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Cold Water Immersion and Cryotherapy in Post-Exercise Recovery: A Narrative

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Abstract

Background. Post-exercise recovery is essential for athletic performance, training adaptation, and injury prevention. Cold water immersion (CWI) and whole-body cryotherapy (WBC) are widely used recovery strategies, yet uncertainty remains regarding their optimal application and long-term effects.

Aim. To synthesise current evidence on the physiological mechanisms, recovery effects, and practical applications of CWI and WBC in athletic populations.

Material and methods. A narrative review of studies indexed in PubMed/MEDLINE, Embase, SPORTDiscus, Web of Science, and the Cochrane Library was conducted. Original studies, systematic reviews, and meta-analyses published between 2009 and 2026 were analysed.

Results. CWI (10–15 min, 10–15°C) consistently reduces delayed-onset muscle soreness (DOMS), lowers markers of muscle damage and inflammation, and improves perceived recovery. WBC (−110 to −190°C, 2–4 min) produces similar analgesic and anti-inflammatory effects and may offer greater practicality in some sporting settings. Both modalities can support short-term performance recovery during periods of intensive competition. However, repeated post-resistance exercise CWI may attenuate muscle protein synthesis and hypertrophic adaptations. Evidence regarding endurance adaptations is generally neutral and, in some cases, suggests potential benefits.

Conclusions. CWI and WBC are effective tools for acute post-exercise recovery, particularly for reducing soreness and improving recovery perception. Their long-term use should be tailored to training goals, with caution advised during hypertrophy-focused resistance training phases. Further standardised, long-term studies are required.

Key words: cold water immersion; whole-body cryotherapy; post-exercise recovery; exercise-induced muscle damage; delayed-onset muscle soreness; muscle hypertrophy; athletic performance; recovery modalities.

1. Introduction

High-intensity and prolonged exercise, particularly activities involving substantial eccentric muscle contractions, inevitably induces a cascade of mechanical and metabolic perturbations collectively termed exercise-induced muscle damage (EIMD). At the ultrastructural level, EIMD is characterised by disruption of myofibrillar organisation, particularly sarcomere disarray, disturbance of intracellular calcium homeostasis, and activation of calcium-dependent proteolytic pathways (Peake, Neubauer, Della Gatta & Nosaka, 2017). These primary mechanical events trigger a secondary inflammatory cascade involving leukocyte infiltration, pro-inflammatory cytokine release (interleukin-1β, interleukin-6 [IL-6], tumour necrosis factor-alpha [TNF-α]), and reactive oxygen species generation (Peake et al., 2017). Clinically, this process manifests as delayed-onset muscle soreness (DOMS), transient reduction in force-generating capacity, localised oedema, and elevated plasma concentrations of sarcoplasmic enzymes including creatine kinase (CK) and lactate dehydrogenase (LDH) (Zhu et al., 2026).

In competitive sport, the capacity to recover efficiently between training sessions, heats, or successive competition bouts is a decisive performance determinant. During congested fixture periods — characteristic of team sport tournaments, multi-stage endurance events, and combat sport competitions — accumulated EIMD may limit the athlete's physiological and psychological readiness to perform, thereby increasing injury susceptibility and impairing competitive output (Kellmann et al., 2018). It is within this applied context that cold-based recovery modalities have gained widespread adoption, driven initially by anecdotal evidence from elite sport environments and subsequently supported by a growing body of controlled experimental research.

Cold water immersion (CWI) is one of the oldest and most extensively studied post-exercise recovery interventions, typically involving immersion of the lower limbs, torso, or entire body in water maintained at ≤20°C — with most research employing temperatures between 8°C and 15°C — for durations of 5 to 20 minutes (Versey, Halson & Dawson, 2013; Machado et al., 2016). More recently, whole-body cryotherapy (WBC) has emerged as a technologically advanced alternative, exposing athletes to cryogenic air at temperatures of −110°C to −190°C within specially engineered cryochambers for 2–4 minutes per session (Lombardi, Ziemann & Banfi, 2017; Rose et al., 2017). Both modalities are postulated to reduce peripheral tissue temperature, induce vasoconstriction, attenuate the secondary inflammatory cascade, and provide potent analgesic effects — thereby accelerating the physiological and perceptual components of recovery.

Despite their widespread application, several fundamental questions regarding cold therapy remain unresolved. The evidence base is characterised by substantial heterogeneity in study populations, exercise protocols, cold exposure parameters, outcome measurement schedules, and comparator conditions, limiting the generalisability of individual study findings (Xiao et al., 2023; Zhu et al., 2026). Moreover, a paradigm shift in the interpretation of post-exercise inflammation — from a deleterious process requiring suppression to an integral driver of adaptive remodelling — has prompted critical re-evaluation of the appropriateness of cold therapy in certain training contexts (Roberts et al., 2015; Piñero et al., 2024). In particular, compelling evidence now indicates that habitual post-resistance exercise CWI attenuates muscle hypertrophy, potentially undermining the primary physiological objective of strength and mass-oriented training programmes.

Research Objective. The aim of this narrative review is to comprehensively evaluate the current scientific evidence on CWI and WBC as post-exercise recovery strategies, with specific focus on: (1) the physiological mechanisms underlying their effects; (2) their impact on acute biochemical, physiological, and perceptual recovery markers; (3) their influence on competitive athletic performance; and (4) their differential effects on endurance versus resistance training adaptations under conditions of chronic application.

Research Problems. What are the primary physiological mechanisms by which cold-based therapies exert their post-exercise recovery effects? Does the evidence consistently support the use of CWI and WBC across diverse exercise types, training phases, and athletic populations? What are the risks of chronic cold therapy application with respect to resistance and endurance training adaptations? How do CWI and WBC compare to other established recovery modalities?

Research Hypotheses. CWI and WBC effectively reduce acute markers of EIMD and DOMS and accelerate perceptual recovery in the short term; however, chronic post-resistance exercise CWI attenuates hypertrophic adaptation through suppression of post-exercise anabolic signalling, while cold therapy applied following endurance exercise does not negatively affect, and may support, mitochondrial and cardiovascular adaptations.

2. Research materials and methods

2.1. Search Strategy

This narrative review was conducted in accordance with established principles of evidence-based synthesis. A systematic literature search was performed in the PubMed/MEDLINE, Embase, SPORTDiscus, Web of Science, and Cochrane Library databases. The search encompassed peer-reviewed articles published between January 2009 and April 2026. Seminal earlier publications (pre-2009) were additionally included where they represented foundational contributions to the field. The following Medical Subject Headings (MeSH) terms and free-text keywords were employed in various Boolean combinations: "cold water immersion", "cryotherapy", "whole-body cryotherapy", "partial-body cryotherapy", "ice bath", "cold-water therapy", "post-exercise recovery", "exercise-induced muscle damage", "delayed onset muscle soreness", "DOMS", "creatine kinase", "inflammatory markers", "interleukin-6", "C-reactive protein", "muscle protein synthesis", "muscle hypertrophy", "resistance training adaptations", "endurance training adaptations", "athletic recovery", and "sports performance".

2.2. Inclusion and Exclusion Criteria

Studies were considered eligible for inclusion if they: (1) investigated the effects of CWI, WBC, or directly comparable cold-based recovery modalities on post-exercise recovery outcomes in human participants; (2) were published as randomised controlled trials (RCTs), crossover trials, systematic reviews, meta-analyses, or well-designed narrative reviews in peer-reviewed scientific journals; (3) reported at least one outcome measure relevant to muscle damage markers, inflammatory response, muscle soreness, neuromuscular performance, subjective recovery, or training adaptations; and (4) were published in English. Studies were excluded if they: (1) were conducted exclusively in clinical, diseased, or non-athletic populations with conditions unrelated to exercise; (2) were published solely in abstract or conference proceedings format without full-text availability; (3) employed CWI or WBC as a primary therapeutic intervention for injury treatment rather than post-exercise recovery; or (4) provided insufficient methodological detail to permit meaningful evaluation of study quality.

2.3. AI

AI tools (Claude by Anthropic) were utilised for two specific purposes in this research. First, for assistance in refining the academic English language of the manuscript, ensuring clarity, consistency, and adherence to scientific writing standards. Second, for organisational support in structuring the narrative and identifying thematic patterns across the literature reviewed. It is emphasised that all AI tools were used strictly as assistive instruments under full human supervision. All interpretations of the evidence, synthesis of findings, evaluation of methodological quality, and formulation of conclusions were determined exclusively by the human authors. AI tools served to enhance efficiency in linguistic refinement and manuscript organisation, and at no point replaced human scholarly judgement in the analytical process.

3. Research results

3.1. Physiological Mechanisms of Cold Therapy in Post-Exercise Recovery

The physiological rationale for cold therapy in post-exercise recovery derives from the well-established thermodynamic and cardiovascular responses to acute cold exposure. When peripheral tissues are exposed to temperatures substantially below thermoneutral conditions, a reproducible and hierarchically organised sequence of physiological adaptations is triggered. These include: cutaneous and subcutaneous vasoconstriction mediated by sympathetic adrenergic activation; progressive reduction in local tissue temperature; decreased local metabolic rate and oxygen consumption; reduced enzymatic activity in temperature-sensitive pathways; slowing of nerve conduction velocity in both afferent sensory fibres and efferent motor neurones; and reduction in inflammatory cell infiltration and pro-inflammatory mediator production (Ihsan, Watson & Abbiss, 2016).

The vasoconstriction response to cold immersion is particularly relevant to the attenuation of post-exercise EIMD. Following mechanical disruption of muscle fibres during eccentric or high-intensity exercise, secondary tissue injury is propagated by infiltrating neutrophils, monocytes, and macrophages, which release reactive oxygen species and proteolytic enzymes that cause bystander damage to adjacent intact muscle tissue (Peake et al., 2017). Cold-induced vasoconstriction reduces capillary filtration pressure and limits the extravasation of pro-inflammatory leukocytes into the damaged tissue, thereby constraining the magnitude of the secondary inflammatory cascade. The hydrostatic pressure exerted by water immersion — independent of temperature — further promotes resorption of interstitial fluid into the intravascular compartment, attenuating oedema formation and potentially accelerating metabolite clearance (Versey, Halson & Dawson, 2013; Ihsan et al., 2016).

Following the cessation of cold therapy, a rebound vasodilatory response occurs, characterised by reactive hyperaemia and increased cutaneous and muscular blood flow. This post-immersion hyperaemia is postulated to facilitate enhanced delivery of nutrients, oxygen, and reparative immune cells to the recovering tissue, while simultaneously accelerating the removal of lactate, hydrogen ions, and other fatigue-related metabolites (Ihsan et al., 2016). The pressure difference created by the transition from cold-induced vasoconstriction to rebound vasodilation may create a physiological ‘pump’ mechanism that enhances circulatory efficiency in recovering tissues.

The analgesic effects of cold therapy are mediated through multiple partially overlapping mechanisms. Direct cooling of cutaneous thermoreceptors, particularly TRPM8 (transient receptor potential melastatin 8) cold-sensitive channels in unmyelinated C-fibres and thin myelinated Aδ-fibres, reduces the transmission of nociceptive signals from the periphery to the central nervous system (Ihsan et al., 2016). Reduced nerve conduction velocity in these paintransmitting fibres further attenuates the afferent pain signal. Additionally, gate control mechanisms at the dorsal horn of the spinal cord may modulate pain perception through competing non-nociceptive cold-specific sensory input. These peripheral and spinal analgesic mechanisms collectively contribute to the reduction in DOMS perception consistently observed following cold therapy (Machado et al., 2016; Xiao et al., 2023).

WBC induces a more rapid and pronounced superficial tissue cooling than CWI, given the extreme air temperatures employed (−110 to −190°C) and the high thermal conductivity differential between body surface temperature and the surrounding cryogenic air. Systemic physiological responses to WBC include pronounced activation of the sympathetic nervous system, marked increases in plasma catecholamines (epinephrine and norepinephrine), and transient elevations in heart rate and blood pressure (Lombardi, Ziemann & Banfi, 2017). Neuroendocrine activation following WBC may contribute to the antinociceptive and mood-enhancing effects of this modality through central opioidergic and monoaminergic pathways. The immunomodulatory effects of WBC — including modulation of circulating leukocyte populations, lymphocyte subsets, and innate immune activity — may additionally contribute to its anti-inflammatory profile in the post-exercise context.

3.2. Effects on Biochemical Markers of Muscle Damage and Inflammation

Creatine kinase (CK) is the most widely used indirect biochemical marker of EIMD in the sports science and clinical literature, with elevated plasma CK concentrations reflecting sarcolemmal disruption and leakage of sarcoplasmic proteins into the systemic circulation (Peake et al., 2017; Zhu et al., 2026). Alongside CK, myoglobin, lactate dehydrogenase (LDH), and troponin I have been employed as complementary markers of muscle damage. A comprehensive network meta-analysis by Zhu et al. (2026) — encompassing 55 randomised controlled trials with 30 studies reporting CK data — demonstrated that both medium-duration low-temperature CWI (10–15 min at 5–10°C) and medium-duration moderate-temperature CWI (10–15 min at 11–15°C) produced statistically significant reductions in post-exercise CK concentrations compared to passive rest, confirming that cold water exposure effectively mitigates the extent of sarcolemmal damage following strenuous exercise across a range of clinically relevant temperature parameters.

The meta-analysis by Xiao et al. (2023), incorporating 20 studies and reporting on CK, LDH, IL-6, and CRP outcomes across multiple post-exercise time points (immediate, 24 h, and 48 h), found that CWI significantly attenuated plasma CK and LDH at 24 and 48 hours post-exercise, while producing significant reductions in IL-6 and CRP concentrations compared to passive recovery. These findings indicate that CWI exerts a measurable attenuating effect on both muscle membrane damage and the systemic acute-phase inflammatory response following exercise. Critically, however, the effect sizes for inflammatory biomarker reduction were heterogeneous across studies, and some investigators have reported no significant difference in inflammatory marker attenuation between CWI and low-intensity active recovery (Peake et al., 2017, as cited in Piñero et al., 2024), suggesting that the anti-inflammatory effects of cold therapy may be partially attributed to general movement rather than temperature-specific mechanisms.

A parallel literature on WBC and inflammatory markers has accumulated over the past two decades, with the most comprehensive synthesis recently provided by Zhang et al. (2025) in a meta-analysis of 11 randomised controlled trials. The authors concluded that WBC statistically significantly reduced multiple pro-inflammatory cytokines, including IL-6 and TNF-α, relative to control conditions, though the overall certainty of evidence was assessed as moderate due to protocol heterogeneity and risk of bias considerations. Earlier foundational work by Banfi and colleagues (2009a, 2009b), as cited in Lombardi et al. (2017), established that repeated WBC sessions produced significant reductions in serum CK, CRP, and high-sensitivity troponin I in competitive athletes, with effects most pronounced following multiple consecutive treatment sessions rather than isolated applications. Siqueira et al. (2018) further demonstrated that multiple CWI sessions (10°C for 20 min at post-exercise and every 24 h for 72 h) significantly attenuated peak CK release ($p = 0.016$) and normalised DOMS earlier than passive rest controls, though without altering systemic inflammation markers including CRP and IL-6, suggesting that the biochemical and inflammatory effects of cold therapy may be dissociated at the molecular level.

Dupuy et al. (2018), in a landmark systematic review with meta-analysis of 99 studies encompassing multiple recovery modalities, identified CWI as among the most effective recovery interventions for reducing CK (moderate effect size) and IL-6 (small-to-moderate effect size), with CWI outperforming active recovery, stretching, and compression garments for most inflammatory markers. Notably, massage emerged as the most effective single modality for DOMS reduction in this analysis, while CWI demonstrated the greatest utility for reducing inflammatory cytokines among the physical modalities evaluated.

3.3. Effects on Muscle Soreness and Perceptual Recovery

DOMS is the subjective clinical manifestation of EIMD and is characterised by diffuse muscular aching, stiffness, and tenderness to palpation, with a characteristic temporal profile typically peaking at 24–72 hours following the damaging exercise bout and resolving within 5–7 days (Peake et al., 2017). DOMS is commonly quantified using visual analogue scales (VAS), numeric rating scales (NRS), or pressure pain threshold measurements. Given its direct impact on athlete comfort, movement quality, and psychological readiness to train, reduction of DOMS represents a primary practical objective of post-exercise cold therapy.

The evidence for CWI-induced DOMS reduction is among the most robust and consistent findings in the cold therapy literature. The systematic review by Hohenauer, Taeymans, Baeyens, Clarys and Clijsen (2015) — one of the most cited analyses in this domain — demonstrated that CWI significantly reduced DOMS at 24, 48, and 72 hours post-exercise relative to passive rest, with moderate effect sizes. A recent systematic review and meta-analysis by Zhu et al. (2026) confirmed these findings, reporting that full-body CWI produced the most consistent DOMS reduction across all post-exercise time points, with effects robust even following statistical correction for potential publication bias. Xiao et al. (2023) further corroborated these findings, reporting significant reductions in both DOMS and perceived exertion at 24 and 48 hours following CWI, with athletes in CWI conditions reporting meaningfully greater perceptual recovery and readiness to train than passive rest controls.

Regarding the optimal CWI parameters for DOMS reduction, Machado et al. (2016) conducted a systematic review and meta-analysis specifically addressing the influence of water temperature and immersion duration on DOMS outcomes. Their analysis, covering 15 studies and 235 participants, concluded that CWI protocols employing 11–15 minutes at 11–15°C produced the most consistent DOMS reduction, while extremely low temperatures (<10°C) did not confer proportionally greater analgesic benefit and were associated with greater discomfort and reduced participant compliance. The emerging consensus therefore supports moderate-temperature, moderate-duration protocols as an effective balance between physiological efficacy and practical tolerability.

Perceptual recovery — encompassing subjective assessments of fatigue, energy, mood, and readiness to perform — represents an increasingly recognised outcome dimension in recovery research, as it directly influences an athlete's willingness and capacity to engage with subsequent training or competition demands (Kellmann et al., 2018). Both CWI and WBC consistently produce improvements in perceived recovery relative to passive rest in experimental investigations (Xiao et al., 2023; Rose et al., 2017). WBC additionally demonstrates benefits for mood state, self-reported energy levels, and quality of life in athletic populations, potentially reflecting the neuroendocrine and sympathoadrenal responses to acute cryogenic exposure (Lombardi, Ziemann & Banfi, 2017). The magnitude of these perceptual effects may partially reflect expectancy and placebo mechanisms — a recognised confound in recovery research given the inherent difficulty of blinding participants to temperature exposure — though several studies have demonstrated that perceived recovery benefits persist beyond the magnitude explained by expectancy alone (Broatch, Petersen & Bishop, 2018).

3.4. Effects on Neuromuscular Performance and Athletic Capacity

The restoration of neuromuscular performance capacity — operationalised as maximal voluntary isometric contraction (MVIC), isokinetic peak torque, countermovement jump height (CMJ), and repeated sprint ability (RSA) — represents the most practically consequential outcome dimension in post-exercise recovery research. An athlete's ability to reproduce maximal or near-maximal neuromuscular outputs during subsequent training or competition sessions is the ultimate litmus test of the effectiveness of any recovery intervention.

Versey, Halson and Dawson (2013), in their comprehensive review of water immersion recovery protocols spanning over 90 studies, concluded that cold water immersion in the range of 10–15°C for 5–15 minutes represented the most effective protocol for accelerating performance recovery across a range of sports-specific outcomes, including repeated sprint ability in team sport contexts, cycling performance in multi-stage formats, and swimming velocity in competitive events. The meta-analysis by Higgins, Greene and Baker (2017), specifically addressing CWI and contrast water therapy (CWT) for team sport recovery, reported that CWI was beneficial for recovery of neuromuscular performance — as assessed by CMJ height and all-out sprint performance — at 24 hours following team sport exercise (CMJ: $p = 0.05$; sprint: $p = 0.02$). Xiao et al. (2023) similarly found that CWI produced significantly greater recovery of CMJ performance at 24 and 48 hours post-exercise compared to passive rest.

In team sport contexts, the ecological validity of recovery interventions is particularly critical. Rowsell, Coutts, Reaburn and Hill-Haas (2009) demonstrated in a seminal applied study that junior elite male soccer players who received CWI treatment (5 × 1 min at 10°C) between successive matches in a 4-day tournament maintained higher high-intensity running distances compared to a thermoneutral water immersion control group. A subsequent investigation by the same research group (Rowsell et al., 2011) confirmed that post-match CWI during a 4-day soccer tournament supported preservation of match running performance, with CWI-treated players maintaining higher mean running speed and high-intensity running distance across successive matches relative to controls. These ecological findings are particularly compelling given their real-world sporting context and underscore the potential match-to-match performance implications of systematic post-competition cold therapy application.

For WBC, Krüger et al. (2015) demonstrated that a single WBC session at −110°C significantly enhanced acute recovery of 400-metre running performance in well-trained athletes compared to passive rest, with WBC-treated athletes demonstrating meaningfully faster times at 1 hour post-exercise. Haq, Ribbans, Hohenauer and Baross (2022) examined the comparative effects of different WBC timing protocols relative to CWI for post-exercise recovery in a randomised crossover design, concluding that both modalities demonstrated comparable effectiveness for reducing DOMS and restoring neuromuscular function, with WBC timing flexibility representing a potential practical advantage in competition settings where immediate post-exercise access to cold water tanks is limited.

3.5. Comparison of CWI and WBC with Other Recovery Modalities

The practical utility of CWI and WBC must be contextualised within the broader landscape of available post-exercise recovery interventions, which includes active recovery, compression garments, massage, sleep optimisation, nutritional strategies, and photobiomodulation, among others. Dupuy et al. (2018), in the most comprehensive comparative meta-analysis of recovery modalities to date, synthesised data from 99 studies and compared the effectiveness of CWI, active recovery, stretching, compression garments, massage, and electrostimulation for reducing DOMS, perceived fatigue, CK, CRP, and IL-6. In this analysis, massage emerged as the most effective single modality for DOMS reduction (effect size: −0.92) and reduction of perceived fatigue, while CWI demonstrated the greatest effectiveness for reducing inflammatory markers (IL-6 and CRP) among the physical modalities examined. Critically, combining modalities — particularly CWI with compression — produced additive effects superior to either modality alone for DOMS reduction, suggesting that multimodal recovery protocols may offer superior outcomes compared to single-modality approaches.

A systematic review with meta-analysis and meta-regression by Versey, Halson and Dawson (2013) established that CWI consistently outperforms passive rest for recovery of athletic performance but demonstrates less consistent superiority over active recovery (low-intensity cycling or jogging), with several studies reporting comparable performance recovery between these two approaches. This observation aligns with mechanistic data suggesting that some of the apparent benefits of CWI — including lactate clearance, metabolic waste removal, and cardiovascular recovery — may be achieved equally well through low-intensity aerobic activity without the potential risks of cold therapy to training adaptations. The evidence comparing

CWI with other advanced modalities such as photobiomodulation therapy, percussion therapy, and normobaric hypoxia remains limited and methodologically heterogeneous.

Contrast water therapy (CWT) — alternating between cold (10–15°C) and hot (38–42°C) water immersion — is another widely used hydrotherapy recovery modality. Higgins et al. (2017) found that CWT was beneficial for perceived recovery of fatigue at 48 hours following team sport, but demonstrated less consistent superiority over CWI alone for neuromuscular performance outcomes. The Cochrane review of CWI for preventing and treating muscle soreness after exercise (Bleakley et al., 2012, as cited in Xiao et al., 2023) similarly concluded that CWI was effective for reducing DOMS but noted the quality of evidence remained limited by methodological heterogeneity across included studies.

3.6. Cold Therapy and Resistance Training Adaptations

The potential for post-exercise cold therapy to interfere with resistance training-induced skeletal muscle adaptations represents the most clinically significant controversy in this field, with implications extending beyond acute recovery to the fundamental question of whether cold therapy use during strength and hypertrophy training programmes is contraindicated. This debate is grounded in the emerging recognition that the post-exercise inflammatory response — specifically the initial pro-inflammatory phase characterised by neutrophil and macrophage infiltration and reactive oxygen species production — is not simply an epiphenomenon of muscle damage but an integral mechanistic driver of satellite cell activation, myofibrillar protein synthesis upregulation, and long-term hypertrophic remodelling (Roberts et al., 2015; Peake et al., 2017).

The foundational evidence for cold therapy-induced interference with resistance training adaptations was provided by Roberts et al. (2015), who conducted a rigorous 12-week randomised controlled trial in young resistance-trained men. Participants performed biweekly lower-body resistance training sessions followed by either post-exercise CWI (10 min at 10.1°C) or active recovery (low-intensity cycling for 10 min). Quadriceps muscle mass assessed by magnetic resonance imaging increased by approximately 15% in the active recovery group versus only approximately 2% in the CWI group — a striking and statistically significant difference. Post-exercise anabolic signalling was correspondingly attenuated in the CWI condition, with blunted phosphorylation of mechanistic target of rapamycin (mTORC1) pathway components and reduced satellite cell activation compared to active recovery. Importantly, maximal isometric knee extensor strength demonstrated a non-significant trend for attenuation with CWI, suggesting that strength gains may be partially preserved through neural adaptations even when morphological adaptations are suppressed.

Fyfe et al. (2019) extended these findings to the skeletal muscle fibre level in a subsequent investigation, demonstrating that post-exercise CWI significantly attenuated resistance training-induced type I and type II fibre hypertrophy relative to active recovery, potentially through blunted post-exercise increases in markers of anabolic signalling (phosphorylated p70S6K1) and elevated indices of protein catabolism. These cellular-level findings provide mechanistic coherence to the functional observation of impaired macroscopic hypertrophy reported by Roberts et al. (2015).

A systematic review with meta-analysis by Piñero et al. (2024), published in the European Journal of Sport Science and constituting the most comprehensive evidence synthesis on this specific question to date, analysed data from all available controlled trials comparing resistance training outcomes with and without post-exercise CWI. The meta-analysis revealed a consistent and statistically significant attenuation of muscle hypertrophy across studies, with the effect present regardless of participant training status and the specific resistance training protocol employed. The authors additionally confirmed that the interference effect was mediated at the level of muscle protein synthesis, consistent with mechanistic data from Fuchs et al. (2020) — cited in Piñero et al. (2024) — who demonstrated that CWI administered 20 minutes post-resistance exercise significantly reduced myofibrillar muscle protein synthesis rates for up to 5 hours post-immersion, implicating CWI-induced impairment of microvascular perfusion and consequent reduction in amino acid delivery to recovering muscle as a key mechanistic pathway.

The hormonal consequences of post-resistance exercise CWI further illuminate the mechanistic basis of the hypertrophy interference effect. Earp et al. (2019), as cited in Piñero et al. (2024) and Broatch et al. (2018), demonstrated that CWI blunts and delays the characteristic post-resistance exercise increases in circulating testosterone and insulin-like growth factor-1 (IGF-1) — key anabolic hormones that augment protein synthetic signalling and satellite cell activation. Additionally, CWI delays the post-exercise inflammatory cytokine response (IL-6 and TNF-α), which, paradoxically to its traditionally conceived deleterious role, now appears to play an anabolic signalling function in the context of resistance exercise-induced hypertrophy.

A critical nuance in this literature is the apparent differential effect of CWI on hypertrophy versus strength development. Several studies, including those of Roberts et al. (2015) and Fyfe et al. (2019), have observed that CWI attenuates muscle hypertrophy without producing proportionally equivalent attenuation of maximal voluntary strength. This dissociation may reflect the relatively greater contribution of neural adaptations — including motor unit recruitment, rate coding, and inter-muscular coordination — to strength expression, particularly in trained individuals and during complex multi-joint movements, where neural contributions to performance improvement predominate over hypertrophic contributions. Meta-regression analyses by Piñero et al. (2024) did not identify participant training status as a significant moderator of the hypertrophy attenuation effect, suggesting that even experienced resistance-trained individuals are susceptible to CWI-induced interference with muscle growth.

3.7. Cold Therapy and Endurance Training Adaptations

In contrast to the concerning interference effects observed in resistance training contexts, the evidence for cold therapy-induced attenuation of endurance training adaptations is considerably more reassuring. Ihsan, Abbiss and Allan (2021) conducted a systematic narrative review of adaptations to post-exercise CWI in the context of endurance training, concluding that regular post-endurance exercise CWI does not negatively affect, and may in some cases enhance, key physiological determinants of endurance performance, including mitochondrial biogenesis, capillary density, and oxidative enzyme activity in skeletal muscle.

The potential for post-exercise CWI to augment endurance adaptations is mechanistically attributed to cold-induced upregulation of peroxisome proliferator-activated receptor gamma coactivator-1 alpha (PGC-1α) gene expression in skeletal muscle — a central transcriptional regulator of mitochondrial biogenesis (Ihsan, Watson, Choo, Lewandowski, Papazzo, Cameron-Smith et al., 2014, as cited in Ihsan et al., 2021). Cold stimulation may additionally promote angiogenic adaptations through VEGF (vascular endothelial growth factor) pathway activation. These molecular effects, if consistently demonstrated in humans, would suggest that CWI represents a complementary rather than antagonistic intervention for endurance athletes. However, definitive human intervention trials with adequate statistical power and long-duration follow-up specifically examining endurance training adaptations with and without post-exercise CWI remain limited, and the molecular evidence currently rests primarily on animal model data and acute gene expression studies in humans.

From a practical standpoint, the differential adaptive consequences of CWI in resistance versus endurance training contexts have important implications for periodised training programme design. Athletes engaged in concurrent training — combining resistance and endurance work within the same macrocycle — may need to selectively apply cold therapy only in proximity to endurance sessions while withholding it after resistance exercise sessions, representing a nuanced periodised approach to recovery intervention timing that has yet to be comprehensively evaluated in controlled intervention research.

4. Discussion

This narrative review has synthesised the current scientific evidence on CWI and WBC as post-exercise recovery strategies, evaluating their physiological mechanisms, acute effects on biochemical and perceptual markers, impact on athletic performance, and implications for long-term training adaptations. The collective evidence supports the short-term efficacy of both modalities for reducing DOMS, attenuating circulating markers of muscle damage and inflammation, and improving perceptual recovery — while simultaneously highlighting critical context-specific limitations that must be integrated into evidence-based practice.

The acute recovery benefits of cold therapy are physiologically plausible and empirically well-supported across a substantial body of controlled experimental literature. Vasoconstriction-mediated limitation of secondary EIMD, hydrostatic pressure-driven fluid redistribution, reduction in nerve conduction velocity, and direct nociceptor cooling collectively constitute a coherent mechanistic framework for the analgesic and anti-inflammatory effects observed following CWI and WBC (Ihsan et al., 2016; Versey et al., 2013). The post-immersion rebound vasodilation response further provides a mechanistic account for the enhanced perceptual recovery and accelerated restoration of some performance parameters observed in the hours following cold therapy. These mechanisms are not mutually exclusive and likely operate synergistically within the complex post-exercise physiological environment.

The heterogeneity of findings across CWI and WBC studies — which has historically been cited as a limitation of the evidence base — is now increasingly understood as reflecting genuine context-dependence of cold therapy effects rather than simply methodological inconsistency. The type, intensity, and volume of preceding exercise; the characteristics of the study population; the specific cold therapy protocol parameters (temperature, duration, immersion depth, timing relative to exercise); and the outcome measurement schedule all demonstrably influence the magnitude and direction of cold therapy effects (Machado et al., 2016; Zhu et al., 2026). Standardisation of reporting and protocol description across future studies is therefore a prerequisite for meaningful meta-analytic synthesis.

The finding that post-exercise CWI consistently attenuates resistance training-induced muscle hypertrophy represents the most consequential practical implication of this literature. The convergent evidence from Roberts et al. (2015), Fyfe et al. (2019), and the meta-analysis of Piñero et al. (2024) presents a compelling case that habitual post-resistance exercise CWI — as a chronic intervention — is incompatible with the goal of maximising muscle hypertrophy. This finding is particularly important given the widespread adoption of ice baths as a routine post-training recovery tool across strength sports, bodybuilding, and power-dominant team sports, where hypertrophy is a primary training objective. Practitioners prescribing post-resistance exercise CWI in these athletic contexts should be cognisant that they may be systematically undermining the morphological adaptations their training programme is designed to produce.

The practical recommendations that emerge from this literature are necessarily nuanced and context-dependent. During competition-heavy periods where rapid recovery between performance bouts takes precedence over chronic adaptation — such as multi-day tournaments, stage races, or combat sport competition blocks — both CWI and WBC represent evidence-based tools for supporting short-term performance restoration (Rowsell et al., 2009, 2011; Higgins et al., 2017). Conversely, during training phases where the primary objective is morphological adaptation through resistance exercise, post-exercise CWI should be minimised or eliminated, and alternative recovery strategies that do not compromise anabolic signalling should be prioritised (Piñero et al., 2024). Active recovery, sleep optimisation, and nutritional strategies — particularly protein intake timing — represent adaptation-compatible alternatives that may be preferentially employed during hypertrophy-focused training blocks.

The comparison between CWI and WBC in terms of physiological efficacy reveals broadly comparable outcomes for most acute recovery parameters, as supported by Rose et al. (2017) and Haq et al. (2022). WBC offers potential practical advantages in terms of treatment duration (2–4 min vs. 10–15 min for CWI), absence of skin maceration associated with prolonged water immersion, and the capacity to treat multiple athletes simultaneously in team sport environments. However, WBC requires substantial capital investment in cryogenic chamber infrastructure and specialised operational expertise, limiting its accessibility in lower-resource sporting contexts. The availability of portable cold water tanks and natural cold water bodies renders CWI a more universally accessible modality. From a safety perspective, both modalities carry risks associated with excessive cold exposure, including hypothermia, cold urticaria, Raynaud's phenomenon, and cardiac arrhythmias in susceptible individuals, though adverse events are rare when protocols are appropriately supervised (Lombardi et al., 2017).

Several methodological limitations of the existing literature warrant acknowledgement when interpreting the findings of this review. A majority of CWI and WBC research has been conducted in young, healthy, recreationally active or collegiate-level male participants, limiting the generalisability of findings to elite athletes, female athletes, older athletes, and athletes with diverse training histories. The challenge of participant blinding inherent to cold therapy research introduces potential expectancy effects that may inflate self-reported perceptual outcomes. The reliance on acute, single-session designs in much of the literature limits conclusions regarding the adaptive consequences of long-term regular cold therapy application beyond the resistance training hypertrophy question. Future research should address these gaps through well-powered, long-duration, sex-inclusive randomised controlled trials employing standardised and ecologically valid cold therapy protocols.

5. Conclusions

The evidence reviewed in this narrative synthesis supports the following primary conclusions. First, both CWI (10–15 min at 10–15°C) and WBC (−110 to −190°C for 2–4 min) are effective evidence-based recovery interventions for reducing DOMS, attenuating circulating markers of muscle damage and systemic inflammation, and improving perceptual recovery in the acute post-exercise period. These effects are mechanistically attributable to vasoconstriction-mediated limitation of secondary inflammatory tissue damage, reduction in nerve conduction velocity and nociceptor sensitivity, and hydrostatic pressure-facilitated fluid redistribution.

Second, both modalities are particularly beneficial for athletes competing in congested schedules where short-term performance restoration between successive bouts takes precedence over long-term adaptation. In team sport tournament contexts, CWI has been demonstrated to support preservation of high-intensity running performance across successive matches, providing direct practical justification for its systematic application during competition periods.

Third, the most critical clinical implication of this review is that habitual post-resistance exercise CWI significantly attenuates skeletal muscle hypertrophy, reduces myofibrillar protein synthesis, blunts anabolic hormonal responses, and impairs satellite cell activation during resistance training programmes. Practitioners working with athletes whose primary objective is maximisation of muscular hypertrophy — including strength athletes, bodybuilders, and power-sport athletes during off-season training — should advise against regular post-resistance exercise CWI during hypertrophy-focused training blocks. Active recovery and nutritional strategies should be considered as adaptation-compatible alternatives in these contexts.

Fourth, in contrast to the resistance training context, post-endurance exercise CWI does not appear to negatively affect mitochondrial or cardiovascular adaptations, and may in some circumstances augment endurance-relevant molecular signalling pathways. Cold therapy may therefore be more liberally applied in the recovery of endurance athletes without comparable concerns regarding adaptive interference.

Fifth, the overall quality of the evidence base would benefit substantially from larger, longer-duration randomised controlled trials incorporating standardised and fully reported cold therapy protocols, diverse athletic populations including female athletes and older competitors, and comprehensive outcome batteries spanning biochemical, physiological, perceptual, and performance dimensions. Dose-response investigations systematically varying temperature, duration, immersion depth, and timing relative to exercise are needed to establish definitive evidence-based protocol recommendations applicable across diverse sport contexts.

6. Supplementary Tables

To facilitate practical application of the evidence reviewed in this article, Table 1 presents a comparative overview of standard CWI and WBC protocol parameters, while Table 2 summarises the design, intervention, and key findings of the principal studies discussed throughout this review.

Table 1. Comparison of cold water immersion (CWI) and whole-body cryotherapy (WBC) protocol characteristics.

Parameter	Cold Water Immersion (CWI)	Whole-Body Cryotherapy (WBC)
Temperature range	8–15°C (most commonly 10–15°C)	−110°C to −190°C
Typical exposure duration	5–20 min (optimal: 10–15 min)	2–4 min
Mode of cooling	Conductive (direct contact with water)	Convective (cryogenic air/nitrogen vapour)
Body coverage	Full-body, torso-plus-limb, or lower-body immersion	Whole body (chamber) or partial, head exposed (cryosauna)
Primary mechanisms	Vasoconstriction, hydrostatic pressure, reduced nerve conduction velocity	Rapid cutaneous cooling, sympathetic activation, catecholamine release
Infrastructure / cost	Low – portable tanks, natural cold water	High – specialised cryochamber required
Athlete tolerability	Moderate; longer exposure, risk of discomfort/shivering	Generally higher; shorter exposure time
Capacity (athletes/session)	Limited by tank size	Multiple athletes can be treated sequentially within minutes
Key supporting evidence	Versey et al. (2013); Machado et al. (2016); Zhu et al. (2026)	Rose et al. (2017); Lombardi et al. (2017); Zhang et al. (2025)

Source: own elaboration based on Versey, Halson & Dawson (2013); Machado et al. (2016); Rose et al. (2017); Lombardi, Ziemann & Banfi (2017); Zhu et al. (2026); Zhang et al. (2025).

Table 2. Summary of key studies examining CWI and WBC effects on post-exercise recovery and training adaptations.

Study	Design / Population	Intervention	Key Findings
Roberts et al. (2015)	RCT, 12 wks, resistance-trained men	CWI 10 min/10°C vs. active recovery, post-RT	Quadriceps hypertrophy: ~2% (CWI) vs. ~15% (control); blunted anabolic signalling
Fyfe et al. (2019)	RCT, resistance-trained men	CWI vs. active recovery, post-RT	Attenuated type I/II fibre hypertrophy; reduced p70S6K1 phosphorylation

Study	Design / Population	Intervention	Key Findings
Piñero et al. (2024)	Systematic review + meta-analysis	Post-RT CWI vs. active recovery (pooled studies)	Consistent hypertrophy attenuation across training status
Zhu et al. (2026)	Network meta-analysis, 55 RCTs	Various CWI doses (temp × duration)	10–15 min at 5–15°C most effective for CK and DOMS reduction
Xiao et al. (2023)	Meta-analysis, 20 studies	CWI vs. passive recovery	↓ DOMS, CK, IL-6, CRP at 24–48 h; ↑ CMJ recovery
Machado et al. (2016)	Systematic review + meta-analysis, 15 studies	CWI – temperature/duration comparison	11–15 min at 11–15°C most consistent for DOMS reduction
Rowsell et al. (2011)	RCT, junior elite soccer players, 4-day tournament	CWI 5×1 min/10°C post-match	Preserved high-intensity running distance across matches
Higgins et al. (2017)	Systematic review + meta-analysis, 23 studies, team sport	CWI / CWT vs. passive recovery	CWI beneficial at 24 h (CMJ, sprint) and 72 h (fatigue)
Krüger et al. (2015)	RCT, well-trained runners	Single WBC session, −110°C	Enhanced 400-m running performance recovery at 1 h
Zhang et al. (2025)	Meta-analysis, 11 RCTs	WBC vs. control	Significant ↓ in IL-6 and TNF-α (moderate-certainty evidence)
Dupuy et al. (2018)	Meta-analysis, 99 studies, multimodal	CWI vs. massage, active recovery, compression, stretching	Massage best for DOMS; CWI best for IL-6/CRP reduction
Ihsan et al. (2021)	Narrative review	Chronic CWI – endurance training context	No negative effect on mitochondrial/cardiovascular adaptations; possible PGC-1α upregulation

Source: own elaboration based on the studies cited in the References section. RT = resistance training; CK = creatine kinase; CMJ = countermovement jump; DOMS = delayed-onset muscle soreness; CWT = contrast water therapy.

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