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# EFFECTS OF COLD-WATER IMMERSION ( $\leq 14^{\circ}$ C) ON PHYSIOLOGICAL RECOVERY, INFLAMMATION, AND PERFORMANCE: A SYSTEMATIC REVIEW OF HUMAN STUDIES

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## ABSTRACT

**Background:** Cold-water immersion (CWI) is a widely used recovery strategy among athletes and physically active individuals, commonly applied to reduce post-exercise fatigue and muscle soreness. Although CWI is known to induce rapid thermoregulatory and autonomic responses, the magnitude and direction of its effects appear strongly dependent on protocol parameters such as water temperature, exposure duration, and immersion depth. Evidence remains fragmented, and many previous reviews have combined cold modalities above 14°C or non-immersion cryotherapies, limiting clarity regarding true cold-water exposure.

**Aim:** This review synthesizes current evidence regarding the physiological and performance-related effects of CWI performed at  $\leq 14^\circ\text{C}$  for  $\geq 1$  minute in healthy adults, with particular focus on recovery, inflammatory and immune responses, cardiovascular function, and neuromuscular performance.

**Methods:** We systematically searched PubMed, Google Scholar, and Cochrane Library using terms including cold water immersion, CWI, ice bath, cold-water immersion recovery, cold immersion muscle soreness, cold immersion performance, and related combinations. Only open-access human experimental studies reporting direct immersion  $\leq 14^\circ\text{C}$  were included. Twenty studies met the eligibility criteria.

**Results:** CWI consistently reduced delayed-onset muscle soreness and improved subjective recovery across protocols. Performance outcomes were variable: benefits were more evident in high-intensity and intermittent sports, whereas strength and endurance recovery showed mixed results. Inflammatory, immune, and oxidative markers demonstrated context-dependent modulation. Cardiovascular and metabolic responses increased with lower temperatures and longer exposures, and limited evidence suggests potential adaptive effects following repeated immersion.

**Conclusion:** CWI at  $\leq 14^\circ\text{C}$  is an effective modality for reducing muscle soreness and enhancing perceived recovery post-exercise, with conditional benefits for performance depending on protocol and sport type. Physiological responses are heterogeneous, underscoring the need for standardized protocols and further longitudinal research to clarify dose–response relationships and long-term adaptive outcomes.

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## KEYWORDS

Cold-Water Immersion, Ice Bath, Exercise Recovery, Muscle Soreness, Inflammation, Performance

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## 1. Introduction

Cold-water immersion (CWI), defined as deliberate exposure of bare skin to cold water, has been practiced for centuries in various cultural and therapeutic contexts, ranging from Nordic winter swimming traditions to contemporary athletic recovery protocols. While historically associated with vigor, resilience, and general health maintenance, scientific interest in CWI has expanded markedly over recent decades due to claims regarding enhanced physical performance, accelerated post-exercise recovery, immune modulation, and psychological benefits. Modern usage within sport and exercise science typically involves whole or partial-body immersion in water at temperatures below 14 °C, often applied immediately following intense training sessions or competition. However, despite its widespread integration into athletic routines, the physiological mechanisms and the magnitude of benefits attributed to CWI remain incompletely understood.

Research into cold exposure intensified during the early 21st century, with experimental trials examining how hydrostatic pressure, thermal shock, and rapid skin cooling influence sympathetic activation, vasoconstriction, cerebral signaling, muscle perfusion, and metabolic substrate utilization (Brazaitis et al., 2014; Versteeg et al., 2023). Cold exposure triggers an acute surge in catecholamines, particularly norepinephrine, and increases the activation of brown adipose tissue, contributing to thermogenesis and shifts in energy expenditure. In sports medicine, CWI is most commonly employed to alleviate delayed-onset muscle soreness (DOMS), mitigate exercise-induced muscle damage, and enhance subjective recovery, yet findings

remain heterogeneous. Some studies report improvements in sprint performance, muscle power restoration, and post-exercise physiological recovery (Tabben et al., 2018; Bouchiba et al., 2022), whereas others demonstrate minimal or no advantage compared to passive or thermoneutral recovery conditions (Egaña et al., 2021; Richards et al., 2025).

A central methodological limitation in earlier literature is the broad variability in water temperature, exposure duration, and immersion depth, making cross-study comparison challenging. Importantly, many reviews mix protocols including temperatures above 14 °C, contrast bathing, cryotherapy chambers, or cold pack application — modalities with distinct mechanisms and outcomes. Therefore, there is a growing need for focused synthesis examining only true cold-water immersion, i.e., temperature  $\leq 14^{\circ}\text{C}$  and duration  $\geq 1$  minute, as these conditions induce markedly different thermal and cardiovascular responses than milder cooling interventions. Cold stress below this threshold stimulates rapid cutaneous vasoconstriction, reduces tissue temperature, and modulates inflammatory and oxidative pathways, potentially influencing both performance recovery and longer-term adaptation (Pawłowska et al., 2021; Peake et al., 2017).

Despite increasing scientific attention, there is no consensus regarding the efficacy of CWI for recovery or adaptation in healthy adults and athletes. Evidence suggests beneficial effects on perceived soreness and well-being, yet objective changes in neuromuscular performance or inflammation markers vary depending on protocol characteristics. Clarifying the magnitude, reliability, and physiological basis of these outcomes is necessary to guide evidence-based implementation in sport science, rehabilitation, and public health contexts.

### 1.1 Aim of the Study

The aim of this systematic review is to evaluate the physiological and performance-related effects of cold-water immersion at  $\leq 14^{\circ}\text{C}$  for a minimum duration of one minute in healthy adults, with emphasis on recovery, inflammation, immune responses, muscle damage, cardiovascular adaptation, and physical performance outcomes.

### 1.2 Method

We systematically searched PubMed, Google Scholar, and Cochrane Library for experimental human studies investigating cold-water immersion defined as direct skin contact with water at  $\leq 14^{\circ}\text{C}$ . Only full-text open-access articles were included. Studies involving cryotherapy chambers, cold packs, or temperatures  $> 14^{\circ}\text{C}$  were excluded. Details of the search strategy, selection criteria, and PRISMA flow are described in the Method section.

## 2. Methodology

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review focused exclusively on human studies investigating cold-water immersion (CWI) defined as direct exposure of bare skin to water at  $\leq 14^{\circ}\text{C}$  for  $\geq 1$  minute, ensuring uniformity of thermal stimulus across included trials. Only articles providing free full-text access were considered eligible to ensure transparency and reproducibility of data extraction.

### 2.1 Eligibility Criteria

Studies were included if they met all of the following criteria:

1. **Population:** Healthy adults or trained athletes, without chronic metabolic or cardiovascular disease.
2. **Intervention:** Cold-water immersion at  $\leq 14^{\circ}\text{C}$ , duration  $\geq 1$  minute, single or repeated exposures.
3. **Study Design:** Experimental or quasi-experimental trials, with a comparator (e.g., passive rest, thermoneutral immersion, active recovery).
4. **Outcomes:** At least one measurable physiological or performance variable, including but not limited to:
  - muscle soreness (DOMS), rate of perceived exertion (RPE), subjective recovery
  - neuromuscular performance (strength, power, sprint metrics)
  - inflammatory, immune, oxidative stress or biochemical markers
  - cardiovascular responses, metabolic stress
5. **Accessibility:** Full-text **open-access** availability (PDF or HTML), not abstract-only.
6. **Language:** English.

Studies were excluded if:

- water temperature exceeded  $14^{\circ}\text{C}$  or was not reported,
- intervention did not involve direct water immersion (e.g., cryotherapy chambers, cold packs),
- the article was commentary, review, theoretical, or lacking extractable primary data,
- the manuscript was paywalled or accessible only as an abstract and there was no possibility of gaining a free insight into a full article
- the study involved animal or in vitro models.

## 2.2 Search Strategy

We systematically searched PubMed, Google Scholar, and Cochrane Library using keyword combinations including "cold water immersion", "CWI", "ice bath", "cold-water immersion recovery", "cold-water immersion performance", "exercise recovery cold", "post-exercise cold immersion", "cold exposure physiology", "cold immersion inflammation", and "cold immersion muscle soreness", focusing on literature published up to 2025. The search included experimental trials, controlled human studies, and open-access research articles.

The search yielded 482 records. After removing duplicates ( $n = 98$ ) and screening titles and abstracts ( $n = 384$ ), 74 studies proceeded to full-text assessment. Fifty-four were excluded due to temperature  $>14^{\circ}\text{C}$ , non-immersion cryotherapy, lack of protocol detail, animal studies, lacking extractory primary data or lack of Open Access. A total of 20 studies met all criteria and were included in this review.

## 2.3 Study Selection and Screening Process

Screening was conducted in three phases:

1. **Title and abstract screening:** Removal of irrelevant and non-primary research.
2. **Full-text evaluation:** Verification of immersion temperature/duration and protocol description.
3. **Eligibility confirmation:** Only open-access trials with extractable outcome measures were retained.

The study selection process is summarized in the PRISMA flow diagram below.

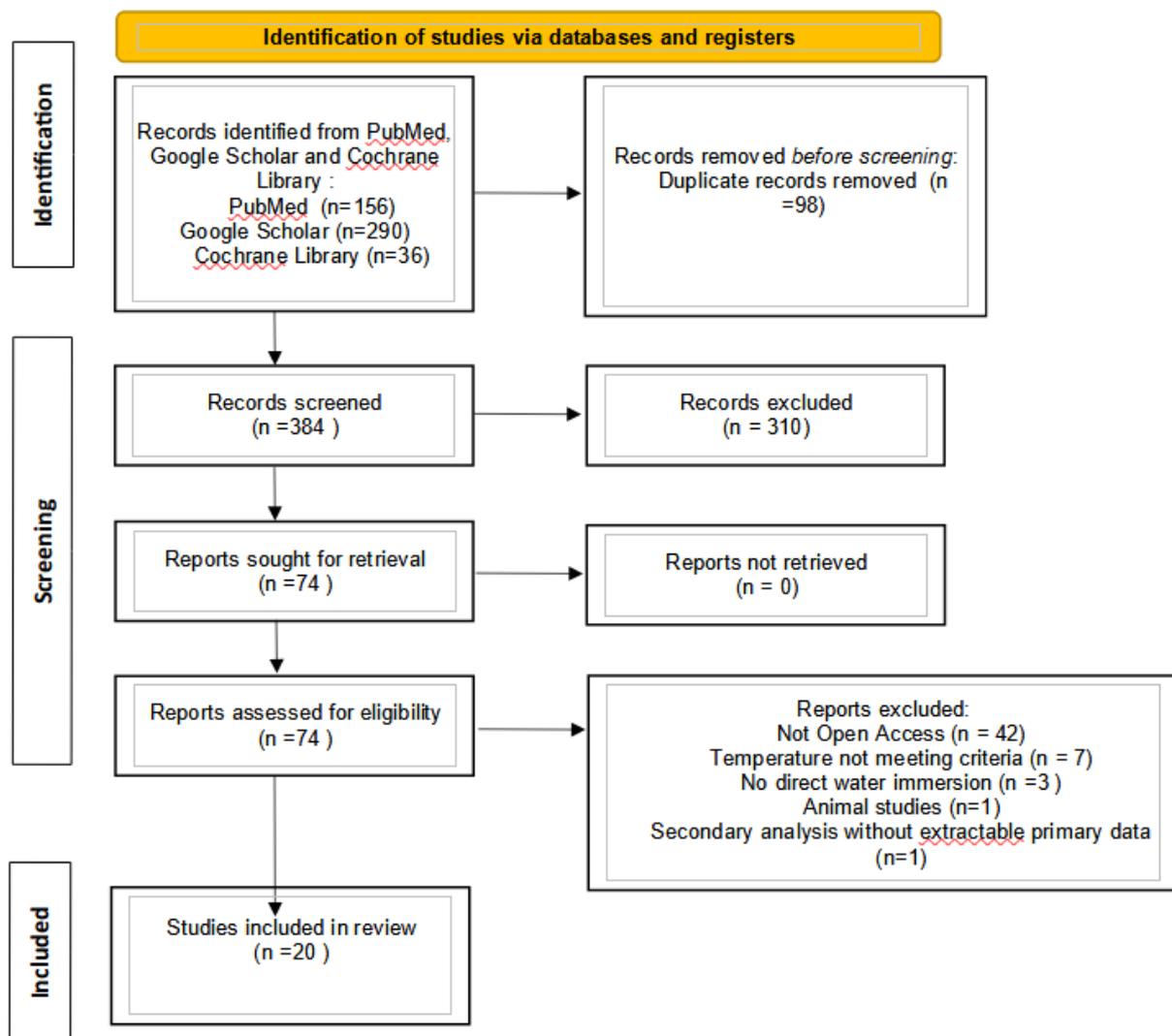


Fig. 1. Flow chart

## 2.4 Data Extraction and Synthesis

From each study, the following data were extracted: sample size, participant characteristics, immersion protocol (temperature, duration, immersion depth), comparator conditions, outcome variables, main findings, and relevance to physiological or performance recovery. Given heterogeneity in study design and outcomes, narrative synthesis was chosen over meta-analysis. Studies were grouped into thematic domains:

1. Performance and neuromuscular recovery
  2. DOMS and perceived recovery
  3. Inflammatory and immune response
  4. Physiological and cardiovascular adaptations
  5. Repeated exposure & cold adaptation
- 2.5 Summary of Included Studies

**Table 1.** Presents all included studies with protocol characteristics and primary outcomes.

Author, Year	Participants	Water Temp	Duration	Immersion Level	Main Focus	Main Outcome Summary
Brazaitis 2014	Healthy males	14°C	60–170 min	Whole body (head-out)	Thermoregulation	Strong thermal stress, neuromuscular changes
Eimonte 2021	Active males	14°C	10 min	Whole body	Inflammation	Short-term cytokine modulation
Versteeg 2023	Healthy adults	7°C	12 min × 21 days	Whole body	Adaptation	↓ HR/BP, mild immunomodulation
Pawłowska 2021	Recreational athletes	8°C	3 min	Whole body	Cytokines	Acute inflammatory spike, later normalization
Egaña 2021	Cyclists	8°C	5/10 min	Chest-level	Performance	No improvement in 4-km TT
Tabben 2018	MMA	10°C	15 min	Whole body	Recovery	Improved 10m sprint at 24h
Nasser 2023	Football players	11.3°C	15 min	Whole body	Match recovery	Better perceived recovery vs control
Peake 2017	Active males	10°C	10 min	Waist-level	Molecular	↑ HSP, no strength gain
Ahokas 2020	Active males	10°C	10 min	Xiphoid-level	Multi-modal	Better recovery perception
Faricier 2023	Healthy adults	8.9°C	6 min	Lower-limb	Neuromuscular	No fatigue reduction effect
Kositsky 2020	U20 soccer	10°C	20 min	Lower-leg	Plyometric recovery	Faster drop-jump recovery
Barros 2025	Kung-Fu	5°C	4×4 min	Whole body	Biochemical	↓ LDH, skin response improved
Bouchiba 2022	Football athletes	10±2°C	10 min	Hip-depth	Performance	Better sprint maintenance
Richards 2025	Healthy adults	10°C	10 min	Lower-leg	Recovery	No significant MVIC benefit
Lotfi 2021	Wushu	6°C	20 min	Whole body	Biochemical	No major AST/ALT changes
Gaspar Jr 2022	Healthy	5°C & 10°C	10 min	Lower-body	Hemodynamics	Temp-dependent effects
Angelopoulos 2022	Athletes	10°C	10 min	Lower-body	DOMS	↓ Muscle soreness; no function change
Park 2021	Taekwondo elite	10°C	20 min	Below-knee	Oxidative stress	↑ Antioxidant enzyme activity
Kusuma 2021	Elite athletes	5°C	15 min	Lower-body	Hormonal stress	↓ Cortisol & lactate; ↓ soreness
Lee 2025	Healthy males	12°C	10 min	Whole/Lower body	DOMS & performance	↓ Pain; protocol-dependent effect

### 3. Results

A total of 20 studies met the inclusion criteria and were analyzed. Protocols differed in temperature (5–14°C), exposure duration (3–20 minutes), immersion depth (lower-limb to whole-body), and timing relative to exercise (immediate vs delayed administration; single vs repeated sessions). Due to outcome heterogeneity, results are presented narratively and grouped into thematic areas reflecting dominant research domains. Overall, findings demonstrate that cold-water immersion consistently improves subjective recovery and muscle soreness, whereas outcomes related to strength, power, sprint performance, inflammation, and biochemical markers vary depending on protocol intensity and participant characteristics.

#### 3.1 Performance and Neuromuscular Outcomes

Several studies investigated whether CWI facilitates physical performance recovery following intense exercise bouts. Evidence indicates that neuromuscular and functional outcomes are mixed, with a trend toward benefit primarily in high-intensity or combat-sport settings.

Tabben et al. (2018) reported that MMA athletes who underwent whole-body CWI at 10°C for 15 minutes demonstrated significantly improved 10-meter sprint performance 24 hours post-exercise compared to passive recovery, suggesting possible mitigation of neuromuscular fatigue in explosive sports. Similarly, Bouchiba et al. (2022) observed greater maintenance of sprint and power output in football players following a 10-minute immersion at ~10°C versus warm-water recovery, highlighting CWI as an effective modality for short-term repeated high-intensity efforts common in team sports.

Conversely, several endurance-oriented trials report neutral effects. Egaña et al. (2021) found no performance improvement in a 4-km cycling time-trial when athletes performed CWI (8°C for 5–10 minutes) compared to active recovery. Richards et al. (2025) also observed no significant enhancement in maximal voluntary isometric contraction (MVIC) after 10°C lower-leg immersion, indicating that CWI may have limited value when muscular force restoration is the primary objective.

Results from Kositsky et al. (2020) suggest that protocol duration may influence outcomes, as 20 minutes of 10°C immersion facilitated faster drop-jump recovery in U20 soccer players. This contrasts with short protocols (3–6 minutes), where neuromuscular benefit appears less consistent.

Collectively, performance data suggest that CWI may be advantageous for intermittent and high-intensity efforts, particularly when applied 10–20 minutes at 5–12°C, whereas its influence on maximal strength and endurance outcomes appears limited or negligible.

#### 3.2 Delayed-Onset Muscle Soreness (DOMS) and Subjective Recovery

Findings related to soreness reduction and perceived recovery are more uniform. Across the majority of included studies, CWI reliably reduced DOMS and improved subjective recovery ratings, regardless of modality or athlete population.

Angelopoulos et al. (2022) demonstrated that a single 10-minute immersion at 10°C reduced self-reported muscle soreness more effectively than massage or passive rest, indicating perceptual benefits even in the absence of functional changes. Kusuma et al. (2021) reported similar reductions in soreness and concurrent improvements in mood and perceived recovery in elite athletes following 15 minutes of 5°C immersion.

Short-duration protocols also showed benefit: Pawłowska et al. (2021) confirmed that a brief 3-minute whole-body immersion at 8°C produced measurable reductions in soreness post-exercise despite transient elevations in inflammatory markers. Likewise, Lee et al. (2025) observed meaningful pain reduction in both whole-body and lower-body immersion groups (12°C/10 min), though functional recovery effects were dependent on immersion depth.

Across trials, DOMS reduction is the most consistent outcome associated with CWI, suggesting strong analgesic effects mediated by cutaneous cooling, nociceptor desensitization, and reduced nerve conduction velocity. These perceptual improvements may explain the widespread adoption of CWI in sport environments, even where objective performance outcomes remain inconsistent.

#### 3.3 Inflammatory, Immune, and Oxidative Stress Markers

Response patterns in inflammation and immune biomarkers were heterogeneous and appear heavily influenced by exposure temperature, duration, and training context.

Eimonte et al. (2021) observed acute modulation of cytokines after a single 10-minute immersion at 14°C, while Pawłowska et al. (2021) reported an initial inflammatory rise post-immersion with a return to baseline over time. Peake et al. (2017) noted increased heat shock protein expression following 10°C

immersion without parallel improvements in muscle strength recovery, suggesting a molecular stress response without direct functional carryover.

Immune outcomes similarly varied: Versteeg et al. (2023) found mild hematological changes after repeated 7°C exposures over 3 weeks, whereas Nasser et al. (2023) demonstrated improved well-being in football players with no major immune shifts. Park et al. (2021) showed enhanced antioxidant enzyme activation following 20 minutes of 10°C immersion below the knee in taekwondo athletes, whereas Gaspar-Junior et al. (2022) reported temperature-dependent hemodynamic changes when comparing 5°C vs 10°C protocols.

On balance, inflammatory and immune effects display moderate, context-dependent responsiveness to CWI, with both pro- and anti-inflammatory signatures reported across studies.

### 3.4 Physiological and Cardiovascular Responses

Cold immersion triggers rapid autonomic and circulatory responses driven by thermal shock. Studies employing lower temperatures (5–10°C) consistently showed increases in sympathetic activation, vasoconstriction, and reduced skin and muscle temperature, while longer exposures allowed for partial thermal adaptation. Versteeg et al. (2023) documented decreased resting blood pressure following repeated CWI across 21 days, indicating chronic cardiovascular adaptation potential.

Faricier et al. (2023) and Richards et al. (2025) reported that short lower-limb immersion (6–10 min) did not significantly modify neuromuscular fatigue markers, suggesting that partial-body protocols may elicit weaker systemic responses compared to whole-body immersion. Barros et al. (2025) noted lower lactate dehydrogenase levels post-immersion at 5°C, while Lotfi et al. (2021) found no significant change in liver-associated enzyme markers.

Cardiovascular and biochemical responses appear to correlate with exposure intensity:

- colder and longer immersions → greater autonomic and metabolic shift,
- short partial immersions → smaller physiological shifts.

### 3.5 Adaptation and Repeated Exposure

Although most studies examined acute recovery, a subset explored multi-session protocols, providing insight into adaptive responses. Versteeg et al. (2023) offer the clearest evidence, where 21 consecutive days of 7°C immersion induced measurable reductions in resting BP and heart rate. This suggests potential for progressive habituation and cold tolerance development, with implications for mental resilience and stress modulation.

The present dataset, however, remains limited in longitudinal scope, indicating a need for more controlled repeated-exposure designs.

#### Synthesis of Results

- Most consistent evidence: Pain/DOMS reduction, improved subjective recovery.
- Mixed outcomes: Strength, power, sprint, neuromuscular restoration.
- Variable/conditional effects: Inflammatory, immune and oxidative responses.
- Long-term adaptation: Suggestive but under-investigated; early indication of cardiovascular benefits.

Cold-water immersion appears optimally effective when used post-exercise, at 5–12°C, for 10–20 minutes, with whole-body immersion producing the strongest physiological effects.

## 4. Discussion

This systematic review synthesizes evidence from 20 open-access experimental studies investigating cold-water immersion at  $\leq 14^\circ\text{C}$  for at least one minute in healthy adults and athletes. The primary findings indicate that CWI reliably improves subjective recovery and delayed-onset muscle soreness, whereas effects on objective performance, neuromuscular function, biochemical markers, and inflammation are heterogeneous and protocol-dependent. These observations align with the broader literature suggesting that CWI provides perceptual relief but may not uniformly enhance physical performance.

The robust reduction in perceived muscle soreness observed across studies can be attributed to several physiological mechanisms. Cold exposure causes cutaneous vasoconstriction, reduced nerve conduction velocity, slowed metabolic activity within muscle tissue, and diminished nociceptive signaling, collectively producing an analgesic effect that explains the rapid improvement in recovery perception reported in trials such as Angelopoulos et al. (2022), Kusuma et al. (2021), and Lee et al. (2025). Although this analgesia offers

practical advantages for athletes returning to training, it also raises questions regarding its influence on adaptation, considering that blunted soreness may allow earlier training resumption without necessarily resolving underlying tissue stress.

When considering performance outcomes, evidence indicates that CWI may be more effective in team and combat sports involving intermittent high-intensity bouts, as shown in Tabben et al. (2018), Kositsky et al. (2020), and Bouchiba et al. (2022), compared to endurance-based exercise models in which studies such as Egaña et al. (2021) and Richards et al. (2025) reported negligible effects. These discrepancies may reflect differences in muscle recruitment patterns and recovery demands; high-intensity anaerobic exercise results in rapid metabolite accumulation and muscle damage, conditions where cold-induced vasoconstriction and edema reduction are most impactful. Conversely, endurance fatigue is more central and oxidative in nature, and acute cooling may not meaningfully accelerate metabolic restoration or neuromuscular readiness.

Inflammatory and immune responses showed greater variability than perceptual outcomes. Short-term exposure occasionally produced transient inflammatory elevations (Pawłowska et al., 2021), whereas repeated or longer exposures demonstrated modulatory tendencies, including improved antioxidant capacity (Park et al., 2021) and subtle immune shifts (Versteeg et al., 2023). This suggests that CWI may act as a hormetic stressor, where acute cold generates controlled physiological disturbance that, when applied repeatedly, fosters adaptive responses. The concept aligns with cold acclimation literature, though only a small subset of included studies explored longitudinal protocols. Therefore, long-term adaptation remains promising but insufficiently studied.

The diversity of protocols across included trials further affects interpretation. Temperatures ranged from 5°C to 14°C, durations from 3 to 20 minutes, and immersion depth varied from lower limbs to full body. Evidence suggests that colder water and longer immersion typically yield stronger cardiovascular and metabolic effects, consistent with findings from Gaspar-Junior et al. (2022) and Barros et al. (2025). Shorter immersions (3–6 minutes) delivered perceptual benefits but limited physiological change, whereas intermediate protocols (10–15 minutes at 8–12°C) appeared most balanced for recovery without excessive stress. Full-body immersion generally produced stronger systemic responses than partial-limb protocols, indicating that surface area exposure is a key determinant of outcome magnitude.

Taken together, results highlight the need for protocol specificity when applying CWI in training environments. Athletes seeking soreness relief and psychological recovery may benefit from short-to-moderate immersions at 8–12°C, while those aiming for anti-inflammatory or conditioning benefits may require repeated cold exposures or lower temperatures. Importantly, the analgesic action of CWI does not guarantee improved performance, particularly if cold exposure blunts anabolic signaling or interferes with muscle protein synthesis, an effect reported in other literature beyond the scope of this review but relevant for strength-focused training.

From a clinical and practical standpoint, CWI can be considered an effective tool to reduce DOMS, improve subjective recovery, and enhance readiness for short-term training cycles, especially during congested competition schedules. Coaches and practitioners should balance its benefits with potential attenuation of training adaptations when goals center around hypertrophy or maximal strength development. Tailoring temperature, timing, and duration to training objectives is therefore recommended.

## 5. Conclusion and Future Directions

Cold-water immersion at  $\leq 14^\circ\text{C}$  is a widely used and accessible recovery method that consistently reduces muscle soreness and enhances subjective recovery following intense exercise. Evidence supporting improvements in sprint performance and neuromuscular function is conditionally positive, particularly in high-intensity intermittent sports, although endurance and strength recovery outcomes remain less definitive. CWI also influences inflammatory, immune, and oxidative processes, yet responses are variable and dependent on protocol parameters such as temperature, immersion duration, and body surface exposure.

Future research should prioritize standardized protocols, enabling direct comparison across trials. Longitudinal studies examining repeated exposure and cold adaptation, especially using whole-body immersion at controlled intensities, are warranted to evaluate long-term physiological implications. Investigations integrating biomarker profiling, thermographic monitoring, and performance outcomes may help clarify the dose-response relationship between cold exposure and recovery. Additionally, exploring population-specific responses—including sex differences, training status, and environmental acclimatization—could inform personalized recovery strategies.

Cold-water immersion remains a valuable but context-dependent tool. When applied with methodological precision, it may support recovery, modulate physiological stress, and enhance training sustainability, though its role in long-term adaptation requires further exploration.

### Disclosure

During the preparation of this work, the author(s) used ChatGPT, an AI language model developed by OpenAI, in order to revise and improve the clarity and fluency of some parts of the English text. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

### Authors' contributions

All authors contributed to the article.

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