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ORIGINAL ARTICLE

A customised cold-water immersion protocol favours one-size-fits-all protocols in improving acute performance recovery

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Abstract
The purpose of the present study was to investigate whether a customised cold-water immersion (CWIc) protocol was more effective in enhancing acute performance recovery than a one-size-fits-all CWI (CWIs) or active recovery (AR) protocol. On three separate testing days, 10 healthy, physically active, non-smoking males completed the same fatiguing protocol (60 squat jumps and a 2′30″ all-out cycling time-trial) followed by CWIc (12°C, 10–17 min), CWIs (15°C, 10 min) or AR (60 W, 10 min). Outcome measures to assess acute recovery were heart rate variability (HRV) as HRVrecovery, muscle power (MP) as absolute and relative decline, and muscle soreness (MS) at 0 and 24 h. HRVrecovery for CWIc was significantly higher compared to CWIs ($p = .026$, $r = 0.74$) and AR ($p = .000$, $r = 0.95$). The relative decline in MP after CWIc was significantly lower than after CWIs ($p = .017$, $r = 0.73$). MS 0 h and MS 24 h post-intervention were not different after CWIc compared to CWIs and AR ($p > .05$). The findings of the present study demonstrated that CWIc outperforms CWIs and AR in the acute recovery of cardiovascular (HRV) and CWIs in neuromuscular (MP) performance with no differences in MS. To optimise the effects of CWI, contributions of the protocol duration and water temperature should be considered to guarantee an optimal customised dose.

Keywords: *Acute recovery, physiology, exercise, cold-water immersion*

Highlights
- Customized cold water immersion protocols outperforms one-size-fits-all cold water immersion protocols and active recovery in the acute recovery of cardiovascular and neuromuscular performance with no differences in muscle soreness.
- The recovery objective and individual characteristics (body composition) should be taken into account to optimize the effects of cold water immersion.

Introduction

Many athletes have to perform several (sub-)maximal efforts in quick succession, signifying the need for optimal acute recovery. To enhance the acute recovery process of athletes, active recovery (AR) and cold-water immersion (CWI) (Barnett, 2006; Cochrane, 2004) are highly implemented in sport practice. Therefore, it is surprising that, particularly for CWI, standardisation on its use is lacking except some general guidelines (Versey, Halson, & Dawson, 2013). Moreover, CWI research does not take into account the (a) recovery objective and (b) the individual characteristics of athletes, irrespective of suggestions made by other colleagues (Schimpchen et al., 2016; Stephens, Halson, Miller, Slater, & Askew, 2016). In fact, it is concluded that this one-size-fits-all approach might be the reason why literature shows variability and disparity in the effectiveness of CWI for acute recovery and contributes to the fact that different studies (Glasgow, Ferris, & Bleakley, 2014; Peiffer, Abbiss, Watson, Nosaka, & Laursen, 2009; White, Rhind, & Wells, 2014) were not able to quantify a dose–response concerning the individual athlete or type of exercise.

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CWI usually consists of full-body immersion (e.g. nipple height) in a cold-water bath and is applied for 5–15 min at a water temperature of 10–15°C (Versey et al., 2013). These ranges conceive the optimal contemporary standards and are considered effective in reducing muscle soreness (MS) (Bleakley et al., 2012), improving power losses (Leeder, Gissane, van Someren, Gregson, & Howatson, 2011) and enhancing reduced sprint performances (Poppendieck, Faude, Wegmann, & Meyer, 2013).

Although no single marker can be taken as an indicator for insufficient (acute) recovery, the regular monitoring of a combination of factors is proposed to be the best strategy (Meeusen et al., 2013). Well-known factors prescribing the acute recovery of the central nervous, cardiovascular and neuromuscular systems are heart rate variability (HRV), power output (muscle power, MP) and perceived MS. HRV is related to the fluctuations of the autonomic nervous system (Aubert, Seps, & Beckers, 2003) and describes the cardiac variation between consecutive heartbeats (Malik, 1996). More rapid increases of HRV indices after CWI have consistently been reported (Al Haddad et al., 2010; Bastos et al., 2012; Buchheit, Mendez-Villanueva, Quod, Poulos, & Bourdon, 2010; Parouty et al., 2010). MP and MS are affected by the repetitive muscle contractions during exercise. CWI induces fluid shifts from the interstitial to intravascular space thereby targeting inflammatory responses and oedema in muscles after exercise (Wilcock, 2005), preventing a reduction in contractibility and thereby performance (Leeder et al., 2011; Wilcock, Cronin, & Hing, 2006).

The stress on the central nervous-, cardiovascular- and neuromuscular system changes when the mechanical and metabolic loading is different. The recovery of these systems will therefore differ as well. Stephens et al. (2016) hypothesised that endurance and stretch-shortening exercise are more responsive to CWI than isolated concentric exercises. Additionally, Machado et al. (2016) demonstrated a higher dosage as more effective in relation to influencing MS in both acute and delayed effects, although treatment temperatures were constrained between 11°C and 15°C. Hypothetically, activities described by a high mechanical and metabolic loading of the muscle should therefore be treated with a higher dosage of CWI compared to activities with a lower mechanical loading.

Furthermore, personal characteristics should be considered as well with CWI in order to optimise its efficacy. Muscle temperature negatively correlates with local fat percentage, (Fiala, Havenith, Bröde, Kampmann, & Jendritzky, 2012; White & Wells, 2013), gender determines differences in cooling rate (Lemire, Gagnon, Jay, & Kenny, 2009), age impacts cold susceptibility and skin temperature responses (Stocks, Taylor, Tipton, & Greenleaf, 2004) and ethnicity illustrates differences in heat conductivity (Rennie & Adams, 1957).

The objective of the present study was to investigate whether a customised cold-water immersion (CWIc) protocol was more effective in enhancing acute recovery than a one-size-fits-all CWI (CWIs) or AR protocol. It was hypothesised that CWIc was more beneficial in the improvement of acute recovery of HRV, MP and MS compared to CWIs and AR as the dose of CWIc was individually tailored to the (a) recovery objective and (b) personal characteristics.

Methods

Study design and participants

The study was a randomised effect study with repeated measures. An ethical proposal has positively been judged by the internal ethics commission of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam. An a priori power analysis (G*power 3.1.7, Universität of Düsseldorf, Düsseldorf, Germany) including a power of 0.80 and alpha of 0.05 was performed to evaluate the differences in HRV between CWIc and CWIs. This resulted in the inclusion of 10 healthy, physically active, non-smoking males (mean ± *SD*; age = 20.4 ± 1.9 years; height = 179.1 ± 7.5 cm; weight = 69.6 ± 7.3 kg; BMI = 21.7 ± 2.4 kg m^{-2}). Participants were considered as physically active as they participated in exercises for at least three times a week. Included participants signed an informed consent and completed a health questionnaire (excluding the contra-indications concerning CWI and supramaximal exercise). Participants were excluded if the supramaximal exercise protocol or CWI protocol could be harmful for their restrictions or diseases.

Experimental overview

Participants visited the sports centre of the Vrije Universiteit Amsterdam during three consecutive weeks in which they conducted the same fatiguing protocol followed by one of the two recovery methods (either CWIc or CWIs) or the AR control condition. Measurements were performed at the same day of the week and at the same time of the day in order to avoid circadian effects (Al Haddad et al., 2010). HRV, MP and MS were used as outcome measures to assess acute recovery and had been measured at the same time points (see Figure 1). Participants were required to refrain

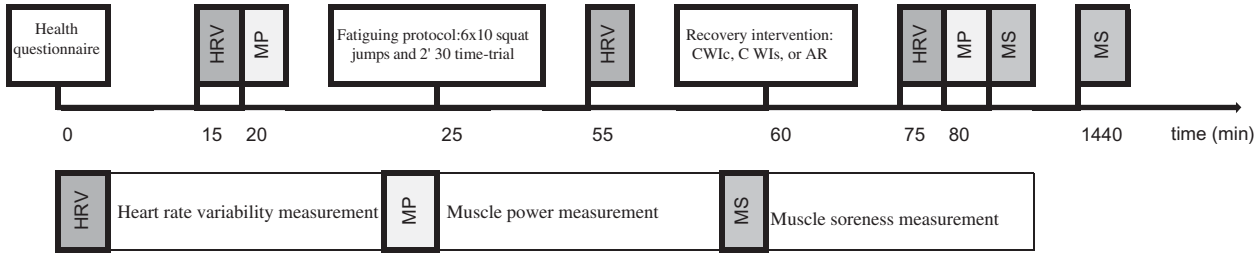

Figure 1. Schematic representation of the experimental design. During three consecutive weeks, participants consequently accomplished above protocol. This protocol consisted of the same fatiguing protocol followed by a different recovery intervention every week: customised cold-water immersion (CWIc); standard cold-water immersion (CWIs) or active recovery (AR). HRV: heart rate variability; MP: muscle power; MS: muscle soreness.

from caffeinated beverages during the preceding 6 h and to refrain from (sub)maximal exercises and alcoholic drinks during the preceding 24 h to minimise influences on HRV. Prior to every testing day, the participant's ability to complete the fatiguing and recovery protocol was assessed by their sleep quality of the night before and their fitness level on each testing day. Both scores were subjectively assigned on a Lickert Scale from 1 to 10 (1 = very low and 10 = very high).

Measurement procedures

On the first testing day, participant's anthropometry was determined. A body weighing impedance scale (Tanita TBF-300A, Tanita, Tokyo, Japan) established body weight and BMI. Body height was measured with a regular tape measure (Comed 44 44 000, Comed, Strasbourg, France).

The fatiguing protocol was conducted after baseline measurements of HRV and MP and included 60 squat jumps and a 2′30″ cycling time-trial (2′30″ TT). Participants started with the 60 squat jumps, divided into 6 sets of 10 performed with a knee flexion of 90°. Participants got proper instructions and were corrected in relation to the right technique. Squat jumps were performed at maximal intensity. After each jump, participants prepared for the next, with a pause of a few seconds between two consecutive squat jumps. Squat jumps were followed by a warm-up of 7 min on the cycle ergometer to prepare the cardiovascular system for exhaustion. Participants cycled an incremental workload (resistance level 1–10) while keeping a constant pace of 100 RPM at every level. Every 30″, the workload was increased with one level sustaining level 10 for the last 2′30″. They covered the largest possible distance at resistance level 15 (with free pedal rate) during the 2′30″ TT to cause central and peripheral fatigue and to disturb the glycolytic system. The resistance level for the TT was estimated and tested during pilot experiments within a comparable study group. The cycled distance of the 2′30″ was notated, and the participants performed a cooling-down at resistance level 1 for 3 min at a constant pace of 60 RPM. Perceived exhaustion for the 2′30″ TT and the total fatiguing protocol was reported on the Borg scale (6–20: 6 = very, very easy and 20 = very, very hard) (Borg, 1982).

The fatiguing protocol was immediately followed by the post-fatiguing HRV estimation, directly followed (after changing into swim gear) by either CWIc, CWIs or AR. The time window between the completion of the fatiguing protocol and commencement of the recovery intervention was 10 min. AR included cycling at 60 W at 80 RPM on a Corival 400 (Lode BV, Groningen, The Netherlands) (Francaux, Jacqmin, de Welle, & Sturbois, 1995). AR lasted 10 min to equalise the duration of CWIs. During CWIs and CWIc, participants were full-body immersed in a ColdTub Icepod PT (Coldtub™, Harwich, USA), consisting of a full immersion (nipple height), with arms immersed as well during CWIc and CWIs. CWIs corresponded with a full-body immersion of 10 min at a water temperature of 15°C in the ColdTub. This protocol appeared to be effective in enhancing the acute recovery of HRV (Parouty et al., 2010), MP and MS (Poppendieck et al., 2013; Vaile, Halson, Gill, & Dawson, 2008). CWIc consisted of immersion in a fixed water temperature of 12°C with a variable immersion duration per participant. The water temperature considered the recovery objective (described by the high mechanical and metabolic load of the fatiguing protocol) and immersion duration counterbalanced the influence of personal characteristics. These customised durations (see Table I) were calculated using the ProCcare software (Zoersel, Belgium, version 1.1). This software contains an algorithm (patent pending) based on a well-validated thermo-physiological model (Fiala et al., 2012). The personalised model contains a scalable human anthropometry and morphology model, and an individual heat-stress response model to predict body temperature and regulatory responses of male and female subjects covering a wide range of

Table I. Immersion duration of customised CWI intervention and resulting dose based on age and anthropometry

Participant	Age (years)	Body height (cm)	Body weight (kg)	Immersion duration (min)	Dose CWIc protocol
1	17	178.0	57.3	10	0.833
2	20	173.0	73.6	17	1.417
3	18	173.0	72.0	14	1.167
4	22	173.8	71.5	17	1.417
5	19	176.5	76.6	15	1.250
6	20	180.0	63.1	11	0.917
7	21	181.0	71.1	15	1.250
8	23	177.9	68.9	12	1.000
9	18	179.3	61.3	10	0.833
10	21	198.7	81.3	11	0.917
Mean ± *SD*	20.4 ± 1.9	179.1 ± 7.5	69.6 ± 7.3	13.0 ± 2.7	1.10 ± 0.23

personal characteristics in relation to the proposed CWI protocol. For comparison in relation to the dose of the CWI protocol, we quantified the dosage of the CWI protocols according to the following equation:

$$\text{Dose} = \text{time immersion} \times (1/\text{water temperature}). \quad (1)$$

Outcome measures

Heart rate variability. HRV was measured in a supine position with a Polar Bluetooth® WearLink®+ transmitter on a WearLink®+ Coded Transmitter belt (Polar Electro Oy, Kempele, Finland). The software of the BioForce HRV System (Performance Sports Inc., Washington, USA) had been used for the estimation of HRV. This system uses the same core algorithm and filtering as the well-validated ithlete™ HRV smartphone application (Flatt & Esco, 2013), with a standard error of the estimate of 1.47. The BioForce System estimates HRV according to the RMSSD of N–N intervals, which is a commonly used and validated time-domain HRV estimate (Malik, 1996). Subsequently, the RMSSD is naturally logarithmic transformed in order to stabilise normality. Ectopic heart beats were eliminated automatically using a proprietary filtering algorithm. At first participants laid down in supine position in a quiet room for 5 min to stabilise heart rate. (Hautala et al., 2001). The HRV assessment was conducted after this 5-min period and lasted 2′30″. Participants were not allowed to move or talk during the HRV measurements. Breathing was not constrained and participants were asked to breath naturally. Three HRV measurements were conducted: before (baseline HRV), after the fatiguing protocol (post-fatiguing HRV) and after the recovery protocol (post-recovery HRV). Main HRV outcome was HRVrecovery, which was the difference between post-recovery HRV and post-fatiguing HRV. This outcome measure indicated how much the HRV recovered as a result of CWIc, CWIs and AR.

Muscle power. Before assessment of MP, a warm-up of 3 min was performed on a LifeFitness 95C Lifecycle ergometer (Life Fitness, Cambridgeshire, UK): 2 min at 80 RPM on resistance level 1 and 1 min at 100 RPM on resistance level 2. MP assessments consisted of a maximal number of squat jumps at maximal height during 30 s. Participants wore a singlet connected to an Acoustic Emission Sensor WS17KT (Mitras Group Inc., Princeton Junction, USA) and Stimula (version 0.464). MP is defined as the mean power of all squat jumps over the 30 s period (Dal Pupo et al., 2014). The modified 30 s Bosco vertical jump test was considered valid to measure the MP (Dal Pupo et al., 2014) with a good test–retest reliability for mean vertical jump height (intra class coefficient = 0.98) and a strong correlation with the mean power of the Wingate ($r = 0.70$). MP was measured twice: after baseline HRV (baseline MP) and after post-recovery HRV (post-recovery MP). The difference between post-recovery MP and baseline MP was considered as the absolute decline in MP (in Watt). Since the average MP may differ among participants, the decline in MP was normalised to baseline MP for each participant and defined as the relative decline in MP (in %).

Muscle soreness. MS was reported on a scale from 1 to 10 (1 = absence of MS and 10 = extremely painful MS) after the post-recovery MP measurement (MS 0 h post-intervention) and 24 h after completion of the protocol (MS 24 h post-intervention).

Statistical analyses

Statistical analyses were performed with IBM SPSS Statistics (version 20, SPSS Inc., Chicago IL) at an alpha level of 0.05. Normal distribution and sphericity were verified by the Shapiro–Wilk normality

and Mauchly's test, respectively. Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. A repeated measures analysis-of-variance (ANOVA) was applied in order to assess the means of HRVrecovery, relative MP decline, MS 0 h post-intervention, and MS 24 h post-intervention with recovery intervention as factor. Repeated measures ANOVA was also used to examine whether the protocols were equally executed by the assessment of the means of the three HRV and two MP measurements, scores of sleep quality, fitness scores, cycled distance during the 2′30″ TT and both Borg scales. In case of significance, a pairwise comparison with Bonferroni correction was applied as post-hoc test to investigate which recovery interventions differed. The strength of the significant effects was statistically examined by estimating effect sizes according to $r = \sqrt{t^2/(t^2 \mp df)}$ (Rosnow, Rosenthal, & Rubin, 2000). Wilcoxon signed-rank test with the Kruskal–Wallis test as post-hoc test were applied when the assumption for parametric test was violated.

Results

The standard dose in the CWIc condition (dose CWIs = 0.67) differed significantly from the dose in the CWIs condition ($t = 6.00$, $p = .000$, $r = 0.89$) condition. Table II shows the means and standard deviations of the main outcome measures.

Heart rate variability

HRVrecovery was significantly greater in CWIc compared with CWIs ($t = 3.34$, $p = .026$, $r = 0.74$) and compared with AR ($t = 9.38$, $p = .000$, $r = 0.95$) (Table II). HRVrecovery in CWIs was significantly higher in comparison to AR ($t = 4.96$, $p = .002$, $r = 0.86$). Post-recovery HRV was significantly higher after CWIc compared with AR ($t = 6.71$, $p = .000$, $r = 0.91$) and after CWIs compared with AR ($t = 6.58$, $p = .000$, $r = 0.91$). CWIc was not significantly different from CWIs in post-recovery HRV ($t = 1.00$, $p > .05$, $r = 0.32$). Furthermore, there were no significant differences in baseline HRV and post-fatiguing HRV among CWIc, CWIs and AR ($p > .05$).

Muscle power

The relative decline in MP during CWIc was significantly lower than the relative decline in MP during CWIs ($t = 3.19$, $p = .017$, $r = 0.73$) (Table II). No significant differences in relative decline in MP were obtained between CWIc and AR ($t = 0.78$, $p > .05$, $r = 0.25$) and between CWIs and AR ($t = 2.49$, $p > .05$, $r = 0.64$). Because of large inter-individual differences in absolute decline in MP, only means of relative decline in MP were reported. No significant correlations coefficients between MP and HRVrecovery for the different recovery interventions were reported, respectively, $r = 0.10$ for CWIc, $r = -0.09$ for CWIs and $r = 0.45$ for AR.

Muscle soreness

No significant differences were reported in MS 0 h post-intervention and MS 24 h post-intervention between CWIc and CWIs (MS 0 h: $t = 1.36$, $p > .05$, $r = 0.41$; MS 24 h: $t = 0.25$, $p > .05$, $r = 0.08$), CWIc and AR (MS 0 h: $t = 0.76$, $p > .05$, $r = 0.25$; MS 24 h: $t = 0.98$, $p > .05$, $r = 0.31$) and CWIs and AR (MS 0 h: $t = 0.72$, $p > .05$, $r = 0.23$; MS 24 h: $t = 0.77$, $p > .05$, $r = 0.25$). However, 7 out of the 10 participants experienced less MS 0 h post-intervention after CWIc compared with CWIs (mean ± *SD*; 2.9 ± 1.7 versus 4.0 ± 2.4).

Table II. Results of outcome measures HRV, MP, MS, HRVrecovery and decline in MP.

	CWIc	CWIs	AR
HRVrecovery (ms)	51.1 ± 11.3[A,B]	37.9 ± 14.3[A,C]	12.6 ± 7.6[B,C]
Baseline HRV (ms)	80.0 ± 8.6	80.0 ± 10.7	82.9 ± 8.3
Post-fatiguing HRV (ms)	23.8 ± 9.4	30.2 ± 17.5	28.4 ± 14.9
Post-recovery HRV (ms)	74.9 ± 9.9[B]	68.1 ± 9.7[C]	41.0 ± 16.4[B,C]
Baseline MP (Watt)	1726.1 ± 512.5	1485.5 ± 367.5	1408.9 ± 400.0
Post-recovery MP (Watt)	1499.4 ± 422.9	1189.6 ± 393.5	1304.4 ± 485.8
Absolute decline in MP (Watt)	−226.8 ± 162.0	−296.0 ± 128.0[C]	−104.5 ± 159.1[C]
Relative decline in MP (%)	−12.6 ± 7.9[A]	−21.1 ± 10.9[A]	−9.8 ± 14.6
MS 0 h post-intervention (1–10)	2.9 ± 1.7	4.0 ± 2.4	3.4 ± 1.8
MS 24 h post-intervention (1–10)	2.9 ± 1.9	2.7 ± 1.7	2.1 ± 1.3

Note: Letters (A, B, C) indicate a significant difference ($p < .05$). A: CWIc and CWIs; B: CWIc and AR; C: CWIs and AR. CWIc: customised cold-water immersion; CWIs: standard cold-water immersion; AR: active recovery; HRV: heart rate variability; MP: muscle power; MS: muscle soreness.

Table III. Scores of sleep quality, fitness scores, distance on time-trial and both Borg scales.

	CWIc	CWIs	AR
Sleep quality (1–10)	7.1 ± 1.1	7.1 ± 0.7	7.0 ± 0.9
Fitness score (1–10)	7.3 ± 0.8	6.9 ± 0.9	6.7 ± 1.2
Distance 2′30″-trial (metre)	1924 ± 264	1951 ± 182	1936 ± 209
Borg scale 2′30″-trial (6–20)	17.6 ± 1.4	17.6 ± 1.4	17.1 ± 2.0
Borg scale fatiguing protocol (6–20)	15.7 ± 1.5	15.9 ± 1.6	15.1 ± 2.1

Note: CWIc: customised cold-water immersion; CWIs: standard cold-water immersion; AR: active recovery.

Sleep quality, fitness, Borg scales and cycled distance

Scores of sleep quality, fitness, Borg scales for 2′30″ TT, fatiguing protocol and cycled distance during the 2′30″ TT were not significantly different among CWIc, CWIs and AR ($p > .05$) (Table III).

Discussion

The main objective of the present study was to investigate whether a CWIc protocol is more effective in enhancing acute recovery than a CWIs or AR protocol. The results imply that CWIc provided a significantly higher HRVrecovery compared to CWIs (large effect size, $r = 0.74$) and AR (large effect size, $r = 0.95$) and a significantly lower relative decline in MP than CWIs (large effect size, $r = 0.73$), with no significant differences with AR (small to medium effect size, $r = 0.25$). In this view, athletes may benefit from a customised CWI approach as it provides positive effects on acute recovery of cardiovascular and neuromuscular performance in comparison with a standard CWI protocol.

Based on baseline HRV and MP, the participants began similarly fit over the different testing days with the rate of fatigue being equally distributed among the different recovery conditions. The higher HRVrecovery in CWIc is likely attributable to the higher dose in CWIc because of the lower temperature and the exposure to more hydrostatic pressure as a result of the longer immersion times. CWIc therefore leads to more pronounced central baroreceptor activation, triggering parasympathetic activity, and lowering sympathetic activity induced by exercise (Al Haddad et al., 2010). Arguably, the standardisation of body temperature and regulatory responses in CWIc may have led to an improved and customised vagal activity. The improved effect on HRV recovery after CWI (Al Haddad et al., 2010; Almeida et al., 2016; Buchheit et al., 2010; Parouty et al., 2010) and the lack of effect on HRV recovery after AR (Bastos et al., 2012) is consistent with studies that investigated the effects of CWI and AR on the recovery of HRV after (supra)-maximal exercises. However, none of these studies used customised CWI protocols, complicating possible comparisons with these studies. Furthermore, there is no causal relationship of HRV with acute performance recovery yet (Makivić, Nikić, & Willis, 2013), though HRV can be seen as a method for monitoring the recovery of the autonomic nervous system based on fundamental physiological knowledge (Aubert et al., 2003). Nevertheless, standardising HRV measurements should be recommended, as standardisation is currently lacking (Makivić et al., 2013).

The acute performance recovery of MP is significantly improved with CWIc compared to CWIs and illustrates a large effect size ($r = 0.73$). Also, there is a tendency (medium effect size, $r = 0.41$) that the acute recovery of MS is more improved after the CWIc protocol These positive findings of customised CWI might be related to the inhibition of the inflammatory response and oedema by improving the fluid shifts from interstitial to intravascular space (Leeder et al., 2011; Wilcock, 2005) and the direct effect on muscle metabolism (White et al., 2014). However, in our study MP did not show a significant correlation to the improved HRVrecovery. Irrespective of this relative improvement in MP, MP is negatively affected by CWI exposure applied in acute recovery settings when measured shortly after immersion. Comparable with White et al. (2014), we also identified a small, though non-significant decline, in the AR condition compared to both CWI conditions. In sports in which MP is essential, CWI should not be prescribed within 60 min to the next performance.

Although we did not measure muscle temperature directly, it is our expectation that muscle temperature after the CWIc protocol was lower than after the CWIs protocol because of a lower water temperature and a longer immersion duration (Peiffer et al., 2009; Gregson et al., 2011; Mawhinney et al., 2013). The CWIc protocols, therefore, resulted in a more pronounced decrease in the power-generating capacity of the muscles due to the negative effect on the temperature dependent enzymatic processes (White & Wells, 2013). Remarkably, the decline in MP in CWIc is lower than in CWIs illustrating that the reduced inflammatory response after CWIc may not have influenced the MP response. Peake et al.

(2017) also questioned the inhibition of the inflammatory responses by CWI, as their results did not identify differences between the CWI and AR after resistance exercise (Peake et al., 2017). This suggests that other processes, like the improved parasympathetic activity, reduced cardiovascular strain, reduced central nervous system fatigue, metabolic efflux and reduced muscle damage (Ihsan, Watson, & Abbiss, 2016), are involved as well. A direct assessment of muscle temperature would have aid to understand the identified results considering the intended equal response in muscle temperature among participants in CWIc and the lack of this standardisation in CWIs. Potentially, the differentiation in dose and standardisation in response could help to signify the induced physiological mechanisms concerning CWI as currently clear dose response relations are lacking.

Different studies (Almeida et al., 2016; Glasgow et al., 2014; Peiffer et al., 2009; White et al., 2014) tried to identify a dose–response relationship between CWI and its response. However, these studies applied similar dosages for each individual. This in combination with the intra-individual design of these studies would essentially mean that potential customised effects of the CWI protocol might have been averaged out which could be the reason why the studies of White et al. (2014), Glasgow et al. (2014) and Peiffer et al. (2009) reported ambiguous results. Almeida et al. (2016) assessed the effects of different dosages of CWI on HRV post-exercise and post-recovery. They concluded that restoration of cardiac autonomic modulation was enhanced using the high-dose CWI protocol (15 min at 14°C) compared to the low-dose CWI protocols (5 min at 9°C and 14°C) which corresponded with our study where a higher dosage leads to improved effects. Machado et al. (2016) also identified that a higher dosage was more effective in relation to MS.

In line with the review from Stephens et al. (2016), customising a CWI protocol in future studies may be a step in the right direction. Since the customised CWI protocol comprised a higher dose for each participant compared to the standard CWI protocol, it is complicated to separate the potential improvement of calculating the intra-individual dose in relation to the colder water temperature due to the consideration of the recovery objective in this study as well. Isolating the potential effect of calculating the intra-individual dose might also help in order to identify the optimal dose–response for other recovery objectives like chronic recovery or sleep enhancement purposes. Adding passive recovery (defined as no particular recovery intervention) as a control condition would make it possible to value the added effect of CWIc, CWIs or AR on central fatigue, cardiovascular and neuromuscular system. While customising the resistance levels of the TT would make sure that each participant experience the same stress level on the anaerobic and aerobic system. Both can be seen as potential limiting factors of the current study. Including the sampling of biomarkers like interleukins, endothelin-1myoglobin could also provide further insights (Bleakley et al., 2012; Rowsell, Coutts, Reaburn, & Hill-Haas, 2009).

In conclusion, the current study suggests that the customised CWI protocols outperform the standard guideline CWI protocol of 10 min at 15°C in the acute recovery of cardiovascular and neuromuscular performance. Furthermore, the customised and standard CWI protocols favour AR in the improvement of the acute recovery of cardiovascular performance. In line with the recommendations of Stephens et al. (2016), the recovery objective and individual characteristics should be taken into account to optimise the effects of CWI. The contributions of the protocol duration and water temperature should be considered to guarantee this optimal customised dose.

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Disclosure statement

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