NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

QUALITY IN SPORT
eISSN 2450-3118 · Open Access · Peer-reviewed
apcz.umk.pl/QS Nicolaus Copernicus University in Toruń

ROCZYŃSKI, Brajan, POLOK, Izabela and MLICZEK, Aleksandra. Cold Water Immersion in Athletic Recovery: A Narrative Review of Current Evidence. Quality in Sport. 2026;65:74207. https://doi.org/10.12775/QS.2026.65.74207

ARTICLE TIMELINE
Received: 10.07.2026. Revised: 03.08.2026. Accepted: 03.08.2026. Published: 10.08.2026.

The journal has been awarded 20 points in the parametric evaluation by the Polish Ministry of Higher Education and Science (Annex to the announcement of 05.01.2024, No. 32553). Unique Journal Identifier: 201398. Scientific disciplines assigned: Economics and finance (Field of social sciences); Management and Quality Sciences (Field of social sciences).
Punkty Ministerialne z 2019 – aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

Cold Water Immersion in Athletic Recovery: A Narrative Review of Current Evidence

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Abstract

Background. Cold water immersion (CWI) is widely used to enhance post-exercise recovery, although its mechanisms, effectiveness, and effects on long-term training adaptations remain debated.

Aim. To critically review current evidence on the physiological mechanisms, recovery effects, and practical applications of CWI in sport.

Material and methods. A narrative review of original studies, systematic reviews, and meta-analyses indexed in PubMed was conducted.

Results. Current evidence shows that CWI consistently reduces delayed onset muscle soreness and improves perceived recovery. However, its effects on muscle strength, biomarkers of muscle damage and inflammation, and overall performance remain inconsistent. The effectiveness of CWI depends on exercise type, immersion protocol, and recovery goals. Repeated use after resistance exercise may reduce myofibrillar protein synthesis and potentially attenuate training adaptations.

Conclusions. CWI is effective for short-term recovery, particularly when rapid return to performance is required. Routine use after resistance training should be applied cautiously, and further research should establish standardized protocols and clarify long-term effects.

Key words: cold water immersion, post-exercise recovery, delayed onset muscle soreness, exercise-induced muscle damage, athletic performance.

1. Introduction

Regular physical activity is essential for maintaining health and optimizing athletic performance. Skeletal muscle, one of the largest and most metabolically active tissues in the human body, is responsible not only for locomotion, posture, and breathing but also for whole-body metabolic homeostasis. Owing to its remarkable plasticity, skeletal muscle continuously adapts to mechanical and metabolic stimuli induced by exercise through structural and functional remodeling. These adaptive responses enable improvements in strength, endurance, and overall physical performance while preserving muscle integrity throughout repeated training cycles [1, 2].

Exercise-induced adaptations depend on the characteristics of the training stimulus. Although regular exercise promotes beneficial physiological adaptations, strenuous or unfamiliar exercise, particularly involving eccentric contractions, may temporarily exceed the muscle's repair capacity, resulting in exercise-induced muscle damage (EIMD). EIMD is characterized by disruption of sarcomeric structures, Z-line streaming, increased sarcolemmal permeability, leakage of intracellular proteins such as creatine kinase and myoglobin, and a transient decline in muscle function. The magnitude of these alterations depends on the type, intensity, and duration of exercise, as well as the individual's training status [3, 4, 5].

Following exercise-induced muscle damage, skeletal muscle initiates a highly coordinated repair process aimed at restoring tissue integrity and functional capacity. Muscle regeneration begins with an acute inflammatory response, during which neutrophils and macrophages remove damaged tissue while simultaneously regulating the regenerative environment through cytokine signaling. Subsequently, satellite cells, the resident stem cells of skeletal muscle, become activated, proliferate, differentiate, and fuse with existing or newly forming muscle fibers, ultimately promoting tissue repair and remodeling. These overlapping processes are essential not only for recovery following muscle injury but also for long-term skeletal muscle remodeling and adaptation [2, 3, 5].

Efficient recovery is therefore a critical component of athletic training, allowing restoration of neuromuscular function, reduction of fatigue, and maintenance of performance during repeated exercise sessions. Among the numerous recovery strategies currently used in sport, cold water immersion (CWI) has become one of the most widely adopted methods. Although CWI is widely implemented in both elite and recreational sport, its effectiveness remains a subject of ongoing debate. Current evidence suggests that CWI may reduce tissue temperature, alleviate delayed onset muscle soreness (DOMS), improve perceived recovery, and facilitate recovery of physical performance. However, considerable uncertainty remains regarding its physiological mechanisms, optimal application protocols, and potential influence on long-term training adaptations, highlighting the need for a critical evaluation of the available evidence [6, 7, 8].

2. Cold Water Immersion as a Recovery Strategy

Cold water immersion (CWI) refers to the partial or whole-body immersion in cold water immediately or shortly after exercise with the aim of facilitating post-exercise recovery. Over recent decades, CWI has become an integral component of recovery protocols in both elite and recreational sports and is now widely used between successive training sessions and competitions. Its popularity has increased alongside the growing physical demands placed on modern athletes, who are frequently required to perform repeated bouts of high-intensity exercise with limited time for complete physiological recovery [6, 7].

Water temperatures ranging from approximately 5°C to 20°C have been investigated in the literature; however, the protocols most commonly evaluated involve immersion at 10–15°C for 5–15 minutes initiated immediately after exercise. CWI has been investigated across numerous sporting disciplines, including football, rugby, cycling, running, swimming, resistance training, and other team and endurance sports. Despite its widespread application, considerable variability in immersion temperature, duration, body area immersed, and timing of application prevents the establishment of universally accepted recommendations [6, 7].

3. Physiological Mechanisms of Cold Water Immersion

Although CWI has been widely implemented in post-exercise recovery protocols, its physiological mechanisms are complex and remain incompletely understood. Current evidence suggests that its effects result from the combined influence of reduced tissue temperature and hydrostatic pressure, leading to a cascade of cardiovascular, metabolic, inflammatory, and neuromuscular responses. These mechanisms are believed to act synergistically to facilitate post-exercise recovery, although their relative contribution may vary depending on exercise type, immersion protocol, and individual characteristics [7].

3.1 Reduction of Tissue Temperature

The primary physiological effect of CWI is a reduction in skin and intramuscular temperature resulting from conductive heat transfer between the body and cold water. Cooling occurs rapidly in superficial tissues, whereas temperature reductions within deeper intramuscular tissues are smaller and develop more slowly because of the insulating properties of subcutaneous tissues [7, 9].

A systematic review evaluating a standardized CWI protocol (10°C for 10 min) demonstrated that intramuscular temperature decreased by up to 6.4°C at a depth of 1 cm and 4.5°C at 2 cm, whereas the reduction at 3 cm reached only 1.6°C and was not statistically significant. These findings indicate that the most pronounced temperature reductions occur at superficial muscle depth, whereas they are progressively alleviated in deeper muscle layers. Furthermore, no significant relationship was observed between skinfold thickness and intramuscular temperature reduction ($p > 0.05$), suggesting that subcutaneous adipose tissue influences intramuscular cooling only to a limited extent [9].

Reduced tissue temperature is considered the primary physiological stimulus initiating many of the subsequent cardiovascular, metabolic, inflammatory, and cellular responses associated with CWI. However, because reductions in intramuscular temperature become progressively smaller with increasing muscle depth, the recovery effects of CWI are likely mediated by the combined influence of tissue cooling and hydrostatic pressure rather than temperature reduction alone [7].

3.2 Hemodynamic and Cardiovascular Responses

In addition to tissue cooling, CWI induces important cardiovascular responses resulting from the combined effects of hydrostatic pressure and cold exposure. Hydrostatic pressure promotes a shift of blood from the peripheral circulation toward the thoracic cavity, leading to increased central blood volume, enhanced venous return, and increased stroke volume. Cold exposure simultaneously induces peripheral vasoconstriction through activation of the sympathetic nervous system, reducing blood flow to the skin and superficial tissues while limiting heat loss [7, 10].

Experimental studies have demonstrated that these responses are accompanied by changes in heart rate, blood pressure, and cardiac output, with the magnitude of cardiovascular adaptation largely depending on water temperature. Compared with thermoneutral immersion, colder water produces greater sympathetic activation and a more pronounced redistribution of blood flow. These hemodynamic alterations may contribute to limiting post-exercise edema and may facilitate the removal of metabolic by-products; however, direct evidence linking these responses to improved recovery remains limited [7, 10].

3.3 Metabolic and Endocrine Responses

Cold exposure activates several metabolic and endocrine pathways involved in thermoregulation. Immersion in cold water increases whole-body metabolic rate and oxygen consumption as the body attempts to maintain core temperature. This response is accompanied by activation of the sympathetic nervous system and increased circulating concentrations of catecholamines, particularly noradrenaline, which stimulate heat production and peripheral vasoconstriction [10].

Beyond acute thermoregulation, CWI may also influence molecular pathways involved in skeletal muscle adaptation. Current evidence suggests that cold exposure can activate signalling pathways associated with peroxisome proliferator-activated receptor gamma coactivator-1 alpha (PGC-1α), a key regulator of mitochondrial biogenesis and cellular energy metabolism. These responses have been proposed to involve β-adrenergic activation, calcium-dependent signalling associated with shivering thermogenesis, and thyroid hormone-mediated pathways, although much of the supporting evidence is derived from mechanistic or preclinical studies rather than direct human intervention trials. However, direct evidence demonstrating that post-exercise CWI induces long-term mitochondrial adaptations in human skeletal muscle remains limited [11].

3.4 Modulation of Inflammation and Muscle Regeneration

Exercise-induced muscle damage initiates a coordinated inflammatory response that is essential for skeletal muscle repair. Following intense exercise, neutrophils rapidly infiltrate damaged tissue and are subsequently replaced by macrophages, which remove cellular debris while releasing cytokines and growth factors that regulate satellite cell activation and muscle regeneration. Therefore, the inflammatory response represents a necessary component of physiological adaptation rather than a purely detrimental process [2, 5].

Cold water immersion has been proposed to influence these processes through reductions in tissue temperature, local blood flow, and vascular permeability. Consequently, CWI may attenuate edema formation and modify the migration of inflammatory cells into damaged muscle. Experimental and clinical studies have also investigated its effects on circulating inflammatory mediators, including inflammatory cytokines such as interleukins, as well as biomarkers of muscle damage such as creatine kinase. However, the findings remain inconsistent. Meta-analytic evidence indicates that CWI may reduce serum creatine kinase concentrations after high-intensity exercise, whereas its effects on inflammatory cytokines remain variable across studies [7, 12].

Recent evidence suggests that the influence of CWI on inflammation is highly dependent on the exercise protocol, immersion conditions, and the timing of biological sample collection. Accordingly, current evidence does not support a uniform anti-inflammatory effect of CWI but rather indicates that CWI may modulate selected components of the inflammatory response without completely suppressing the physiological processes required for muscle regeneration [12, 13].

3.5 Analgesic and Neuromuscular Mechanisms

Another proposed mechanism underlying the recovery effects of CWI is its influence on the neuromuscular system. Cooling reduces nerve conduction velocity and decreases the excitability of sensory nerve endings, thereby increasing pain threshold and reducing the perception of muscle soreness. These analgesic effects are considered one of the principal mechanisms underlying the widespread use of CWI following strenuous exercise [7, 14].

In addition to its analgesic properties, cooling may alter muscle contractile function by slowing contraction velocity and reducing the rate of force development as muscle temperature decreases. However, the extent to which these physiological responses translate into improved post-exercise recovery remains uncertain and is discussed in the following section [14, 15].

3.6 Summary of Physiological Mechanisms

The physiological effects of CWI arise from the interaction of multiple mechanisms rather than a single biological pathway. Reductions in tissue temperature together with hydrostatic pressure initiate a cascade of cardiovascular, metabolic, inflammatory, and neuromuscular responses that may collectively facilitate post-exercise recovery. Current evidence also suggests that CWI can modulate molecular pathways involved in skeletal muscle adaptation, although the long-term implications of these responses remain incompletely understood. Importantly, the magnitude of these physiological effects depends on immersion temperature, duration, exercise characteristics, and individual factors. Consequently, despite the biological rationale supporting the use of CWI, the extent to which these mechanisms translate into meaningful improvements in recovery and athletic performance requires evaluation through experimental and clinical studies [7, 13].

4. Effects of Cold Water Immersion on Post-Exercise Recovery

Cold water immersion has been evaluated mainly for reducing delayed onset muscle soreness, restoring performance, and modifying markers of muscle damage. Overall, the strongest evidence supports a short-term reduction in muscle soreness, whereas effects on objective performance outcomes, biomarkers of muscle damage, and inflammation remain less consistent [6, 12].

4.1 Delayed Onset Muscle Soreness

The most consistent benefit of CWI concerns perceived muscle soreness. In a Cochrane review including 17 trials and 366 participants, CWI reduced soreness compared with passive recovery at 24 h, 48 h, 72 h, and 96 h after exercise. When results were converted to a 10-cm VAS, soreness was lower by -1.27 cm at 24 h, -1.58 cm at 48 h, and -2.16 cm at 72 h, suggesting clinically relevant effects [6].

A later meta-analysis of 32 RCTs involving 1098 participants confirmed that cold therapy applied within 1 h after exercise reduced DOMS within 24 h (SMD -0.57, 95% CI -0.89 to -0.25; $p = 0.0005$). Specifically for CWI, the effect within 24 h was also significant (SMD -0.48, 95% CI -0.84 to -0.13; $p = 0.008$), whereas evidence beyond 24 h was inconclusive ($p = 0.05$) [13].

The effect may depend on exercise type. Leeder et al. reported that CWI was highly effective after high-intensity exercise at 24 h and 48 h (Hedges' g = 1.675 and 1.391; $p < 0.001$), but not at 24 h after eccentric exercise (Hedges' g = 0.116; $p = 0.440$). A moderate effect was observed at 48 h after eccentric exercise (Hedges' g = 0.532; $p = 0.001$) [16].

4.2 Muscle Performance

Although reduction of muscle soreness is the most consistent outcome associated with CWI, restoration of physical performance is of greater practical importance for athletes returning to training or competition. The effect of CWI on performance recovery is less uniform than its effect on soreness. In a meta-analysis of 52 studies, CWI improved muscular power 24 h after eccentric exercise (SMD 0.34, 95% CI 0.06-0.62) and after high-intensity exercise (SMD 0.22, 95% CI 0.004-0.43). However, no significant effect was found for strength recovery after either eccentric or high-intensity exercise [12].

In the same review, CWI showed clearer benefits after high-intensity exercise than after eccentric exercise. After high-intensity exercise, CWI improved muscular power, soreness, CK, and perceived recovery at 24 h. After eccentric exercise, the only consistent positive effect was on muscular power at 24 h [12].

A randomized trial by Yeung et al. found that CWI attenuated the reduction in muscle tissue oxygenation during a second bout of fatiguing knee exercise by approximately 4% compared with passive recovery. However, despite lower heart rate and skin temperature ($p < 0.05$) and lower soreness 24 h later ($p < 0.05$), CWI did not significantly improve subsequent muscle performance [17].

Recent evidence also suggests that CWI is not always superior to heat-based recovery. In a randomized trial comparing CWI at 11°C, hot water immersion at 41°C, and warm-water control, peak torque returned to baseline at 48 h after both CWI and hot water immersion. However, rate of force development and pressure pain threshold returned to baseline only after hot water immersion. These findings suggest that hot water immersion may be preferable to CWI in athletic settings where rapid force development is a key performance determinant [15].

Although CWI may provide short-term recovery benefits, its repeated use after resistance exercise may influence longer-term training adaptations. Fuchs et al. demonstrated that post-exercise CWI reduced the incorporation of dietary amino acids into myofibrillar proteins and lowered both acute and daily myofibrillar protein synthesis rates during resistance training. These findings demonstrate that routine post-exercise CWI reduces acute and prolonged myofibrillar protein synthesis and may consequently impair anabolic adaptations to resistance training despite its potential short-term recovery benefits [8].

4.3 Biomarkers of Muscle Damage and Inflammation

In addition to functional outcomes, numerous studies have evaluated biochemical markers as objective indicators of muscle recovery. Overall, biochemical markers show more variable responses than subjective measures of recovery. Moore et al. found that CWI reduced serum creatine kinase 24 h after high-intensity exercise (SMD -0.85, 95% CI -1.61 to -0.08), but this effect was not consistent across all exercise types [12].

Xiao et al. included 20 studies and reported that CWI lowered CK at 24 h and lactate at 24 h and 48 h. However, CWI did not significantly affect CRP or IL-6 concentrations during the 48-h recovery period [18].

Consistent with these findings, Eimonte et al. reported that cold-water immersion delayed rather than abolished the pro-inflammatory cytokine response, indicating that cold exposure may alter the temporal pattern of the inflammatory response rather than uniformly suppress inflammation [19].

Human muscle biopsy data also question a strong anti-inflammatory effect. Peake et al. found that resistance exercise increased neutrophils, macrophages, and mRNA expression of several inflammatory cytokines, but these responses did not differ significantly between CWI and active recovery. The authors concluded that CWI was not more effective than active recovery for reducing inflammation or cellular stress in skeletal muscle after resistance exercise [20].

4.4 Perceived Recovery and Fatigue

Besides physiological and biochemical outcomes, athletes frequently evaluate recovery using subjective measures. CWI appears to have more consistent effects on perceived recovery than on biochemical markers of muscle recovery. The Cochrane review found significantly lower fatigue ratings after CWI in pooled data from two studies (MD -1.70 on a 10-point scale, 95% CI -2.49 to -0.90), with a possible improvement in perceived physical recovery [6].

Moore et al. also reported improved perceived recovery 24 h after high-intensity exercise (SMD 0.66, 95% CI 0.29-1.03). These findings indicate that CWI may be particularly useful when rapid restoration of perceived recovery is required before subsequent training sessions or competitions [12].

5. Practical Recommendations for the Use of Cold Water Immersion

5.1 Situations in Which CWI May Be Beneficial

Current evidence supports the use of CWI primarily after competitions, tournaments, or periods of congested training schedules, where rapid recovery between exercise bouts is prioritized over long-term physiological adaptation. In these situations, reductions in muscle soreness and improved perceived recovery may facilitate readiness for subsequent performance [6,12].

5.2 Situations in Which Routine CWI Should Be Avoided

Routine application of CWI after resistance training aimed at maximizing muscle hypertrophy or strength development should be considered with caution. Experimental evidence indicates that repeated post-exercise cooling may reduce myofibrillar protein synthesis and potentially attenuate adaptive responses to resistance training [8].

5.3 Practical Considerations

Although no universally accepted protocol has been established, current evidence indicates that immersion for approximately 10–15 min is associated with the most consistent recovery benefits. Medium-temperature water (11–15°C) appears to be most effective for reducing delayed onset muscle soreness, whereas lower temperatures (5–10°C) may provide greater benefits for reducing creatine kinase concentrations and improving neuromuscular performance. Therefore, the choice of immersion temperature should depend on the primary recovery objective [7,21].

6. Limitations and Future Perspectives

Despite the widespread use of CWI in sport, several limitations prevent definitive conclusions regarding its effectiveness. First, substantial methodological heterogeneity exists across studies. Considerable variation in water temperature, immersion duration, body area immersed, exercise protocols, and outcome measures makes direct comparison between studies difficult and contributes to inconsistent findings reported in systematic reviews and meta-analyses [6, 12].

Second, although CWI consistently reduces perceived muscle soreness, its effects on objective recovery outcomes remain inconsistent. Improvements in maximal strength, biomarkers of muscle damage, and inflammatory markers are less evident than improvements in subjective outcomes, indicating that reduced muscle soreness does not necessarily correspond to measurable improvements in objective indices of recovery [12, 18, 20].

Another important limitation is the limited external validity of current evidence. Most studies have included small samples of healthy young men, whereas female athletes, older individuals, and elite athletic populations remain underrepresented. Consequently, the generalizability of current findings is limited [6, 13].

While CWI may improve short-term recovery, repeated application after resistance exercise has been associated with reduced myofibrillar protein synthesis, raising concerns that routine use may attenuate adaptive responses to resistance training. Therefore, the timing and frequency of CWI should be carefully considered according to the primary training objective [8].

Finally, placebo effects should also be considered, as evidence suggests that some of the perceived benefits of cold-water immersion may be attributable to placebo rather than physiological mechanisms. In a randomized trial, placebo treatment produced recovery outcomes comparable to those observed after CWI for several performance and perceptual measures, indicating that participants' expectations may contribute to the reported benefits of CWI [22]. Moreover, recent evidence indicates that alternative recovery strategies, such as hot water immersion, may be equally or even more effective for selected outcomes, including recovery of explosive force following exercise-induced muscle damage [15].

Future research should focus on establishing standardized CWI protocols, include larger and more diverse populations, and investigate the long-term effects of repeated CWI on training adaptations. Further high-quality randomized controlled trials comparing CWI with other recovery modalities are required to establish evidence-based recommendations for different sports and training goals.

7. Conclusions

Cold water immersion remains one of the most widely used recovery strategies in sport, with the strongest evidence supporting its effectiveness in reducing delayed onset muscle soreness and improving perceived recovery after exercise. In contrast, its effects on objective indicators of recovery, including muscle strength, biomarkers of muscle damage, and inflammatory responses, remain inconsistent. Current evidence also suggests that repeated post-exercise CWI following resistance training may attenuate adaptive responses by reducing myofibrillar protein synthesis, indicating that its routine use should be carefully matched to the athlete's training goals. Overall, CWI appears to be most beneficial when rapid recovery between competitions or training sessions is prioritized, whereas its long-term application should be individualized according to the specific demands of the sport and the desired training adaptations.

DISCLOSURE

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All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable. This article is a narrative review based on previously published studies and did not involve direct research on humans or animals performed by the authors.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article because no new datasets were generated or analyzed by the authors.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Declaration of the Use of Generative AI and AI-Assisted Technologies in the Writing Process: During the preparation of this work, the authors used ChatGPT (OpenAI) for linguistic support, structural editing of the manuscript, and improvement of readability. After using this tool, the authors reviewed and edited the manuscript as necessary, verified the content against the cited sources, and take full responsibility for the content of the publication.

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