

SYSTEMATIC REVIEW

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Strategic Application of Post-exercise Cold-Water Immersion to Enhance Performance Recovery and Adaptation: An Umbrella Review of 15 Published Systematic Reviews with Meta-analysis

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Abstract

Background Athletes commonly implement post-exercise cold-water immersion (CWI), with several meta-analyses having assessed its effectiveness.

Objectives To thoroughly review, appraise, and summarise existing systematic reviews with meta-analyses (SRMA) examining the effects of post-exercise CWI on the recovery of exercise performance and adaptation.

Methods An umbrella review was conducted in accordance with the Joanna Briggs Institute guidelines. Methodological quality was assessed using AMSTAR 2, and certainty of evidence using GRADE. PROSPERO registration: (CRD420251103267). Eight databases were searched, including Web of Science, Scopus, SPORTDiscus, CINAHL, Cochrane Library, Embase, MEDLINE, and PubMed. Systematic reviews with meta-analyses of peer-reviewed randomised controlled trials examining post-exercise CWI vs passive rest or other recovery modalities on performance, training adaptation, or physiological, biochemical, and perceptual outcomes in healthy humans were included, with restriction to the English language.

Results Fifteen SRMAs published between 2011 and 2025, comprising 161 unique studies, were included. Overall methodological quality was low to critically low, and certainty of evidence was low to very low, mainly due to inconsistency and imprecision. Protocols of 10–15 min at 10–15 or 5–10 °C appear to be most effective for improving performance and recovery. Post-exercise CWI resulted in significant improvements in muscular power at 24 h post-high-intensity exercise and at 24–48 h post-eccentric exercise, and in jump performance at 24–48 h, despite impaired jump performance in the initial hours after post-exercise CWI. Endurance performance improved immediately after CWI, but CWI produced no later benefits or positive effects on adaptations. CWI did not improve muscular strength performance, and impaired strength and hypertrophic gains. CWI improved heart rate variability immediately after exercise, reduced muscle soreness up to 96 h, and lowered creatine kinase (CK) concentrations between 24 and 72 h, with no significant effects on C-reactive protein or interleukin-6 up to 72 h. No immediate impact on blood lactate or lactate dehydrogenase was found, although some reductions appear 24–72 h post-exercise.

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Conclusions Post-exercise CWI confers outcome-specific recovery benefits but may impair resistance training adaptations with chronic use. These findings support a periodised, context-driven approach to CWI implementation rather than routine application after all exercise sessions.

Key Points

1. Decision makers should individualise and periodise CWI use based on training phase, performance goals, and individual response
2. Post-exercise CWI improves performance in a time-specific manner, enhancing endurance within ~1 h and power and jump performance at 24–72 h, but may impair acute explosive performance
3. Post-exercise CWI consistently reduces muscle soreness and CK and accelerates vagal reactivation.
4. Repeated CWI after resistance training may attenuate strength and hypertrophy adaptations, while endurance adaptations appear unaffected. Effects on strength may be protocol-dependent, with exercise-limb immersion associated with reduced gains, whereas whole-body immersion shows no clear detrimental effect

Keywords Hydrotherapy, Cold-water immersion, Exercise, Athletes, Recovery

Introduction

Post-exercise cold-water immersion (CWI) is widely used by athletes as a recovery method, aiming to reduce fatigue, sustain higher training loads, promote greater adaptations, and ultimately enhance performance [1]. Initially adapted from the clinical application of cryotherapy for musculoskeletal injury management [2], CWI has been increasingly studied in the field of exercise science over the past two decades. The effectiveness of CWI has been investigated across different exercise modalities and outcomes, including perceptual and physiological markers [3, 4], long-term adaptations [5] and performance-based measures [6–8]. The beneficial effects of CWI have traditionally been attributed to increasing hydrostatic pressure and decreasing tissue and muscle temperature during immersion, which collectively alter blood flow, reduce post-exercise fluid retention, and lower metabolic activity [9]. These physiological responses may facilitate recovery by reducing muscle damage, swelling, inflammation, muscle spasm, musculoskeletal pain, and thermal strain [9]. In addition, CWI may improve perceptual recovery through analgesic effects, mitigate muscular soreness, and potentially enhance mood by releasing dopamine [10], serotonin [11] and endorphins [12]. These actions may support overall muscle recovery processes, returning performance to its pre-exercise state.

Recovery is multifactorial and thus cannot be explained by a single measure or variable. To account for this, a variety of markers, such as performance, biochemical, physiological, and psychological markers, are collectively used to evaluate the effectiveness of a recovery strategy [13]. Importantly, performance indicators can be seen as key metrics for monitoring athlete fatigue and recovery, as maintaining or enhancing performance is typically

the primary goal for athletes. Other indicators, such as biochemical (e.g. CK, inflammation), physiological (e.g. heart rate and heart rate variability (HRV), VO_2max), and subjective markers (e.g. muscle soreness and pain perception), can assist in understanding the mechanisms and processes involved in fatigue and recovery [13–15]. For instance, it has been suggested that the peak plasma concentration of biochemical markers (e.g. creatine kinase (CK), lactate dehydrogenase) is associated with a decline in performance in the 48 h post-competition [16]. Notably, while various markers are used, it is often difficult to determine whether a recovery strategy is truly effective, as positive changes may appear in some but not all markers [17]. Therefore, assessing performance tests alongside other physiological and perceptual indicators can provide a more comprehensive evaluation of a recovery strategy's effectiveness [18].

In recent years, numerous systematic reviews with meta-analyses (SRMAs) have evaluated the effectiveness of post-exercise CWI across diverse recovery, performance, and adaptational outcomes [19–21]. These reviews have addressed various research questions, including the effects of post-exercise CWI on parasympathetic reactivation [22], biochemical and performance outcomes [19], the optimization of immersion protocols (e.g. duration, temperature, and protocol) [23, 24], the most effective exercise contexts for application [25] and comparison with other recovery modalities [26]. Although these reviews offer valuable insights, a higher-level synthesis of the data can provide a clearer, more robust understanding of the overall effects of post-exercise CWI on exercise performance recovery and adaptation, enabling appropriate implementation to optimise short-term responses and longitudinal adaptations. Malta

et al. [27] in their SRMA concluded that post-exercise CWI has adverse effects on long-term muscular strength adaptations, while Grgic [20] noted in their subgroup analysis that exercised-limb immersion, but not whole-body CWI, dampened longer-term muscular strength adaptations. In addition, recovery and performance outcomes may be influenced by immersion parameters, such as temperature and duration [23, 24], underscoring the need to establish optimal protocols to achieve the best outcomes.

In the context of post-exercise CWI, which has been examined from various perspectives, an umbrella review is warranted to comprehensively evaluate the available evidence and provide an integrated, evidence-based overview for sport scientists and practitioners. This approach will assist sport scientists and practitioners in understanding the contexts and exercise conditions in which athletes may benefit from CWI while minimising its potential detrimental effects. This umbrella review aims to synthesise and critically appraise existing SRMAs that have examined the effects of post-exercise CWI on the recovery of exercise performance, physiological, biochemical, and perceptual responses, as well as long-term training adaptations, thereby providing a comprehensive and conclusive framework to guide the implementation of post-exercise CWI for both researchers and practitioners.

Methods

This umbrella review adhered to the reporting guidelines of the Joanna Briggs Institute, developed by Aromataris and colleagues [28], and was prospectively registered in the PROSPERO database (CRD420251103267). Eight databases were searched (Web of Science, Scopus, SPORTDiscus, CINAHL, Cochrane Library, Embase, MEDLINE, and PubMed). All databases were searched from the start of their indexing period through to 12th

June 2025. The search strategy combined terms for the intervention, outcomes, and study type, as shown in Table 1. All results were imported into EndNote 21, where two authors (EB and HM) independently screened titles, abstracts, and, where applicable, full texts to minimise selection bias. During each full-text review, the reference list was also checked to ensure all relevant studies were captured. Both authors' lists of included and excluded studies were compared, with disagreements resolved through discussion and mutual agreement between the authors.

Inclusion Criteria

Table 2 presents the eligibility criteria for systematic reviews with meta-analyses being included. The PICOS (population, intervention, comparison, outcomes, study design) framework was used to establish the inclusion criteria.

Data Extraction

Data extracted from each SRMA included the author(s), the country of publication, year of publication, total sample size, duration and temperature of CWI, comparison group, measurement indicators, time of measurement, pooled effect size with 95% confidence interval (CI), *p* values, and *I*² values. Data extraction was conducted independently by the same two authors responsible for the literature search (EB and HM). All data were manually entered into a spreadsheet, and both authors cross-checked the data entries to verify accuracy.

Methodological Quality Evaluation

The methodological quality of all included SRMAs was independently assessed by two authors (KAH and HM) using the validated A MeaSurement Tool to Assess systematic Reviews 2 (AMSTAR 2) checklist [29]. Any uncertainties and disagreements were discussed and

Table 1 Search strategy and keywords

Database row	Search terms
Row 1	("cold water immersion" OR "cold-water immersion" OR "cryotherapy" OR "CWI" OR "contrast water therapy" OR "post-exercise cooling" OR "ice bath" OR "cold therapy" OR "cold plunge" OR "cold application" OR "ice-water bath" OR "cold treatment")
AND	
Row 2	("exercise performance" OR "exercise adaptation" OR "exercise recovery" OR "muscle soreness" OR "DOMS" OR "strength" OR "strength adaptation" OR "endurance" OR "endurance adaptation" OR "training adaptation" OR "subsequent performance" OR "recovery")
AND	
Row 3	("systematic review" OR "meta-analysis" OR "systematic review and meta-analysis")

Final Boolean combination: row 1 and row 2 and row 3

Table 2 Inclusion criteria of the present umbrella review

Domain	Eligibility criteria
Study design	Systematic reviews with meta-analyses that assessed the impact of post-exercise CWI on recovery of exercise performance, physiological/biochemical/perceptual, or adaptation outcomes were included Meta-analyses that included only peer-reviewed randomised controlled designs published in English were included In addition, meta-analyses that included CWI as a recovery method post-exercise in subgroup analyses were also considered
Population	Healthy humans of any age, sex, and training status (e.g. recreationally active, trained athletes)
Intervention	Post-exercise CWI across various temperatures, durations, and immersion depths
Comparison	Passive rest, or other recovery modalities
Outcomes	At least one outcome related to exercise performance (e.g. strength, power, endurance, sprint performance), training adaptations (e.g. hypertrophy, aerobic/anaerobic capacity, strength gains), or autonomic, biochemical, and perceptual responses

resolved through consultation with a third author (EB). This checklist comprises 16 items (7 of them are critical and 9 are non-critical) that cover various aspects, including the use of a PICO framework in the inclusion criteria, prior registration of the review protocol, the scope of the literature search, the number of authors involved in searching and data extraction, detailed descriptions of included studies, quality assessment of primary studies, disclosure of funding sources, appropriate statistical methods, heterogeneity evaluation in meta-analyses, and potential conflicts of interest.

Certainty of Evidence

The certainty of evidence was evaluated by the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) principle [30]. Evidence from randomised controlled trials was initially considered high certainty and downgraded according to GRADE criteria. Five factors that could reduce the certainty of evidence were evaluated, including risk of bias, inconsistency, imprecision, indirectness, and publication bias [30, 31]. Two authors independently assessed the certainty of evidence, with disagreements resolved through discussion and mutual agreement (EB, HM). A detailed and comprehensive description of the GRADE methodology used for certainty of evidence can be found in Supplementary Material. Supplementary Table 1 details the certainty of evidence assessment.

Overlap Analysis

The degree of overlap of primary studies between included SRMAs was calculated based on the corrected covered area formula:

$$CCA = \frac{N - r}{r \times c - r}$$

where N represents the total number of primary studies across all reviews, r is the count of unique primary studies, and c denotes the total number of reviews [32], and

is classified as follows: 0–5% slight overlap, 6–10% moderate overlap, 11–15% high overlap, and > 15% very high overlap [32].

Study-Level Statistical Power

Study-level statistical power was calculated following the approach described by Quintana [33], using the R package *metameta* (v0.2; Quintana, 2023). Briefly, for SRMAs implementing frequentist methods on non-nested data (e.g. frequentist univariate meta-analysis, two-level random-effects model; only one effect size is provided by each study for the relevant meta-analytic model), study-level power for the reported effect size was calculated using the pooled effect size and the effect size and standard errors of each included study. The median statistical power was used to represent the statistical power of each of the SRMAs eligible for this analysis. The statistical power of meta-analytic models which utilise more than one effect size from their included studies was not determined as the calculations for median statistical power are likely to be biased [33]; consequently, the median statistical power of three SRMAs [20, 22, 24] was calculated. Supplementary Figure 1 represents a firepower plot of the observed statistical power of each SRMA.

Results

Search Results

From the literature search, 644 results were identified. Twenty-eight articles were selected for full-text review; 13 were excluded, leaving 15 studies included in this umbrella review. The total sample size was 3210 participants, of which 320 were female, 2823 were male, and the remaining were not determined, across a total of 161 original studies. Figure 1 depicts the process of the literature search. Supplementary Table 1 provides the extracted data of the included studies.

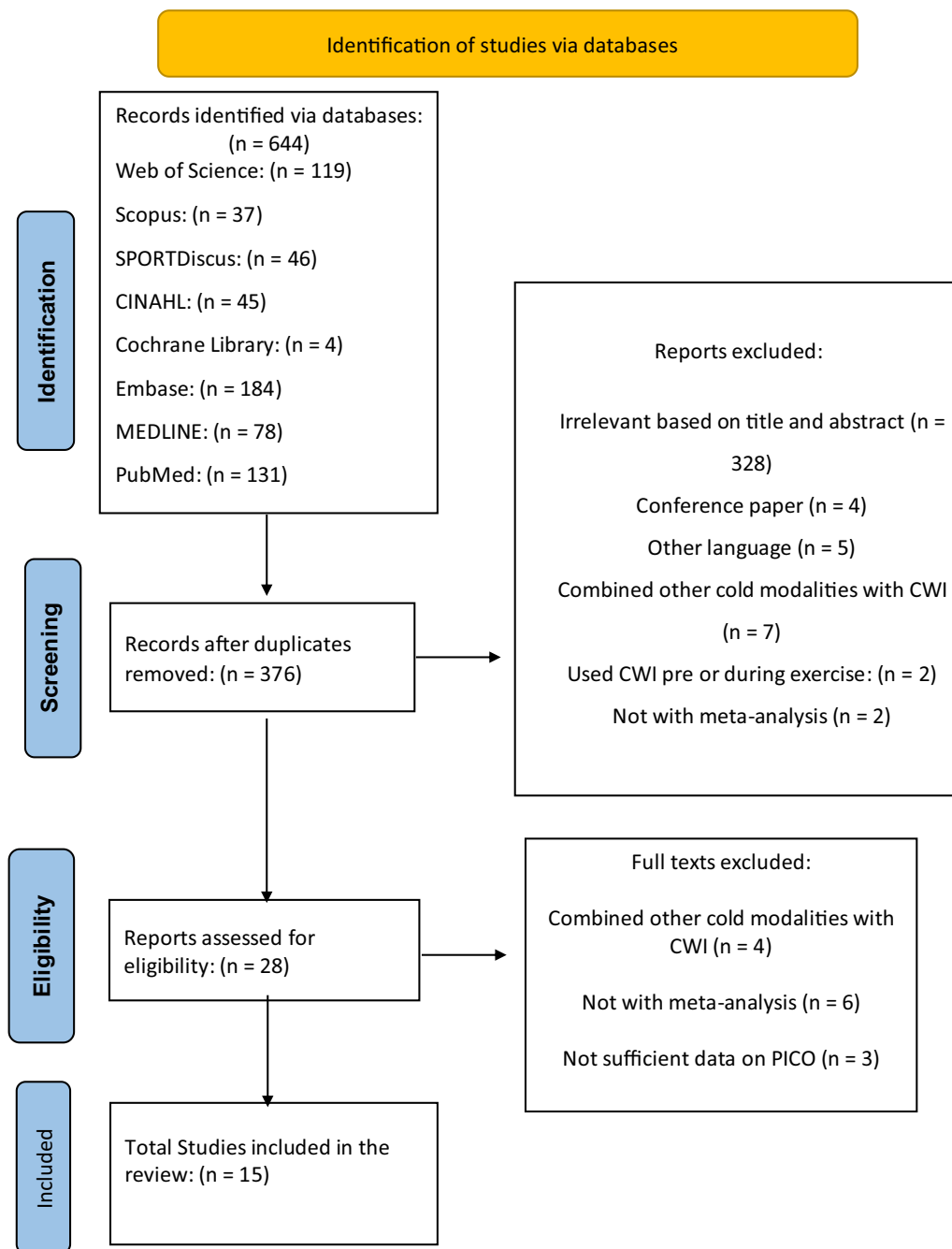


Fig. 1 Flowchart of the included and excluded studies

Characteristics of Included Systematic Reviews with Meta-analyses

The meta-analyses included in this review were published between 2011 and 2025. Within the included studies, post-exercise CWI protocols ranged in duration from 3 to 20 min, with water temperatures from 5 to 15 °C, using either intermittent or continuous protocols, and whole-body, lower-body, or single-limb

immersion. Control or comparison conditions typically involved passive recovery, active recovery, thermoneutral or warm-water immersion, air cryotherapy, massage, or contrast-water therapy. The study populations consisted of healthy young adults (predominantly males), ranging from untrained to well-trained. Supplementary Table 1 provides an overview of the included studies. From these fifteen studies, one was conducted in Germany [22], one

in Russia [34], two in China [35, 36], one in the U.S.A. [21], four in Australia [20, 25, 26, 37], one in the U.K. [38], three in Brazil [23, 24, 27], one in Singapore [19] and one in Qatar [39]. One SRMA [37] did not present an overall effect size and did not specify which individual studies corresponded to each measurement timepoint in its forest plot, nor was I^2 reported. Consequently, this meta-analysis was included only in the methodological quality assessment (AMSTAR 2) and excluded from the quantitative summary.

Methodological Quality Evaluation

All the SRMAs were classified as low or critically low quality. All included SRMAs had at least one failed critical item. Supplementary Table 2 represents AMSTAR 2 checklist items for each included study.

Certainty of Evidence

Most of the evidence across the included SRMAs was rated as low-to-very low quality due to inconsistency, imprecision in the findings, and the risk of bias from lack of blinding. In addition, most samples included only males, limiting generalizability to females. Supplementary Table 1 provides the certainty of evidence for each outcome in all included studies in this umbrella review.

Overlap of Included Studies

The overall CCA of 10.4% indicated moderate overlap across the included reviews. However, visual inspection of the pairwise overlap heat map (Fig. 2) demonstrated that overlap was not evenly distributed across studies. Reviews investigating strength and hypertrophy adaptations [20, 21] demonstrated high overlap

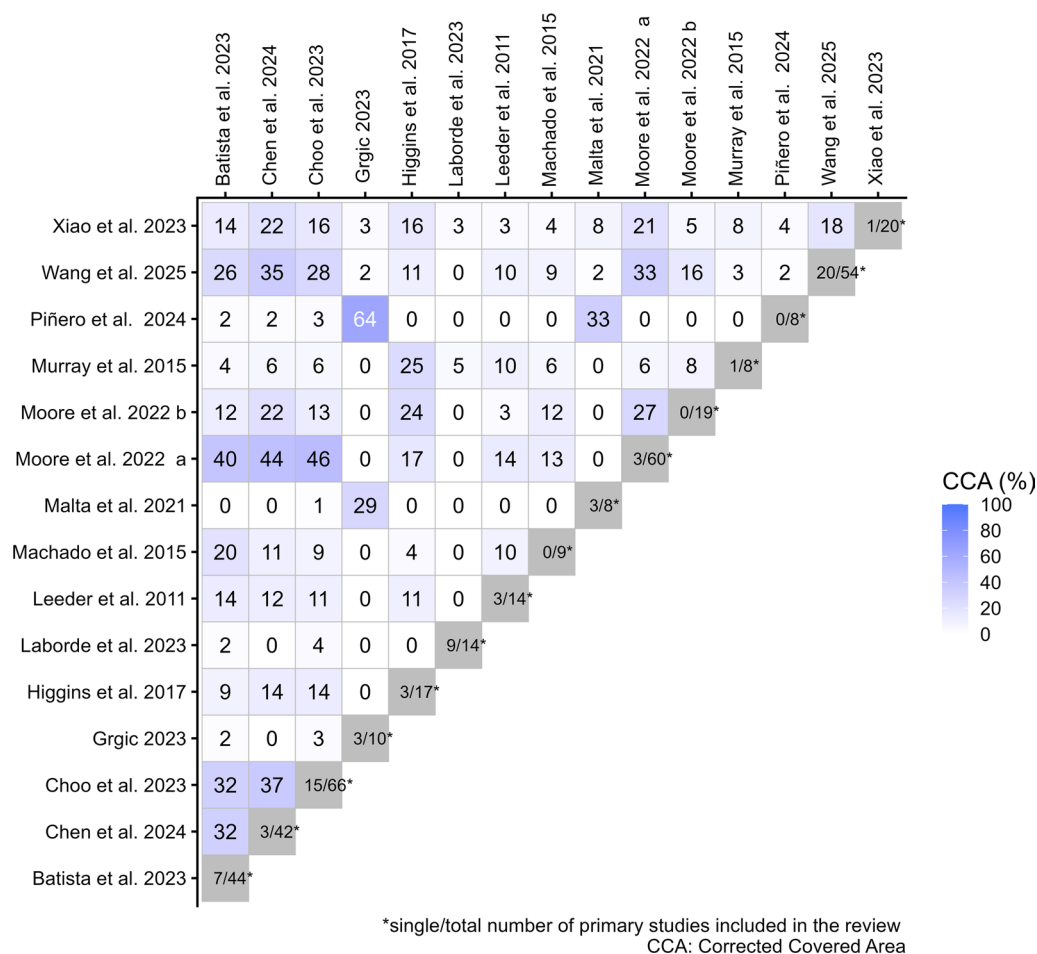


Fig. 2 Pairwise overlap heat map of the primary studies included across systematic reviews with meta-analysis, illustrating the shared number of studies and degree of overlap. Darker shading indicates greater overlap. Overall overlap across reviews was moderate (CCA = 10.4%), although substantial clustering was observed among strength and hypertrophy reviews. Diagonal grey cells indicate, for each review, the number of primary studies not shared with any other review relative to the total number of primary studies included in that review (unique studies/total studies). CCA: corrected covered area

(64%), indicating that chronic adaptation conclusions are derived from a relatively concentrated group of primary trials.

Summary of the Key Findings of the Included Systematic Reviews with Meta-analysis

Effects of Post-exercise Cold-Water Immersion on the Recovery of Exercise Performance

Muscle Strength Across four SRMAs [19, 25, 26, 38], post-exercise CWI did not significantly improve muscular strength recovery compared with passive or alternative recovery modalities. A SRMA [38] including 9 studies reported no significant overall effect (standardised mean difference (SMD)=0.13). Similarly, a meta-analysis of 29 studies found no significant differences between CWI and warm-water immersion or air-cryotherapy at 1, 24 or 48 h post-exercise (SMD range: -0.31 to 0.30) [26]. When comparing post-exercise CWI with passive recovery, a meta-analysis [25] including 38 studies reported no significant improvement up to 168 h following eccentric exercise (SMD range: -0.30 to 2.31) or high-intensity exercise (SMD range: -0.11 to 0.12) [25]. A further review (31 studies) similarly reported no significant differences between 1 and 96 h (SMD range: -0.13 to 0.35), except for a small significant improvement at 24 h (SMD=0.27) [19].

Endurance Across three meta-analyses [19, 25, 39], post-exercise CWI did not consistently improve endurance performance compared with passive or alternative recovery modalities. Two SRMAs (5 and 7 studies per analysis) [25, 39] reported no significant effects at 24 h post-exercise (SMD range -0.19 to -0.14), with no significant benefits observed at 48 h (SMD=0.12) [25] or 96 h (SMD=0.427) [39]. In contrast, one meta-analysis (14 studies) identified a significant improvement when endurance performance was assessed within 1-h post-immersion (SMD=0.50), although effects at 6 and 24 h were non-significant (SMD range: 0.31–0.46) [19].

Jumping Across three meta-analyses [19, 34, 35], the effects of post-exercise CWI on jump performance varied by timepoint. One SRMA consisting of six studies revealed a large and significant jump height impairment when performed immediately after CWI (mean difference (MD)=-2.71 cm) and a large, significant improvement at 24 h (MD=4.77 cm) [34]. Another SRMA comprising sixteen studies found trivial and small significant impairments at 1 and 6 h (SMD range -0.17 to -0.48), followed by small significant improvements at 24 h (SMD=0.22), and a large significant improvement at 96 h post-exercise (SMD=1.34) [19]. Similarly, a further network meta-analysis [35] (23 studies) reported a small, significant improvement between 24 and 48 h post-exercise (SMD=0.37).

Muscle Power Across three meta-analyses [25, 26, 38], post-exercise CWI demonstrated time-dependent effects on muscular power. One SRMA (six studies) reported significant improvements at 24–72 h post-exercise (SMD range: 0.539–0.648) [38]. Similarly, a larger meta-analysis (28 studies) found significant improvements following eccentric exercise at 24–72 h (SMD range: 0.34–0.62), with no significant effects observed at 1, 96 or 168 h [25]. After high-intensity exercise, improvements were limited to 24 h (SMD=0.22), with no significant effects at other timepoints [25]. In contrast, when compared with alternative recovery modalities (warm-water immersion, contrast-water therapy, active recovery or massage), CWI showed no consistent advantage across timepoints [26]. A single significant difference was reported at 1 h compared with air cryotherapy (SMD=-0.7), but this effect was not sustained at 24 or 48 h.

Effects of Post-exercise Cold-Water Immersion on Training Adaptations

Studies described here evaluated the chronic effects of post-exercise CWI applied regularly over several weeks on muscle and performance adaptations. This differs from the Exercise Performance section, which examined the acute application of post-exercise CWI. One SRMA (five studies) reported significant reductions in one-repetition maximum, maximal isometric strength, strength endurance, and ballistic performance (SMD range: -0.50 to -0.73) [27]. Similarly, another SRMA (10 studies) found an overall negative effect on muscular strength (SMD=-0.23, median statistical power=0.07) [20]. Subgroup analyses indicated that limb-only immersion significantly impaired strength gains (SMD=-0.31), whereas whole-body immersion showed no meaningful effect compared with control (SMD=-0.08) [20]. Regarding hypertrophy, a Bayesian meta-analysis concluded that post-exercise CWI likely reduces muscle hypertrophy following resistance training, although the magnitude was small (cSMD=-0.22) [21]. In contrast, endurance adaptations appear largely unaffected [27]. An SRMA examining chronic CWI use reported no significant effects on endurance performance outcomes [27], with trivial pooled effects for time-trial mean power, maximal aerobic power (SMD $\approx$ -0.07), and time-trial performance (SMD $\approx$ 0.00).

Effects of Post-exercise Cold-Water Immersion on Autonomic Recovery

One SRMA with 15 studies evaluated HRV following exercise [22]. CWI demonstrated a moderate to significant positive effect on post-exercise vagal reactivation

(root mean square of successive differences), compared with passive recovery (SMD=0.75, median statistical power=0.53).

Effects of Post-exercise Cold-Water Immersion on Biochemical Markers of Muscle Damage Recovery

No significant reductions were observed immediately post-exercise at CK concentration (1–6 h; SM=−0.27 to 0.85; MD=−2.63) [19, 25, 34]. From 24 to 72 h, significant reductions were generally reported, with pooled SMDs ranging from −0.221 to −1.30 [19, 25, 35, 38]. Specifically, significant effects were observed at 24 h (SMD=−0.38 to −0.85; MD=−86.04), 48 h (SMD=−0.36 to −1.30), and 72 h (SMD=−0.27) [25, 35, 38]. No significant effect was evident at 96 h (SMD=−0.11; MD=−5.44) [19, 34]. Following eccentric exercise, effects between 1 and 96 h were non-significant (SMD=−0.15 to 0.85), with a significant reduction reported only at 168 h (SMD=−0.62) [25]. In contrast, inflammatory markers were unaffected. CRP showed no significant changes at any timepoint (SMD range=−0.17 to 0.11; MD=−0.20 to 0.06) [19, 34], and IL-6 was not significantly altered between 1 and 72 h post-exercise (SMD=−2.07 to 0.47) [19]. One review reported significant reductions in lactate dehydrogenase at 24–48 h (SMD=−0.61 to −0.82) [34], whereas another found no significant effects at 1–48 h (SMD=−0.04 to −0.67) but observed a significant reduction at 72 h (SMD=−0.88) [19].

Effects of Post-exercise Cold-Water Immersion on Perceptual Recovery

Muscle soreness was the most consistently reported perceptual outcome. Across meta-analyses, CWI significantly reduced soreness immediately (SMD range: −0.59 to −1.10) [19, 25, 34] and between 24 and 72 h (SMD range: −0.34 to −0.89) [19, 25, 35]. One review reported sustained benefits up to 96 h (SMD range=0.34 to 0.67) [38], whereas another observed no significant effect at 48 h (SMD=−0.25) [34] and no effect at 96 h (SMD=−0.20) [19]. Effects varied by exercise modality, with clearer benefits after high-intensity exercise (up to 72 h; SMD range: −0.82 to −1.10) [25]. In contrast, after eccentric exercise, no significant effects were observed at 1 h (SMD=0) or 24 h (SMD=−0.51), with small significant reductions only at 48–96 h (SMD range: −0.41 to −0.55), and no effect at 168 h (SMD=−0.78) [25]. When compared with other recovery modalities, CWI was generally not superior to active recovery (SMD=0.06 to 0.35), warm-water immersion (SMD=0.03 to 1.00), air cryotherapy (SMD=−0.51 to 0.11), or contrast-water therapy at most timepoints (SMD=0.05 to 0.55). However, CWI demonstrated greater benefits than

contrast-water therapy at 48 h (SMD=0.54) and was superior to active recovery at 1 h (SMD=0.35), but not at 24–48 h (SMD=0.06 to 0.10) [26].

Optimal Time, Temperature, and Protocol for Recovery

An SRMA [24] reported that water temperatures of 10–15 °C (immediate: MD=0.27, median statistical power=0.10; delayed: MD=0.31, median statistical power=0.10) and immersion durations of 10–15 min (immediate: MD=0.22, median statistical power=0.07; delayed: MD=0.31, median statistical power=0.10) produced the greatest reductions in muscle soreness. A larger meta-analysis [23] similarly found that short (≤ 10 min) and moderate (11–15 min) immersions were superior to passive recovery for both immediate (MD=0.80 to 1.58) and delayed outcomes (MD=1.02 to 1.25), whereas longer durations (16–20 min) were not consistently beneficial (MD=0.69 to 0.75). Both intermittent and continuous protocols were effective immediately (MD=0.92 to 1.47) and at delayed timepoints (MD=0.86 to 1.85), with no clear superiority between them. Regarding temperature, both 5–9 °C and 10–15 °C outperformed passive recovery for immediate (MD=0.99 to 1.00) and delayed effects (MD=0.68 to 1.22). A network meta-analysis [36] indicated that 10–15 min at 5–10 °C had the highest probability of being optimal for reducing CK (SMD=−0.90) and improving jump performance at 24–48 h (SMD=0.48). For delayed onset muscle soreness, 10–15 min at 11–15°C was most likely optimal (SMD=−1.45).

Discussion

This umbrella review synthesised 15 SRMAs that examined the effects of post-exercise CWI on physical performance recovery, and biochemical, perceptual, autonomic, and adaptive outcomes. Figure 3 represents a summary of post-exercise CWI on different outcomes. Overall, the evidence indicates that CWI results in context- and time-dependent performance recovery benefits and cautions against treating post-exercise CWI as either universally beneficial or detrimental [40–42].

Effects on Exercise Performance

Muscular Strength, Power, and Jump Performance

A key finding of this review is that CWI does not meaningfully accelerate recovery of maximal strength up to 168 h post-exercise, with trivial or non-significant effects across muscular strength outcomes, irrespective of exercise type [25, 38]. Small benefits reported at 24–48 h in Choo et al. [19] likely reflect narrower protocol restrictions and time-stratified analyses (whole-body immersion, > 8.5 °C, < 20 min), which may detect effects that are diluted when broader cryotherapy

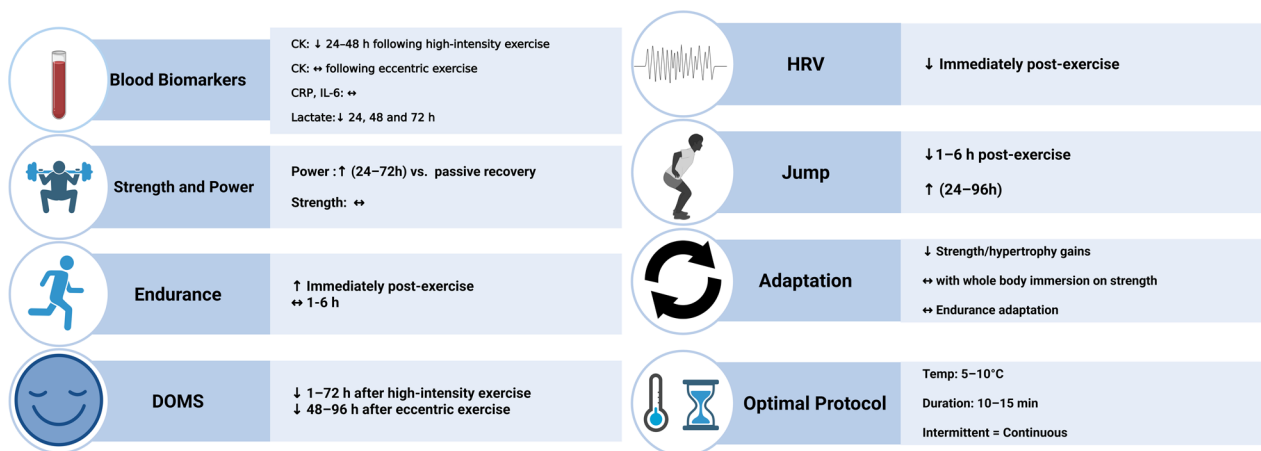


Fig. 3 Summary of findings from included systematic reviews with meta-analyses examining the acute and chronic effects of post-exercise cold-water immersion on performance, training adaptation, physiological, and perceptual outcomes. Muscle strength ($n=4$ reviews): no consistent improvement up to 168 h post-exercise. Muscle power ($n=3$ reviews): improved at 24–72 h post-exercise; transient impairment at ~1 h. Jump performance ($n=3$ reviews): impaired post-immersion immediately; improved at 24–96 h. Endurance performance ($n=3$ reviews): improved within ~1 h post-immersion; no consistent benefit ≥ 24 h. Strength Adaptation ($n=2$ reviews) Attenuated with repeated post-resistance training CWI. Hypertrophy ($n=1$ review): small reduction in muscle growth with chronic use. Endurance adaptation ($n=1$ review): no clear effect on aerobic adaptations. Heart rate variability ($n=1$ review): enhanced immediately post-exercise. Creatine kinase ($n=5$ reviews): reduced at 24–72 h post-exercise, particularly after high-intensity exercise. C-reactive protein ($n=2$ reviews): no consistent effect. Interleukin-6 ($n=1$ review): no consistent effect. Lactate/LDH ($n=2$ reviews): no immediate effect; inconsistent reductions at later timepoints. Muscle soreness ($n=6$ reviews): reduced 1–96 h post-exercise; greater effects after high-intensity exercise. Protocol parameters ($n=3$ reviews): 10–15 min immersion, 5–15 °C water temperature was frequently associated with a favourable outcome. No clear difference between intermittent and continuous protocols. CK: creatine kinase; CRP: C-reactive protein; IL-6: Interleukin-6; DOMS: delayed onset of muscle soreness

modes and protocols are pooled. These findings should also be interpreted with caution, particularly at longer post-exercise timepoints, where muscular strength has been assessed in only a small number of studies. The limited number of studies and sample size may reduce the statistical power and precision of the evidence and increase uncertainty around the observed effects, specifically in longer duration and different exercise types (e.g. 168 h post-eccentric exercise). By contrast, power and jump outcomes appear time-dependent, with CWI potentially impairing explosive performance in the early post-immersion period (1–6 h) [19], consistent with reduced muscle temperature and slower force–power characteristics [43, 44]. Where subsequent high-velocity efforts are required soon after cooling, CWI should be avoided or paired with re-warming and a structured warm-up. Beyond this acute window, small-to-moderate improvements are more evident from ~24 h, particularly with cooler temperatures (5–10 °C) and shorter immersions (10–15 min) [25]. This selective later benefit for stretch-shortening cycle tasks may relate to reduced soreness and altered musculotendinous stiffness [45–47], facilitating performance once tissue temperature normalises [26]. Collectively, CWI is unlikely to benefit maximal strength recovery but may be selectively useful for power and jump recovery

when adequate time (24 h onward) separates immersion from the next explosive task.

Endurance Performance

The present umbrella review indicates post-exercise CWI improves endurance performance only in the immediate recovery window (~1 h), with negligible effects thereafter. This pattern aligns with Choo et al. [19] and experimental studies showing improved recovery when CWI is applied after exercise in the heat or between closely spaced efforts [6–8, 48]. Importantly, meaningful heat strain can occur beyond hot conditions; constrained heat dissipation during high metabolic workloads (including cool-temperate outdoor and indoor sports) can produce substantial hyperthermia [49, 50]. Therefore, CWI use should be guided by expected heat strain and time to the next bout, rather than ambient temperature alone. Despite evidence that fatigue can accumulate across consecutive days of exercise in the heat [51–53], our synthesis does not support CWI as a strategy to attenuate cumulative endurance decrements across days. The practical implication is that any benefit is likely acute and most relevant when the subsequent endurance task is imminent (~1 h), consistent with heat-related constraints on endurance performance [54] and their rapid alleviation with cooling [9], whereas effects are trivial or

inconsistent when heat strain is modest or recovery is ≥ 24 h [19].

Biochemical Markers and Perceptual Recovery

Across meta-analyses, the most consistent biochemical effect of CWI is a small reduction in circulating CK at 24–48 h post-exercise, particularly following high-intensity exercise [25]. Proposed explanations include reduced CK efflux and secondary tissue damage [55, 56]. In contrast, CWI shows no consistent effect on systemic inflammatory markers (e.g. CRP, IL-6) up to 72 h, and effects on lactate are inconsistent, and unlikely to be practically meaningful given rapid natural clearance. Changes in perceptual outcomes more consistently favour CWI. Reduced muscle soreness from 1 to 72 h vs passive recovery was evident, with small-to-moderate effects (e.g. SMD ≈ -0.48 to -0.89 at 24–72 h). Benefits appear larger after high-intensity exercise, whereas after predominantly eccentric protocols, reductions are smaller, delayed (emerging from ~ 48 h), and absent by 168 h. Mechanistically, early analgesia is plausibly related to acute cooling effects, but longer-term reductions remain less clear; notably, CWI did not systematically alter neurotrophins linked to nociception (Nerve Growth Factor, Glial cell line-derived neurotrophic factor) in one study [57]. A parsimonious interpretation is that sustained soreness reductions may reflect, at least partly, attenuated secondary muscle damage, with CK providing a relatively consistent (albeit indirect) marker of this process, while unchanged CRP and IL-6 suggest these benefits do not require broad suppression of systemic inflammation. It is also worth mentioning that the evidence base for CRP and IL-6 is drawn from a comparatively small number of trials, and the null findings for these markers should be interpreted with the possibility of inadequate statistical power in mind.

Autonomic Recovery

Only one meta-analysis evaluated CWI's effects on cardiac autonomic recovery via HRV. Laborde et al. [22] reported moderate-to-large improvements in vagally mediated HRV indices (e.g. RMSSD) when CWI was applied post-exercise across resistance, intermittent, and continuous exercise contexts, consistent with experimental studies showing faster parasympathetic reactivation after exhaustive exercise in temperate and hot conditions [4, 58, 59]. Temperature appears to moderate this response. Benefits were evident with CWI (~ 2 – 15 °C), whereas thermoneutral immersion (~ 28 – 35 °C) showed no effect on HRV [22], supported by studies demonstrating larger HRV improvements with colder immersion (9 °C vs 15 °C vs 35 °C) [59] and effects at ~ 14 – 15 °C but not ~ 33 – 34 °C [60]. Practically, HRV may reflect

restoring physiological homeostasis [61], and repeated CWI during intensified training has been associated with improved HRV and perceived sleep [62, 63]. However, given HRV sensitivity to multiple confounders, changes should be interpreted alongside performance, perceptual, and biochemical markers rather than in isolation [61].

Training Adaptations

A major concern regarding the regular use of post-exercise CWI is its potential to dampen adaptive responses to resistance training. The present umbrella review indicates CWI attenuates gains in maximal strength, strength endurance, and ballistic performance when applied repeatedly after strength training. These outcomes align with mechanistic evidence of reduced muscle protein synthesis and dampened anabolic and ribosomal signalling and satellite cell activity when CWI follows resistance exercise [5, 64, 65]. Interestingly, strength gains appear sensitive to the mode of immersion [20]. Sub-group analyses indicated that immersion mode may matter as immersing just the exercised limbs attenuated strength gains (SMD ~ -0.31), whereas whole-body immersion did not influence strength development compared to control (SMD ~ -0.08) [20], but from a translation perspective, limb-only protocols are less common in applied sport settings [20]. Usage frequency across a training block is also relevant, with larger negative effects emerging with sustained, repeated use [20]. However, in short-term contexts, where immediate recovery outweighs longer-term adaptation (e.g. congested fixtures or tournament phases), targeted CWI may be defensible [66], particularly if it is reserved for technical, tactical, or conditioning sessions and separated from key resistance training sessions [20, 40]. In contrast, endurance adaptations appear largely unaffected by repeated post-exercise CWI [27]. This is supported by intervention studies reporting comparable improvements in maximal oxygen uptake, peak aerobic power and time-trial performance with or without CWI across 4–6 weeks of sprint- or aerobic-interval training [67, 68], and by data in competitive cyclists showing broadly similar performance gains during 3–4 weeks of intensified training, with some indices tending to improve slightly more with CWI [69]. While some molecular work suggests augmented mitochondrial-related signalling and vascular markers with post-exercise cooling [70–75], these signals have not translated into consistent superior endurance performance outcomes. In effect, strength gains can be protected simply by not programming CWI immediately after the sessions in which maximal hypertrophy or strength development is desired. In contrast to resistance training, endurance adaptations appear largely unaffected by the repeated post-exercise CWI [27].

Optimization of Protocol

This umbrella review indicates a coherent dose–response pattern between CWI parameters and recovery outcomes. While both temperature ranges enhanced recovery of soreness and CK [23, 24, 36], 10–15 °C tended to be superior for soreness, whereas 5–10 °C benefited CK and jump performance [36], suggesting an outcome-specific approach to selecting protocols. At the same time, experimental work cautions against the use of prolonged or aggressive cooling, which may impair glycogen restoration and contractile function, and delay recovery from muscle damage [41, 76, 77]. Collectively, these data support that for most acute recovery scenarios involving CWI at 10–15 °C for 10–15 min, or 5–10 °C for 10–15 min when the priority is mitigating muscle damage (e.g. CK) and enhancing jump recovery, provided that subsequent performance is not required within the first few hours after immersion. Given that, it is important to develop recovery plans tailored to the individual needs and characteristics of each athlete, as evidence for different protocols regarding duration and temperature is unevenly distributed across SRMAs.

Methodological Considerations and Future Directions

Most participants across the included reviews were healthy young males; only ~10% of participants were female. Sex-specific responses to cold exposure, including differences in thermoregulation, vascular responses, and the hormonal milieu, remain underexplored [78]. Accordingly, future trials should recruit more females and mixed-sex athlete cohorts while also reporting variables likely to influence the cooling “dose” and response to CWI (e.g. training status, body size/adiposity, habitual CWI exposure/cold acclimation, and the environmental context). Interpretation is further limited by heterogeneity in exercise modality, environmental conditions and the timing of outcome assessments. Many meta-analyses pooled eccentric and high-intensity exercise, and conflated temperate and hot ambient conditions, potentially obscuring context-specific effects. Recent reviews [19, 25, 26] have addressed this by stratifying analyses by modality and environment, and future work should follow such approaches. Given the predominantly low-to-very low certainty evidence base, greater methodological rigour (randomisation, blinded outcome assessment where feasible, and reliable performance testing) is needed to enable actionable, context-specific recommendations for both recovery and performance outcomes. Even though a few studies include blinding in their methodology [79], not all aspects of the intervention, particularly those related to temperature and intervention duration,

can feasibly be blinded. Furthermore, attempts to implement blinding in such contexts may increase the burden on both participants and researchers. Therefore, it may be more appropriate for researchers to prioritise other aspects of methodological rigour. For example, athletic calibre could offer a more effective methodological approach, since Burke [80] suggested that trained athletes might exhibit greater reliability in exercise performance than untrained individuals, leading to less day-to-day variation of exercise performance. Theoretically, athletes with lower training status might exhibit greater variability in performance test results, thereby reducing the likelihood of detecting small benefits from any recovery intervention; therefore, calibrating athletic training status may yield more reliable results. Finally, methodological quality of all SRMAs was rated as low or critically low mainly due to failure to report critical items. SRMAs can benefit from applying AMSTAR 2 items to their study design to improve research quality, especially analysing publication bias (item 15), reporting source of funding (item 10), and whether the authors assessed the potential impact of risk of bias in individual studies on the results of the meta-analysis (item 12). In addition, future SRMAs should pay particular attention to the critical items of the checklist, as these carry greater weight in determining the overall confidence rating of the methodological quality of the evidence base.

Conclusion

Integrating CWI Within a Recovery Framework

Findings from this umbrella review may assist with a more systematic, context-driven approach to CWI application [42]. CWI appears particularly valuable when recovery time is limited and when exercise imposes substantial thermal and cardiovascular strain. In this context, CWI, especially after high-intensity exercise, may accelerate recovery by reducing soreness, expediting autonomic restoration, reducing biochemical markers of muscle damage, and reducing thermal strain. Even though thermal strain was not included in this evidence pool, it is well-established that CWI appears more effective at reducing thermal strain following exercise in hot conditions [3, 6, 7]. Typical scenarios include tournament play, matches across consecutive days, and high-intensity endurance sessions in the heat. In these contexts, CWI can lower thermal and cardiovascular strain, accelerate perceptual and autonomic recovery, and restore endurance performance within hours, thereby helping athletes sustain competition demands [4, 6, 7, 17, 48, 81]. Findings for outcomes such as CRP and IL-6 should be interpreted with caution, as null or inconsistent results may partly reflect inadequate study power rather than a true absence of an effect.

Practitioners should exercise caution when subsequent performance requirements prioritise high-velocity movements or jumping within 1–6 h. Given the transient decrements in jump performance and impairments in contractile function following muscle cooling, alternative recovery strategies may be preferable. Where CWI is implemented, sufficient re-warming and an appropriate warm-up must be incorporated before the task. Importantly, during strength- or hypertrophy-focused training phases, routine CWI immediately after resistance sessions should be avoided due to its dampening effect on anabolic signalling, protein synthesis, and subsequent adaptation [5, 20, 21, 27]. Whole-body CWI can still be used strategically after technical or aerobic sessions within the same week, e.g., to support recovery, maintain training quality, and reduce cumulative fatigue, as highlighted in applied longitudinal studies in high-level athletes [41, 82–85]. Finally, this umbrella review reinforces that post-exercise CWI should be matched to the individual's needs and the desired outcomes at a given timepoint [42, 50]. CWI should, therefore, not be viewed as an inherently beneficial or harmful intervention, but as one tool within a wider array of strategies to be administered based on a needs analysis and symptom-driven decision making.

Limitation

A key limitation of this study is that we did not conduct a meta-analysis of the unique, non-overlapping primary studies included across the systematic reviews. Future umbrella reviews should consider conducting meta-analyses of unique primary studies for variables of interest to provide more robust estimates of treatment effects.

Abbreviations

CWI	Cold-water immersion
SRMA	Systematic review with meta-analysis
AMSTAR 2	Assessment of Multiple Systematic Reviews-2
GRADE	Grading of Recommendations Assessment, Development, and Evaluation
CK	Creatine kinase
HRV	Heart rate variability
CRP	C-reactive protein
IL-6	Interleukin-6
DOMS	Delayed onset muscle soreness
VO ₂ max	Maximal oxygen uptake
PICOS	Population, intervention, comparison, outcomes, study design
CI	Confidence interval
I ²	I-squared statistic (measure of heterogeneity)
CCA	Corrected Covered Area
SMD	Standardised mean difference
MD	Mean difference
cSMD	Corrected standardised mean difference
RMSSD	Root mean square of successive differences

Supplementary Information

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Supplementary material 1.

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E.B. and H.M. conceptualised the work; E.B. and H.M. developed the search strategy and conducted data extraction; H.M. and K.A.H. performed the critical appraisal of the methodology; E.B. and M.I. wrote the manuscript; K.K., L.R., K.A.H., and C.A. provided feedback and edited and revised the manuscript. All authors read and approved the final version of the manuscript.

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Data Availability

All data relevant to the study are included in the article.

Declarations

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

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Competing Interests

The authors declare no competing interests regarding this research.

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References

1. Versey NG, Halson SL, Dawson BT. Water immersion recovery for athletes: effect on exercise performance and practical recommendations. *Sports Med.* 2013;43(11):1101–30. <https://doi.org/10.1007/s40279-013-0063-8>.
2. Swenson C, Swärd L, Karlsson J. Cryotherapy in sports medicine. *Scand J Med Sci Sports.* 1996;6(4):193–200. <https://doi.org/10.1111/j.1600-0838.1996.tb00090.x>.
3. Peiffer JJ, Abbiss CR, Nosaka K, Peake JM, Laursen PB. Effect of cold water immersion after exercise in the heat on muscle function, body temperatures, and vessel diameter. *J Sci Med Sport.* 2009;12(1):91–6. <https://doi.org/10.1016/j.jsams.2007.10.011>.
4. Buchheit M, Peiffer JJ, Abbiss CR, Laursen PB. Effect of cold water immersion on postexercise parasympathetic reactivation. *Am J Physiol Heart Circ Physiol.* 2009;296(2):H421–7. <https://doi.org/10.1152/ajpheart.01017.2008>.
5. Roberts LA, Raastad T, Markworth JF, Figueiredo VC, Egner IM, Shield A, et al. Post-exercise cold water immersion attenuates acute anabolic signalling and long-term adaptations in muscle to strength training. *J Physiol.* 2015;593(18):4285–301. <https://doi.org/10.1113/JP270570>.

6. Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen P. Effect of a 5-min cold-water immersion recovery on exercise performance in the heat. *Br J Sports Med*. 2010;44(6):461–5. <https://doi.org/10.1136/bjism.2008.048173>.
7. Peiffer JJ, Abbiss CR, Watson G, Nosaka K, Laursen PB. Effect of cold water immersion on repeated 1-km cycling performance in the heat. *J Sci Med Sport*. 2010;13(1):112–6. <https://doi.org/10.1016/j.jsams.2008.08.003>.
8. Rowsell GJ, Coutts AJ, Reaburn P, Hill-Haas S. Effect of post-match cold-water immersion on subsequent match running performance in junior soccer players during tournament play. *J Sports Sci*. 2011;29(1):1–6. <https://doi.org/10.1080/02640414.2010.512640>.
9. Ihsan M, Watson G, Abbiss CR. What are the physiological mechanisms for post-exercise cold water immersion in the recovery from prolonged endurance and intermittent exercise? *Sports Med*. 2016;46(8):1095–109. <https://doi.org/10.1007/s40279-016-0483-3>.
10. Šrámek P, Šimečková M, Janský L, Šavlíková J, Vybíral S. Human physiological responses to immersion into water of different temperatures. *Eur J Appl Physiol*. 2000;81(5):436–42. <https://doi.org/10.1007/s004210050065>.
11. Hirvonen J, Lindeman S, Joukamaa M, Huttunen P. Plasma catecholamines, serotonin and their metabolites and beta-endorphin of winter swimmers during one winter. Possible correlations to psychological traits. *Int J Circumpolar Health*. 2002;61(4):363–72. <https://doi.org/10.3402/ijch.v61i4.17494>.
12. Suzuki K, Maekawa K, Minakuchi H, Yatani H, Clark GT, Matsuka Y, et al. Responses of the hypothalamic–pituitary–adrenal axis and pain thresholds in the orofacial region upon cold pressor stimulation in normal volunteers. *Arch Oral Biol*. 2007;52(8):797–802. <https://doi.org/10.1016/j.archoralbio.2007.01.008>.
13. Lee EC, Fragala MS, Kavouras SA, Queen RM, Pryor JL, Casa DJ. Biomarkers in sports and exercise: tracking health, performance, and recovery in athletes. *J Strength Cond Res*. 2017;31(10):2920–37. <https://doi.org/10.1519/JSC.0000000000002122>.
14. Li S, Kempe M, Brink M, Lemmink K. Effectiveness of recovery strategies after training and competition in endurance athletes: an umbrella review. *Sports Med Open*. 2024;10(1):55. <https://doi.org/10.1186/s40798-024-00724-6>.
15. Heidari J, Beckmann J, Bertollo M, Brink M, Kallus KW, Robazza C, et al. Multidimensional monitoring of recovery status and implications for performance. *Int J Sports Physiol Perform*. 2019;14(1):2–8. <https://doi.org/10.1123/ijspp.2017-0669>.
16. Ipsiridis I, Fatouros IG, Jamurtas AZ, Nikolaidis MG, Michailidis I, Douroudos I, et al. Time-course of changes in inflammatory and performance responses following a soccer game. *Clin J Sport Med*. 2008;18(5):423–31. <https://doi.org/10.1097/JSM.0b013e3181818e0b>.
17. Rowsell GJ, Coutts AJ, Reaburn P, Hill-Haas S. Effects of cold-water immersion on physical performance between successive matches in high-performance junior male soccer players. *J Sports Sci*. 2009;27(6):565–73. <https://doi.org/10.1080/02640410802603855>.
18. Chalchat E, Gaston AF, Charlot K, Peñalillo L, Valdés O, Tardo-Dino PE, et al. Appropriateness of indirect markers of muscle damage following lower limbs eccentric-biased exercises: a systematic review with meta-analysis. *PLoS ONE*. 2022;17(7):e0271233. <https://doi.org/10.1371/journal.pone.0271233>.
19. Choo HC, Lee M, Yeo V, Poon W, Ihsan M. The effect of cold water immersion on the recovery of physical performance revisited: a systematic review with meta-analysis. *J Sports Sci*. 2022;40(23):2608–38.
20. Grgic J. Effects of post-exercise cold-water immersion on resistance training-induced gains in muscular strength: a meta-analysis. *Eur J Sport Sci*. 2023;23(3):372–80. <https://doi.org/10.1080/17461391.2022.2033851>.
21. Piñero A, Burke R, Augustin F, Mohan AE, DeJesus K, Sapuppo M, et al. Throwing cold water on muscle growth: a systematic review with meta-analysis of the effects of postexercise cold water immersion on resistance training-induced hypertrophy. *Eur J Sport Sci*. 2024;24(2):177–89. <https://doi.org/10.1002/ejsc.12074>.
22. Laborde S, Wanders J, Mosley E, Javelle F. Influence of physical post-exercise recovery techniques on vagally-mediated heart rate variability: a systematic review and meta-analysis. *Clin Physiol Funct Imaging*. 2024;44(1):14–35. <https://doi.org/10.1111/cpf.12855>.
23. Batista NP, de Carvalho FA, Machado AF, Micheletti JK, Pastre CM. What parameters influence the effect of cold-water immersion on muscle soreness? An updated systematic review and meta-analysis. *Clin J Sport Med*. 2023;33(1):13–25. <https://doi.org/10.1097/JSM.0000000000001081>.
24. Machado AF, Ferreira PH, Micheletti JK, de Almeida AC, Lemes IR, Vanderlei FM, et al. Can water temperature and immersion time influence the effect of cold water immersion on muscle soreness? A systematic review and meta-analysis. *Sports Med*. 2016;46(4):503–14. <https://doi.org/10.1007/s40279-015-0431-7>.
25. Moore E, Fuller JT, Buckley JD, Saunders S, Halson SL, Broatch JR, et al. Impact of cold-water immersion compared with passive recovery following a single bout of strenuous exercise on athletic performance in physically active participants: a systematic review with meta-analysis and meta-regression. *Sports Med*. 2022;52(7):1667–88. <https://doi.org/10.1007/s40279-022-01644-9>.
26. Moore E, Fuller JT, Bellenger CR, Saunders S, Halson SL, Broatch JR, et al. Effects of cold-water immersion compared with other recovery modalities on athletic performance following acute strenuous exercise in physically active participants: a systematic review, meta-analysis, and meta-regression. *Sports Med*. 2023;53(3):687–705. <https://doi.org/10.1007/s40279-022-01800-1>.
27. Malta ES, Dutra YM, Broatch JR, Bishop DJ, Zagatto AM. The effects of regular cold-water immersion use on training-induced changes in strength and endurance performance: a systematic review with meta-analysis. *Sports Med*. 2021;51(1):161–74. <https://doi.org/10.1007/s40279-020-01362-0>.
28. Aromataris E, Fernandez R, Godfrey CM, Holly C, Khalil H, Tungpunkom P. Summarizing systematic reviews: methodological development, conduct and reporting of an umbrella review approach. *JBI Evid Implement*. 2015;13(3):132–40. <https://doi.org/10.1097/XEB.0000000000000055>.
29. Shea BJ, Reeves BC, Wells G, Thuku M, Hamel C, Moran J, et al. AMSTAR 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *BMJ*. 2017. <https://doi.org/10.1136/bmj.j4008>.
30. Schünemann H, Brożek J, Guyatt G, Oxman A. The GRADE handbook. London, UK: Cochrane Collaboration; 2013.
31. Guyatt GH, Oxman AD, Vist GE, Kunz R, Falck-Ytter Y, Alonso-Coello P, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ*. 2008;336(7650):924–6. <https://doi.org/10.1136/bmj.39489.470347.AD>.
32. Pieper D, Antoine S-L, Mathes T, Neugebauer EA, Eikermann M. Systematic review finds overlapping reviews were not mentioned in every other overview. *J Clin Epidemiol*. 2014;67(4):368–75. <https://doi.org/10.1016/j.jclinepi.2013.11.007>.
33. Quintana DS. A guide for calculating study-level statistical power for meta-analyses. *Adv Methods Pract Psychol Sci*. 2023;6(1):25152459221147260. <https://doi.org/10.1177/25152459221147260>.
34. Xiao F, Kabachkova AV, Jiao L, Zhao H, Kapilevich LV. Effects of cold water immersion after exercise on fatigue recovery and exercise performance—meta analysis. *Front Physiol*. 2023;14:1006512. <https://doi.org/10.3389/fphys.2023.1006512>.
35. Chen R, Ma X, Ma X, Cui C. The effects of hydrotherapy and cryotherapy on recovery from acute post-exercise induced muscle damage—a network meta-analysis. *BMC Musculoskelet Disord*. 2024;25(1):749. <https://doi.org/10.1186/s12891-024-07315-2>.
36. Wang H, Wang L, Pan Y. Impact of different doses of cold water immersion (duration and temperature variations) on recovery from acute exercise-induced muscle damage: a network meta-analysis. *Front Physiol*. 2025;16:1525726. <https://doi.org/10.3389/fphys.2025.1525726>.
37. Higgins TR, Greene DA, Baker MK. Effects of cold water immersion and contrast water therapy for recovery from team sport: a systematic review and meta-analysis. *J Strength Cond Res*. 2017;31(5):1443–60. <https://doi.org/10.1519/JSC.0000000000001559>.
38. Leeder J, Gissane C, Van Someren K, Gregson W, Howatson G. Cold water immersion and recovery from strenuous exercise: a meta-analysis. *Br J Sports Med*. 2012;46(4):233–40. <https://doi.org/10.1136/bjssports-2011-090061>.
39. Murray A, Cardinale M. Cold applications for recovery in adolescent athletes: a systematic review and meta analysis. *Extrem Physiol Med*. 2015;4(1):17. <https://doi.org/10.1186/s13728-015-0035-8>.
40. Allan R, Bieuzen F, Alexander J, Thorpe R, Ihsan M. Adaptations to post-exercise cooling: context matters! *Physical Activity*. 2025;3(1):16–24. <https://doi.org/10.63020/pa.2025.3.1.16>.

41. Ihsan M, Abbiss CR, Allan R. Adaptations to post-exercise cold water immersion: friend, foe, or futile? *Front Sports Act Living*. 2021. <https://doi.org/10.3389/fspor.2021.714148>.
42. Thorpe RT. Post-exercise recovery: cooling and heating, a periodized approach. *Front Sports Act Living*. 2021. <https://doi.org/10.3389/fspor.2021.707503>.
43. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiol Scand*. 1979;107(1):33–7. <https://doi.org/10.1111/j.1748-1716.1979.tb06439.x>.
44. Sargeant AJ. Effect of muscle temperature on leg extension force and short-term power output in humans. *Eur J Appl Physiol Occup Physiol*. 1987;56(6):693–8. <https://doi.org/10.1007/bf00424812>.
45. Radák Z, Pucsok J, Mecseki S, Csont T, Ferdinandy P. Muscle soreness-induced reduction in force generation is accompanied by increased nitric oxide content and DNA damage in human skeletal muscle. *Free Radic Biol Med*. 1999;26(7–8):1059–63. [https://doi.org/10.1016/s0891-5849\(98\)00309-8](https://doi.org/10.1016/s0891-5849(98)00309-8).
46. Twist C, Eston RG. The effect of exercise-induced muscle damage on perceived exertion and cycling endurance performance. *Eur J Appl Physiol*. 2009;105(4):559–67. <https://doi.org/10.1007/s00421-008-0935-z>.
47. Wilson GJ, Murphy AJ, Pryor JF. Musculotendinous stiffness: its relationship to eccentric, isometric, and concentric performance. *J Appl Physiol* (1985). 1994;76(6):2714–9. <https://doi.org/10.1152/jappl.1994.76.6.2714>.
48. Vaile J, Halson S, Gill N, Dawson B. Effect of cold water immersion on repeat cycling performance and thermoregulation in the heat. *J Sports Sci*. 2008;26(5):431–40. <https://doi.org/10.1080/02640410701567425>.
49. Henderson MJ, Chrisman BCR, Stevens CJ, Coutts AJ, Taylor L. Changes in core temperature during an elite female rugby sevens tournament. *Int J Sports Physiol Perform*. 2020;15(4):571–80. <https://doi.org/10.1123/ijsp.2019-0375>.
50. Ihsan M, Kwok V, Wong HY, Girard O, James C. Squash in Los Angeles: heat strain and performance considerations at the 2028 Olympic Games. *Int J Sports Physiol Perform*. 2025;20(7):1017–20. <https://doi.org/10.1123/ijsp.2024-0355>.
51. Pryor RR, Pryor JL, Vandermark LW, Adams EL, Brodeur RM, Armstrong LE, et al. Exacerbated heat strain during consecutive days of repeated exercise sessions in heat. *J Sci Med Sport*. 2019;22(10):1084–9. <https://doi.org/10.1016/j.jsams.2019.06.003>.
52. Reeve T, Gordon R, Laursen PB, Lee JKW, Tyler CJ. Impairment of cycling capacity in the heat in well-trained endurance athletes after high-intensity short-term heat acclimation. *Int J Sports Physiol Perform*. 2019;14(8):1058–65. <https://doi.org/10.1123/ijsp.2018-0537>.
53. Schlader ZJ, Colburn D, Hostler D. Heat strain is exacerbated on the second of consecutive days of fire suppression. *Med Sci Sports Exerc*. 2017;49(5):999–1005. <https://doi.org/10.1249/mss.0000000000001191>.
54. Nybo L, Rasmussen P, Sawka MN. Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue. *Compr Physiol*. 2014;4(2):657–89. <https://doi.org/10.1002/cphy.c130012>.
55. Eston R, Peters D. Effects of cold water immersion on the symptoms of exercise-induced muscle damage. *J Sports Sci*. 1999;17(3):231–8. <https://doi.org/10.1080/026404199366136>.
56. Bleakley CM, Davison GW. What is the biochemical and physiological rationale for using cold-water immersion in sports recovery? A systematic review. *Br J Sports Med*. 2010;44(3):179–87. <https://doi.org/10.1136/bjism.2009.065565>.
57. Peake JM, Roberts LA, Figueiredo VC, Egner I, Krog S, Aas SN, et al. The effects of cold water immersion and active recovery on inflammation and cell stress responses in human skeletal muscle after resistance exercise. *J Physiol*. 2017;595(3):695–711. <https://doi.org/10.1113/jp272881>.
58. Bastos FN, Vanderlei LC, Nakamura FY, Bertollo M, Godoy MF, Hoshi RA, et al. Effects of cold water immersion and active recovery on post-exercise heart rate variability. *Int J Sports Med*. 2012;33(11):873–9. <https://doi.org/10.1055/s-0032-1301905>.
59. Choo HC, Nosaka K, Peiffer JJ, Ihsan M, Yeo CC, Abbiss CR. Effect of water immersion temperature on heart rate variability following exercise in the heat. *Kinesiology*. 2018;50:67–74.
60. Al Haddad H, Laursen PB, Chollet D, Lemaitre F, Ahmaidi S, Buchheit M. Effect of cold or thermoneutral water immersion on post-exercise heart rate recovery and heart rate variability indices. *Auton Neurosci*. 2010;156(1–2):111–6. <https://doi.org/10.1016/j.autneu.2010.03.017>.
61. Stanley J, Peake JM, Buchheit M. Cardiac parasympathetic reactivation following exercise: implications for training prescription. *Sports Med*. 2013;43(12):1259–77. <https://doi.org/10.1007/s40279-013-0083-4>.
62. Al Haddad H, Parouty J, Buchheit M. Effect of daily cold water immersion on heart rate variability and subjective ratings of well-being in highly trained swimmers. *Int J Sports Physiol Perform*. 2012;7(1):33–8. <https://doi.org/10.1123/ijsp.7.1.33>.
63. Stanley J, Peake JM, Buchheit M. Consecutive days of cold water immersion: effects on cycling performance and heart rate variability. *Eur J Appl Physiol*. 2013;113(2):371–84. <https://doi.org/10.1007/s00421-012-2445-2>.
64. Figueiredo VC, Roberts LA, Markworth JF, Barnett MP, Coombes JS, Raastad T, et al. Impact of resistance exercise on ribosome biogenesis is acutely regulated by post-exercise recovery strategies. *Physiol Rep*. 2016. <https://doi.org/10.14814/phy2.12670>.
65. Fuchs CJ, Kouw IWK, Churchward-Venne TA, Smeets JSJ, Senden JM, Lichtenbelt W, et al. Postexercise cooling impairs muscle protein synthesis rates in recreational athletes. *J Physiol*. 2020;598(4):755–72. <https://doi.org/10.1113/jp278996>.
66. Mohammed Ihsan MI, François Bieuzen FB, Robin Thorpe RT, Jill Alexander JA, Robert Allan RA. Physiological mechanisms and performance recovery following post-exercise cold water immersion. *Asian Soc Kinesiol*. 2025. <https://doi.org/10.63020/pa.2025.3.1.25>.
67. Aguiar PF, Magalhães SM, Fonseca IA, da Costa Santos VB, de Matos MA, Peixoto MF, et al. Post-exercise cold water immersion does not alter high intensity interval training-induced exercise performance and Hsp72 responses, but enhances mitochondrial markers. *Cell Stress Chaperones*. 2016;21(5):793–804. <https://doi.org/10.1007/s12192-016-0704-6>.
68. Broatch JR, Petersen A, Bishop DJ. Cold-water immersion following sprint interval training does not alter endurance signaling pathways or training adaptations in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol*. 2017;313(4):R372–84. <https://doi.org/10.1152/ajpregu.00434.2016>.
69. Halson SL, Bartram J, West N, Stephens J, Argus CK, Driller MW, et al. Does hydrotherapy help or hinder adaptation to training in competitive cyclists? *Med Sci Sports Exerc*. 2014;46(8):1631–9. <https://doi.org/10.1249/mss.0000000000000268>.
70. D'Souza RF, Zeng N, Markworth JF, Figueiredo VC, Roberts LA, Raastad T, et al. Divergent effects of cold water immersion versus active recovery on skeletal muscle fiber type and angiogenesis in young men. *Am J Physiol Regul Integr Comp Physiol*. 2018;314(6):R824–33. <https://doi.org/10.1152/ajpregu.00421.2017>.
71. Ihsan M, Markworth JF, Watson G, Choo HC, Govus A, Pham T, et al. Regular postexercise cooling enhances mitochondrial biogenesis through AMPK and p38 MAPK in human skeletal muscle. *Am J Physiol Regul Integr Comp Physiol*. 2015;309(3):R286–94. <https://doi.org/10.1152/ajpregu.00031.2015>.
72. Ihsan M, Watson G, Buchheit M, Choo H, Govus A, Abbiss C. Influence of Regular post-exercise cold water immersion on skeletal muscle microvascular function assessed by near infrared spectroscopy. 2013:92.
73. Ihsan M, Watson G, Choo H, Lewandowski P, Papazzo A, Cameron-Smith D, et al. Postexercise muscle cooling enhances gene expression of PGC-1. *Med Sci Sports Exerc*. 2014;46(10):1900–7. <https://doi.org/10.1249/mss.0000000000000308>.
74. Ihsan M, Watson G, Abbiss CR. PGC-1 α mediated muscle aerobic adaptations to exercise, heat and cold exposure. 2014. <https://doi.org/10.7457/cmep.v3i1.e7>.
75. Joo CH, Allan R, Drust B, Close GL, Jeong T-S, Bartlett JD, et al. Passive and post-exercise cold-water immersion augments PGC-1 α and VEGF expression in human skeletal muscle. *Eur J Appl Physiol Occup Physiol*. 2016;116(11):2315–26. <https://doi.org/10.1007/s00421-016-3480-1>.
76. Cheng AJ, Willis SJ, Zinner C, Chaillou T, Ivarsson N, Ørtenblad N, et al. Post-exercise recovery of contractile function and endurance in humans and mice is accelerated by heating and slowed by cooling skeletal muscle. *J Physiol*. 2017;595(24):7413–26. <https://doi.org/10.1113/jp274870>.
77. Fu FH, Cen HW, Eston RG. The effects of cryotherapy on muscle damage in rats subjected to endurance training. *Scand J Med Sci Sports*. 1997;7(6):358–62. <https://doi.org/10.1111/j.1600-0838.1997.tb00167.x>.
78. Stephens JM, Halson S, Miller J, Slater GJ, Askew CD. Cold-water immersion for athletic recovery: one size does not fit all. *Int J Sports Physiol Perform*. 2017;12(1):2–9. <https://doi.org/10.1123/ijsp.2016-0095>.

79. Broatch JR, Petersen A, Bishop DJ. Postexercise cold water immersion benefits are not greater than the placebo effect. *Med Sci Sports Exerc.* 2014;46(11):2139–47. <https://doi.org/10.1249/mss.0000000000000348>.
80. Burke LM. Caffeine and sports performance. *Appl Physiol Nutr Metab.* 2008;33(6):1319–34. <https://doi.org/10.1139/h08-130>.
81. Vaile J, Halson S, Gill N, Dawson B. Effect of hydrotherapy on recovery from fatigue. *Int J Sports Med.* 2008;29(7):539–44. <https://doi.org/10.1055/s-2007-989267>.
82. Abbiss CR, Laursen PB. Models to explain fatigue during prolonged endurance cycling. *Sports Med.* 2005;35(10):865–98. <https://doi.org/10.2165/00007256-200535100-00004>.
83. Seco-Calvo J, Mielgo-Ayuso J, Calvo-Lobo C, Córdova A. Cold water immersion as a strategy for muscle recovery in professional basketball players during the competitive season. *J Sport Rehabil.* 2020;29(3):301–9. <https://doi.org/10.1123/jsr.2018-0301>.
84. Tavares F, Beaven M, Teles J, Baker D, Healey P, Smith TB, et al. Effects of chronic cold-water immersion in elite Rugby players. *Int J Sports Physiol Perform.* 2019;14(2):156–62. <https://doi.org/10.1123/ijsp.2018-0313>.
85. Tavares F, Simões M, Matos B, Smith TB, Driller M. The acute and longer-term effects of cold water immersion in highly-trained volleyball athletes during an intense training block. *Front Sports Act Living.* 2020;2:568420. <https://doi.org/10.3389/fspor.2020.568420>.

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