI-5 (small ES) whereas they were 0.3 min shorter in Ex2 following CWI-10 (trivial ES). The total work done during the intermittent high-intensity exercise was, as a consequence, significantly larger \((P < 0.05, \text{ moderate ES})\) during Ex2 in both CWI-5 (87 ± 44 kJ) and CWI-10 (89 ± 46 kJ) compared with passive rest (70 ± 39 kJ); while it was similar among the 3 conditions during Ex1 (CWI-5: 103 ± 66 kJ; CWI-10: 93 ± 47 kJ; passive rest: 103 ± 60 kJ). Similarly, the total number of high-intensity bouts completed did not differ during Ex1 (CWI-5: 8.3 ± 4.8 bouts; CWI-10: 7.6 ± 3.6 bouts; passive rest: 8.3 ± 2.4 bouts; Ex2 (CWI-5: 6.9 ± 3.6 bouts; CWI-10: 6.3 ± 3.6 bouts; passive rest: 7.0 ± 3.6 bouts).

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4.4 bouts); while it was significantly larger ($P < 0.05$, moderate ES) during Ex2 in both CWI-5 (7.1 ± 3.5 bouts) and CWI-10 (7.2 ± 3.4 bouts) compared with passive rest (5.7 ± 3.2 bouts).

**Core Temperature**

$T_{\text{core}}$ responses across all conditions over time are presented in Fig 3A. During all time points of Ex1 $T_{\text{core}}$ values were similar between the three conditions. $T_{\text{core}}$ progressively increased reaching by the end of Ex1, 38.2 ± 0.4°C (passive rest), 38.1 ± 0.3°C (CWI-5) and 38.2 ± 0.4°C (CWI-10). $T_{\text{core}}$ then declined during the recovery phase under all conditions but CWI-5 induced significantly lower $T_{\text{core}}$ responses during the final 10 min of the recovery interval compared with both passive rest and CWI-10 (Fig 3A). During the entire period of Ex2, both CWI-5 and CWI-10 evoked significantly lower $T_{\text{core}}$ responses compared with the passive rest trial (Fig 3A).

**Heart Rate**

There was no significant variation in HR between the three experimental sessions during Ex1 (Fig 3B). However, CWI-10 and CWI-5 evoked a significantly lower HR compared with passive rest during the constant load period of Ex2. In addition, HR was significantly lower at the mid point of the recovery but higher at the end of the recovery during the CWI-10 compared with CWI-5 trial. This was, however, likely due to the movement of participants in the transitions between the bath and the cycling ergometer. HR responses were similar among the 3 conditions during the intermittent high-intensity exercise period of Ex 2.

**VO$_2$ Kinetics**

The time constant for VO$_2$ phase II ($\tau_p$) was significantly reduced in all 3 conditions during Ex 2 (CWI-5: 28.2 ± 6.4s; CWI-10: 24.2 ± 6.0s; passive rest: 27.5 ± 5.8s) compared with Ex 1 (CWI-5: 31.9 ± 6.5s; CWI-10: 32.5 ± 8.5s; passive rest: 30.8 ± 7.2s) and it was not different among the 3 conditions at Ex1 or Ex2. The amplitude of phase II of VO$_2$ response ($A_2$) during Ex2 was not affected by the recovery condition and in all 3 conditions it was higher than in Ex1.

**Rating of Perceived exertion**

There were no significant differences in rates of perceived exertion values during Ex1 among the three trials (Fig 3C). Rates of perceived exertion were significantly lower for the entire Ex2 during CWI-10
compared with passive rest trials and they were also lower at the beginning and end of the moderate constant load and at the onset of the intermittent high-intensity exercise bout of the Ex2 following CWI-5 in comparison to passive rest (Fig 3C).

Discussion
To our knowledge this is the first study exploring the effectiveness of a short post-exercise CWI treatment on subsequent exhaustive high-intensity exercise performance employed within a recovery time applicable to half time intervals of most team sports in normothermic ambient conditions. The main finding of the present study, in accordance with our principal hypothesis, was that both cold water immersion interventions elicited a significantly longer time to failure and higher total work done in the subsequent intermittent high-intensity exercise protocol compared with passive rest, and that the magnitude of this effect on exercise performance was similar between the CWI-10 and CWI-5 trials. In addition, CWI treatments evoked reduced $T_{core}$ responses during the second exercise bout, but despite these lower $T_{core}$ responses, VO$_2$ kinetics at the onset of the moderate intensity constant-load exercise in Ex2 were not different among the 3 conditions, while they were significantly faster in Ex2 than Ex1 for all 3 interventions. This implies that the CWI-induced reductions in $T_{core}$ (and most likely muscle temperature) were not severe enough to impair the ‘priming’ effect of the pre-recovery high-intensity exercise bout on the dynamic response of VO$_2$ of the subsequent post-recovery exercise. These combined effects also induced a significant reduction in the perception of effort during the subsequent exercise bout.

The ergogenic effects observed in the present study are in agreement with previous studies reporting significant benefits on sustained intense endurance exercise performance immediately following a relatively short CWI period compared with passive and/or active rest in normothermia (Heyman et al. 2009; Crampton et al. 2013; Dunne et al. 2013) and hyperthermia (Yeargin et al. 2006; Peiffer et al. 2010); but provide new evidence showing that a 5 to 10 min CWI intervention within a 15 min recovery period applicable to half-time intervals in normothermic lab conditions increases subsequent high-intensity intermittent exercise performance compared with passive rest.

The lowered $T_{core}$ response during Ex2 and the associated increased heat storage induced by the two CWI protocols are likely to be partly responsible for the beneficial effects on the intermittent high-intensity exercise performance during Ex2 (Lee and Haymes 1995; Booth et al. 1997; Kay et al. 1999).
Immediately after each water immersion intervention there was a significant afterdrop (hypothermic undershoot) effect that is caused by a rapid redistribution of blood from the cooled peripheral tissues to the core (Arborelius et al. 1972; Mittleman and Mekjavic 1988; Bristow et al. 1994). Following CWI-5 $T_{core}$ was reduced by ~0.2°C by the end of the 5 min transition period and by a further ~0.2°C by the onset of the 12 min constant-load bout. Similarly, upon removal of the cold stimulus in CWI-10 $T_{core}$ dropped by ~0.15°C by the end of the 2.5 min transition period and by a further ~0.23°C by the mid-point of the 12 min constant load bout. The magnitude of the $T_{core}$ reduction was, however, larger during water immersion compared with post-immersion given that conductive heat loss from the participant occurs far more rapidly when that participant is surrounded by water than air (Fig 3A). Within the 15 min recovery period it was noted that the absolute reduction in $T_{core}$ was unexpectedly larger after the 5 min CWI compared with the 10 min CWI (and passive) conditions. This was due to the fact that 3 participants showed an exaggerated reduction in $T_{core}$ following the 5-min (but not 10 min) CWI condition (and hence, the variation of the mean $T_{core}$ response was larger compared with the other 2 conditions, see Fig 3A). Given the high sensitivity to the cold stimulus, it is possible that these participants may have shivered during the 10 min CWI conditions which could have increased metabolic heat production and risen core temperature. Importantly, the magnitude of the afterdrop effect, relative to the end-point of the 15 min recovery period, was identical in both CWI interventions, and during the intermittent high-intensity exercise protocol in Ex2, $T_{core}$ was ~0.5°C lower following both CWI trials compared with the passive trial. These afterdrop effects are consistent with previous similar studies (Crampton et al. 2013; Dunne et al. 2013). The drop in $T_{core}$ in the present study was accompanied by reductions in HR during the 12-min constant-load bouts, possibly due to a decrease in thermoregulatory strain (Parkin et al. 1999; Marino 2002). Thus, it is possible that CWI induced an increase in central blood volume, improving venous return and cardiac efficiency (Vaile et al. 2011), and that these combined effects contributed to the lower rates of perceived exertion and the subsequent delayed onset of fatigue.

Despite the reductions in $T_{core}$ following CWI, the time constant of VO$_2$ during the post-recovery moderate exercise bout was not different among the 3 conditions; and it was faster compared with the pre-recovery moderate exercise bout in all 3 conditions. This indicates that the ‘priming’ effect of the pre-recovery exercise bout influenced the VO$_2$ kinetics responses of the post-recovery exercise (Burnley et al. 2006; Murias et al. 2011) and that the moderate drop in $T_{core}$ observed following CWI was not severe enough to impair the oxygen extraction activity of the active skeletal muscles (Shiojiri et al. 1997). This finding is
somehow unexpected given that cooling muscle (and core) temperature has been shown to prolong the time constant of VO\textsubscript{2} during subsequent moderate intensity exercise compared with a normal muscle temperature condition (Shiojiri et al. 1997). However, in the study by Shiojiri et al. (1997) pre-exercise \( T_{\text{core}} \) was on average 1.8°C lower in the ‘cold’ condition, whereas in the present study \( T_{\text{core}} \) was \(~0.5°C\) lower than the passive condition following the immersion protocols. Also in contrast with our findings, Stanley et al (2014) reported significantly longer time constants of VO\textsubscript{2} during high-intensity cycling exercise following a short (5 min) post-exercise CWI intervention when compared with passive recovery (Stanley et al. 2014). The causes of the different outcomes in VO\textsubscript{2} kinetics between our study and the study by Stanley et al. (2014) are unclear, but they might be related to methodological differences, including differences in exercise intensities used to fit VO\textsubscript{2} responses (moderate vs. severe) and the fact that \( T_{\text{core}} \) responses following CWI were elevated compared with the passive condition during subsequent exercise in the study by Stanley et al. (2014).

While it is possible that the performance benefits observed following cold water immersions could be induced by the hydrostatic pressure during water immersion, it is likely that this would have a minimal influence given that the time sustained during high-intensity exercise has been shown to be significantly shorter immediately after a post-exercise warm water immersion (34°C) compared with cold water immersion (15°C) in similar normothermic conditions to the present study (Crampton et al. 2013). Given that water immersion during recovery is generally passive, in the present study we used a passive control condition. However, active recovery is one of the most common recovery interventions used in applied settings, as, among other factors, enhances lactate clearance (Bangsbo et al. 1994). While active recovery has been shown to be as effective as cold water immersion maintaining ‘lead’ style climbing endurance performance (which involves eccentric exercise that induces some degree of muscle damage and high lactate levels) (Heyman et al. 2009), active recovery is less beneficial than CWI for subsequent concentric non-damaging submaximal exercise similar to that employed in the present study (Vaile et al. 2008a; Vaile et al. 2011; Crampton et al. 2013).

Even if exercise performance was quantitatively reduced to a marginally higher extent in Ex2 relative to Ex1 following CWI-5 than CWI-10 (small vs. trivial effect sizes respectively), the physiological and ergogenic benefits following 5 and 10 min of cold water immersion were overall similar suggesting that an immersion period beyond \(~5\) min, within a 15 min recovery period, does not induce additional benefits
in subsequent high-intensity endurance exercise performance. This is practically relevant given that a 5-min immersion protocol is more applicable to half time intervals of team sports. While our findings are encouraging to support the use of cold water immersion during half-time intervals in normothermic ambient conditions, our high-intensity protocol was preceded by a moderate intensity bout, thus, from a practical perspective a brief warm up routine within the half-time period after the cold water immersion should be considered. Further studies assessing the effect of a short (5 min or shorter) CWI followed by a brief warm-up routine within the recovery intervention on subsequent exercise performance that more closely mimic activity patterns of specific team sports would help elucidate this.

Limitations
Given that VO₂ kinetics were modeled using a single bout of exercise, these results need to be taken with caution as multiple bouts are recommended to increase the dynamic resolution of subtle response characteristics (Lamarra et al. 1987). Participants in the present study exercised with a relatively low airflow of 3 km.h⁻¹ while they created larger speeds and would, therefore, generate larger equivalent facing windspeeds. While inducing high levels of air velocity (10 to 50 km.h⁻¹) significantly reduces the heat storage and core temperature compared with windstill conditions in hot (33-35°C) laboratory environments (Adams et al. 1992; Saunders et al. 2005), Adams et al (1992) showed that under moderate ambient laboratory conditions (24°C) the core temperature and heart rate responses were similar when participants cycled for 60 min at a moderate intensity with an air velocity of 12.6 km.h⁻¹ compared with a windstill condition (Adams et al. 1992). This was likely due to a combination of a large convection and radiation heat loss and the intrinsic airflow created by leg movement providing an increased evaporative heat dissipation in moderate ambient conditions. However, the work rate used in the present study was larger than the work rate used in the study by Adams et al (1992), and thus, it is possible that \( T_{core} \) responses during exercise in the present study could have been lower had we used higher air velocities, potentially influencing the magnitude of the positive benefits of CWI recoveries.

For practical reasons we used gastrointestinal temperature using ingestible sensors and a data recorder as an index of core temperature. When comparing with esophageal and rectal temperature, gastrointestinal temperature provides similar measurements of core temperature when participants are immersed in cold water, both during passive rest as well as constant-load moderate exercise (O'Brien et al. 1998). However, gastrointestinal temperature demonstrates a ~50% slower response time or delay to an increase in
temperature relative to esophageal temperature, but not rectal temperature, during transitions to moderate and high-intensity exercise in hot ambient conditions (Kolka et al. 1993; Teunissen et al. 2012), although this slower response time to an increase in temperature is less pronounced (~30% slower) during transitions to moderate exercise in normothermic conditions (Lee et al. 2000). Thus, it is likely that the rate of change in core temperature in the present study may have been faster if esophageal temperature was employed to assess core temperature. Despite this limitation, in the present study the thermal afterdrop occurred relatively fast (i.e. it reached the lowest \( T_{\text{core}} \) value within the first ~5 min post-recovery), and thus, it is likely that this slower dynamic change in temperature observed using gastrointestinal relative to esophageal temperature has a small influence in the interpretation of the present findings.

In conclusion, this study showed that when compared with passive rest, a short-term (5 to 10 min) post-exercise cold water immersion at 8°C employed within a 15 min recovery period increases the time to failure and work performed during a subsequent high intensity intermittent exercise protocol (which reflects the time spent performing high-intensity efforts during team sports) in normothermia. These performance benefits following cold water immersion were, at least in part, due to an enhanced thermal capacity and a reduced cardiovascular strain and perception of effort.

**Conflict of interest statement**

The authors declare that there are no conflicts of interest.
REFERENCES


Figure legends

**Figure 1**: Timeline of protocol for the treatments of passive recovery, 5 min cold water immersion (CWI-5) and 10 min cold water immersion (CWI-10). Workloads for the intermittent high-intensity exercise to exhaustion are relative to the % peak power ($P_{peak}$). VT, ventilatory threshold. Discontinuous lines represent a 2 min passive rest period.

**Figure 2**: Mean (±SD) cycling times to failure during the intermittent high-intensity exercise for Ex1 and Ex2 for the three experimental conditions. *Significantly different from passive rest during Ex2 (P < 0.05); † Significantly different from Ex1 (P < 0.05).

**Figure 3**: Mean (±SD) core temperature (A), heart rate (B) and rates of perceived exertion (C) responses at different time points during the experimental trial for the three conditions. Mod, 12-min moderate-intensity constant-load exercise; mid, mid time point; High-int, intermittent high-intensity exercise to failure. * CWI-5 significantly different from passive rest (P < 0.05); † CWI-10 significantly different from passive rest (P < 0.05); ‡ CWI-10 significantly different from CWI-5 (P < 0.05).
Figure 1

<table>
<thead>
<tr>
<th>Exercise 1</th>
<th>Recovery (15 min)</th>
<th>Exercise 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate-intensity exercise (3’ at 10W, 12’ at 85%VT)</td>
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</tr>
<tr>
<td><strong>High-intensity exercise to exhaustion</strong> (30s 40% / 30s 90%)</td>
<td>1) Passive rest</td>
<td>Moderate-intensity exercise (3’ at 10W, 12’ at 85%VT)</td>
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<tr>
<td>2) CW1-5</td>
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<tr>
<td>3) CW1-10</td>
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<tr>
<td></td>
<td></td>
<td><strong>High-intensity exercise to exhaustion</strong> (30s 40% / 30s 90%)</td>
</tr>
</tbody>
</table>
Figure 2

![Bar graph showing time to failure for different conditions.](image)

- High-intensity exercise during Ex1
- High-intensity exercise during Ex2

**Y-axis**: Time to failure (min)

**X-axis**: Recovery intervention

- Passive rest
- CVI-5
- CVI-10

Statistical significance marked with symbols:
- †
- *

209x296mm (300 x 300 DPI)
Figure 3

A

Core Temperature (°C)

Ex 1 15° Recovery Ex 2

Passive rest CWI 6 CWI 10

B

Heart rate (beats/min)

C

Rate of perceived exertion

Time within experimental trial

209x296mm (300 x 300 DPI)