NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

QUALITY IN SPORT

eISSN 2450-3118 · Open Access · Peer-reviewed

apcz.umk.pl/QS Nicolaus Copernicus University in Toruń



WACH, Tomasz, WYSKIEL, Natalia, RUBAJ, Michalina, RACHWAŁ, Julia, RAK, Patrycja, RĄPAŁA, Kornelia, RUMIERZ, Martyna, RUPEĆ, Zuzanna, RYDZIK, Anna, SZULAR, Weronika and WIŚNIEWSKI, Karol. The Cold Water Immersion After Exercise. Quality in Sport. 2026.78.76478. https://doi.org/10.12775/QS.2026.78.76478

ARTICLE TIMELINE

Received: 05.10.2026.
Accepted: 15.10.2026.
Published: 05.11.2026.

INDEXING & EVALUATION

MEiN points: 20 Unique ID: 201398
Disciplines: Economics & Finance; Management & Quality Sciences

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. Annex to the announcement of the Minister of Higher Education and Science 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).

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Cold Water Immersion After Exercise: Benefits, Limitations And Impact On Long Term Training Adaptations

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Abstract

Cold-water immersion (CWI) is widely used after exercise to accelerate recovery, reduce muscle soreness and restore performance. However, the same physiological responses that may facilitate short-term recovery can potentially interfere with molecular processes responsible for long-term training adaptation. This review critically evaluates the acute benefits, physiological mechanisms, methodological limitations and chronic effects of post-exercise CWI, with particular emphasis on the distinction between resistance- and endurance-training adaptations. A structured narrative review of human experimental studies, randomized and crossover trials, longitudinal training interventions, systematic reviews and meta-analyses available up to September 2026 was performed. Particular attention was given to muscle soreness, neuromuscular performance, biomarkers of muscle damage, hemodynamic and thermal responses, muscle protein synthesis, hypertrophy, strength and endurance adaptations. CWI can reduce perceived muscle soreness and improve perceived recovery, with selected benefits for next-day muscular power. Immediate explosive performance may transiently deteriorate. Regular CWI following resistance training can attenuate muscle protein synthesis, anabolic signaling and hypertrophy and may modestly reduce strength gains. In contrast, endurance adaptations appear largely preserved, although enhanced molecular signaling does not consistently translate into superior performance. CWI should be periodized according to the athlete's primary goal. Its greatest value is during congested competition schedules, high thermal strain and situations in which rapid recovery is more important than maximizing adaptive signaling.

Keywords: cold-water immersion; recovery; muscle soreness; resistance training; hypertrophy; training adaptation

Introduction:

Recovery interventions are an integral component of modern sports training, particularly when athletes are exposed to high training volumes, repeated competitions, eccentric muscle loading or multiple training sessions within a short period. Among the most frequently implemented physical recovery strategies is cold-water immersion (CWI), usually defined as partial- or whole-body immersion in water sufficiently cold to induce a meaningful reduction in skin and muscle temperature. Protocols used in sport typically involve water temperatures between

approximately 8 and 15°C and exposure lasting 5–15 min, although considerable methodological variability exists [1–5].

The popularity of CWI is supported by a combination of physiological plausibility, widespread athlete acceptance and evidence that cooling can reduce perceived muscle soreness and fatigue. Nevertheless, recovery should not be equated with adaptation. Exercise-induced fatigue, inflammation and transient cellular stress are not merely undesirable consequences of training; they also contribute to signaling cascades involved in mitochondrial biogenesis, muscle remodeling, ribosomal biogenesis, satellite-cell activation and muscle protein synthesis. Consequently, suppressing some components of the post-exercise response may improve short-term perceptions of recovery while simultaneously reducing the magnitude of selected chronic adaptations [6–8].

This distinction has become particularly relevant after longitudinal resistance-training studies demonstrated smaller hypertrophic responses when CWI was routinely performed immediately after exercise [9–12]. Conversely, endurance-training studies generally show neutral or occasionally favorable effects on molecular markers related to oxidative adaptation, without convincing evidence of impaired aerobic performance [13–18]. These findings have produced a recovery–adaptation paradox: a strategy may be beneficial when the principal objective is to perform again within hours or days but disadvantageous when the principal objective is to maximize long-term adaptation to a training stimulus.

An additional challenge is that CWI research demonstrates substantial heterogeneity. Studies differ in water temperature, exposure duration, immersion depth, timing, exercise modality, training status and the outcomes used to define recovery. Subjective outcomes may also be influenced by athlete expectations and placebo effects [19,20]. Furthermore, evidence is disproportionately derived from young, healthy men, limiting generalizability to female athletes, older populations and some elite sporting environments.

A critical synthesis should therefore move beyond the binary question of whether CWI “works”. The clinically and practically relevant questions are which outcomes it affects, at what time points, in which athletes and exercise settings, and whether short-term recovery benefits justify potential interference with chronic adaptation.

AIM OF THE WORK

The aim of this review is to critically evaluate current evidence concerning post-exercise cold-water immersion, with particular emphasis on: acute recovery of soreness and physical performance; physiological mechanisms underlying the response to immersion; the influence of temperature, duration, depth and individual characteristics; methodological and practical limitations; and the consequences of repeated CWI for long-term resistance- and endurance-training adaptations.

A secondary objective is to provide a goal-oriented framework for the practical periodization of CWI in sport, distinguishing circumstances in which rapid recovery should be prioritized from phases in which preservation of the adaptive exercise stimulus is more important.

MATERIAL AND METHODS

This article was designed as a structured narrative review. Scientific literature available up to 9 September 2026 was examined using AI-assisted scholarly literature discovery and citation-network exploration, supplemented by backward and forward citation tracking and targeted searches of the *Quality in Sport* archive. Priority was given to peer-reviewed human studies.

Eligible evidence included randomized controlled trials, crossover interventions, prospective longitudinal training studies, systematic reviews, meta-analyses and mechanistic human experiments evaluating CWI performed following exercise. Studies investigating resistance exercise, endurance exercise, sprint or high-intensity interval exercise and intermittent/team-sport activity were considered.

The principal outcomes were delayed-onset muscle soreness (DOMS), perceived recovery and fatigue, maximal strength, power and jump performance, endurance performance, creatine kinase (CK), inflammatory markers, hemodynamic and thermal responses, autonomic recovery, muscle protein synthesis, intracellular anabolic signaling, satellite-cell responses, muscle-fiber cross-sectional area, muscle mass, strength development, mitochondrial signaling, angiogenesis and aerobic performance.

Animal and cell-culture research was considered only where required to explain a biological mechanism and was not used as the primary basis for practical recommendations. Particular weight was assigned to systematic reviews and meta-analyses, followed by longitudinal human

interventions and controlled mechanistic studies. Because substantial heterogeneity exists between CWI protocols and study populations, findings were synthesized qualitatively rather than by performing a new meta-analysis.

RESULTS

Acute effects on delayed-onset muscle soreness and perceived recovery

Reduction of muscle soreness represents the most reproducible benefit of post-exercise CWI. Earlier systematic evidence indicated that immersion can reduce DOMS during the first several days after damaging exercise [4]. Subsequent meta-analyses have generally supported this conclusion while demonstrating that effect magnitude depends on exercise modality, timing and protocol [3,5,6].

Moore et al. found that following high-intensity exercise, CWI significantly reduced muscle soreness at 24 h, with a standardized mean difference of approximately −0.89 compared with passive recovery. Perceived recovery was also improved at 24 h [3]. These effects were less consistent following isolated eccentric exercise, indicating that the effectiveness of CWI is dependent on the type of preceding exercise.

Xiao et al. similarly reported lower DOMS immediately after immersion and at 24 h, although the difference was no longer significant at 48 h [6]. Considerable heterogeneity existed, emphasizing that a statistically significant pooled effect does not imply a uniform response among all athletes or protocols.

More recent temporal analyses reinforce the distinction between subjective and functional recovery. Zhu et al. reported an overall reduction in soreness but found that the strongest statistically detectable effect was immediately post-exercise, whereas objective strength recovery was essentially unchanged [7]. Athletes can therefore feel more recovered without demonstrating proportional restoration of muscle function.

Analgesia is physiologically plausible. Lower tissue temperature decreases sensory nerve conduction velocity and may modify nociceptor activity. Hydrostatic pressure may additionally influence interstitial fluid shifts and perceived swelling. Nevertheless, subjective recovery is particularly susceptible to expectation effects.

Broatch et al. demonstrated that some perceived and functional benefits attributed to CWI were not greater than those obtained using a thermoneutral placebo intervention accompanied by

information suggesting that it was an effective recovery strategy [19]. Similar expectancy-related effects have subsequently been demonstrated in football players [20]. Therefore, the subjective benefits of CWI probably reflect a combination of physiological cooling and contextual/placebo mechanisms rather than cooling alone.

Effects on neuromuscular performance

Evidence concerning objective performance is less consistent than evidence concerning soreness.

Meta-analysis by Moore et al. showed improved recovery of muscular power 24 h after both eccentric and high-intensity exercise. After eccentric exercise, the standardized mean difference at 24 h was approximately 0.34, and beneficial effects remained detectable at later follow-up points in some analyses. After high-intensity exercise, the effect at 24 h was smaller, approximately 0.22 [3].

In contrast, maximal strength recovery was not significantly improved at 24 h. Thus, CWI appears more likely to benefit selected power-related outcomes than maximal force production.

Timing is critical. Immediately after immersion, cooling can reduce explosive performance. Xiao et al. observed a significant acute decline in countermovement-jump performance followed by improved recovery at approximately 24 h [6]. The 2026 meta-analysis by Zhu et al. quantified the immediate reduction in countermovement-jump performance at approximately Hedges' $g = -0.68$, while maximal voluntary isometric contraction remained largely unchanged [7].

Experimental work provides a mechanistic explanation. Treigyte et al. showed that moderate muscle cooling alters contractile kinetics, with slower relaxation and lower dynamic torque, while maximal isometric contraction may remain comparatively preserved [21]. Cooling therefore has a greater effect on tasks requiring rapid shortening velocity and high rates of force development than on slower maximal-force tasks.

This distinction has important practical implications. Immersion immediately before a subsequent sprint, jump, resistance or high-power activity may be counterproductive if the muscle remains substantially cooled. In contrast, CWI performed after the final session of the day may facilitate perceived recovery and potentially next-day power restoration.

Exercise performance during repeated bouts

The capacity of CWI to improve performance when recovery intervals are short depends strongly on the type of activity and environmental conditions.

Yeung et al. observed that CWI between repeated bouts of fatiguing exercise improved indices of muscle oxygenation but did not significantly improve peak torque, total work or fatigue rate during the subsequent bout [22]. This finding illustrates an important principle: physiological changes induced by cooling do not necessarily translate directly into performance enhancement.

Studies involving repeated cycling, sprint exercise or team-sport simulations have produced more favorable but variable findings. The strongest practical rationale exists when exercise is performed in hot conditions or when repeated high-intensity activity occurs during tournaments and congested schedules. In these circumstances, removal of body heat and reduction of cardiovascular strain can have direct performance relevance.

However, if another explosive performance is required immediately after CWI, residual tissue cooling can offset these benefits. The optimal interval between immersion and subsequent exercise therefore depends on the balance between thermoregulatory benefit and restoration of muscle temperature.

Muscle damage and inflammatory biomarkers

Creatine kinase is frequently used as an indirect marker of exercise-induced muscle damage. Several meta-analyses have reported lower CK concentrations following CWI, particularly 24–48 h after high-intensity exercise. Moore et al. found reductions at 24 and 48 h after high-intensity exercise, whereas effects after eccentric exercise were less consistent [3]. Xiao et al. similarly identified reduced CK at 24 h but not consistently at earlier or later time points [6].

These observations should be interpreted cautiously. Circulating CK demonstrates large interindividual variability and is an imperfect proxy for structural muscle damage or functional recovery. A reduction in CK does not necessarily mean that muscle architecture has recovered more rapidly.

Evidence regarding systemic inflammatory mediators is even less consistent. Meta-analytic data do not provide strong evidence for meaningful reductions in commonly measured markers such as C-reactive protein or interleukin-6 during the early post-exercise period [6].

Furthermore, mechanistic resistance-training research questions the assumption that CWI simply suppresses a harmful inflammatory response. Peake and colleagues found that post-exercise CWI did not uniformly abolish inflammatory or cellular-stress responses in skeletal muscle. The biological consequences are more complex than generalized “anti-inflammatory” effects.

For this reason, CK and inflammatory biomarkers should not be considered sufficient standalone indicators of successful recovery.

Thermal, vascular and autonomic mechanisms

The principal direct effect of CWI is a rapid reduction in skin temperature followed by slower cooling of superficial and deeper skeletal muscle. Tissue temperature is affected by water temperature, exposure duration, immersion depth, subcutaneous adipose tissue and body composition [1,2,23].

Peripheral vasoconstriction is traditionally considered a major mechanism. Reductions in cutaneous blood flow are well demonstrated, although the response of skeletal-muscle perfusion is more heterogeneous than previously assumed. Mawhinney et al. showed that the distribution of post-immersion quadriceps perfusion varies between superficial and deep muscles and with water temperature. Very cold water does not necessarily produce a uniform reduction in perfusion across the entire muscle compartment [24].

Hydrostatic pressure also distinguishes CWI from local ice application or whole-body cryotherapy. Immersion increases external pressure on dependent tissues and may facilitate central redistribution of blood volume. This may contribute to reduced limb swelling and altered cardiovascular recovery.

Cooling can additionally reduce heart rate and modify autonomic balance toward greater parasympathetic activity after exercise. This response may be particularly relevant following prolonged endurance exercise or exercise in the heat, where cardiovascular and thermal strain contribute substantially to fatigue.

However, faster autonomic recovery should not automatically be interpreted as improved skeletal-muscle repair. Autonomic, perceptual, metabolic and structural recovery occur on different timescales.

Dose: water temperature, duration and immersion depth

There is no universally optimal CWI protocol.

Machado et al. reported that water temperatures of approximately 11–15°C for 11–15 min produced the most consistent reductions in muscle soreness in the available literature [5]. Importantly, the underlying studies were generally small and of modest methodological quality.

Moore et al. subsequently identified different dose-response patterns following high-intensity exercise. Shorter immersion durations were associated with more favorable effects for some performance and CK outcomes, whereas lower temperatures were associated with larger CK reductions [3]. Consequently, the dose associated with improved soreness is not necessarily the same as that associated with biochemical or performance outcomes.

Recent evidence also suggests that increasing the immersed body area does not automatically increase efficacy. A 2026 systematic review and meta-analysis comparing lower-body and more extensive immersion found no consistent superiority of whole-body CWI for DOMS, CK or maximal strength recovery [25]. Partial lower-body immersion may therefore offer comparable effects when the primary exercise stress involves the lower limbs while imposing less systemic cold stress.

The common recommendation of approximately 10–15°C for 10–15 min should therefore be viewed as a pragmatic starting range rather than an evidence-based universal optimum.

Individual variability and body composition

Identical water temperatures and exposure durations do not produce identical intramuscular cooling.

Subcutaneous adipose tissue provides thermal insulation. Individuals with greater adiposity cool skeletal muscle more slowly, whereas lean athletes can experience more rapid and pronounced reductions in intramuscular temperature. Consequently, fixed CWI protocols may provide very different physiological doses across athletes.

This variability has important methodological implications. Studies frequently prescribe exposure according to water temperature and time rather than the actual reduction in tissue temperature. Two participants assigned to the same experimental condition may therefore experience substantially different biological interventions.

Sex differences require particular attention. Most chronic CWI studies have included almost exclusively young men. Female athletes are underrepresented, and effects of sex-specific body composition, hormonal status and thermoregulation remain poorly characterized. Similar gaps exist for adolescent, older and para-athlete populations.

Repeated CWI and resistance-training adaptations

The strongest evidence for a potentially adverse chronic effect of CWI concerns resistance training.

Roberts et al. conducted a landmark 12-week strength-training intervention in physically active men. Participants performed lower-body resistance exercise followed by either 10 min of CWI at approximately 10°C or active recovery. Quadriceps muscle mass increased substantially more following active recovery than following regular CWI. MRI-derived muscle-mass gain was approximately 309 g in the active-recovery group compared with approximately 103 g in the CWI group [9].

Strength development was also attenuated. Leg-press 1RM increased by approximately 201 kg following active recovery and approximately 133 kg following CWI, while knee-extension 1RM increased by approximately 33.8 and 17.8 kg, respectively [9].

The study incorporated an acute mechanistic experiment demonstrating reduced activation of anabolic signaling and attenuated satellite-cell responses after CWI. These findings provided a plausible biological bridge between acute cooling and smaller long-term adaptations.

Fyfe et al. subsequently investigated seven weeks of whole-body resistance training followed by 15 min at 10°C. CWI attenuated the increase in type II muscle-fiber cross-sectional area, although 1RM strength improved similarly between groups [11]. Thus, hypertrophy may be more consistently affected than strength, which is also influenced by neural adaptation and motor learning.

The most direct mechanistic evidence is provided by measurements of muscle protein synthesis. Fuchs et al. used a within-subject design in which exercised legs were exposed to either 8°C or thermoneutral water. Cooling reduced incorporation of dietary amino acids into myofibrillar protein by approximately 24% and decreased acute myofibrillar protein synthesis. Importantly, daily myofibrillar protein-synthesis rates over two weeks of repeated resistance exercise were also lower in the cooled leg [10].

These findings are reinforced by work showing that post-exercise recovery strategies can influence ribosomal biogenesis and translational capacity [26]. Together, the evidence indicates that repeated immediate cooling after resistance exercise interferes with multiple levels of the adaptive process: perfusion and amino-acid delivery, intracellular anabolic signaling, ribosomal biogenesis, satellite-cell responses and ultimately muscle-fiber hypertrophy.

Meta-analytic evidence for hypertrophy and strength

The longitudinal literature has now been synthesized quantitatively.

Piñero et al. examined eight resistance-training studies and reported a pooled comparative standardized effect of approximately −0.22 for hypertrophy, favoring resistance training without CWI. Although the credible interval included a trivial difference, the probability that regular CWI caused at least a small attenuation of hypertrophy was high [12].

Evidence for strength is similar but somewhat less consistent. Grgic reported an overall effect size of approximately −0.23 for strength gains when CWI was repeatedly used after resistance training. Heterogeneity was low, although the evidence base was small and heavily dominated by male participants [27].

A broader systematic review and meta-analysis of regular CWI use also concluded that resistance-training adaptations are more vulnerable to cooling than endurance adaptations [28].

The size of the chronic effect should therefore be interpreted realistically. CWI does not prevent all muscle or strength development. Athletes can still improve while using it. Rather, routine immediate use may reduce the magnitude of adaptation relative to what could have occurred without post-exercise cooling.

For a competitive athlete, whether this difference is meaningful depends on the training objective. A small attenuation may be unacceptable during a hypertrophy block but largely irrelevant during a tournament in which maintaining performance over the next 24–48 h is the dominant goal.

Molecular mechanisms underlying attenuated hypertrophy

Several complementary mechanisms have been proposed.

First, lower muscle temperature and vasoconstriction can decrease post-exercise microvascular perfusion and potentially reduce amino-acid delivery to muscle. The direct finding that dietary

amino-acid incorporation into myofibrillar proteins is reduced after cooling supports this pathway [10].

Second, CWI can attenuate activation of the mechanistic target of rapamycin complex 1 (mTORC1) pathway and downstream proteins involved in translation [9,11]. The magnitude and timing vary between studies, suggesting that the effect is not an absolute blockade but a reduction or delay in anabolic signaling.

Third, ribosome biogenesis can be reduced by post-exercise cooling [26]. Because chronic hypertrophy requires an increase in translational capacity as well as acute translational efficiency, repeated small reductions in ribosome-related responses may accumulate across many sessions.

Fourth, Roberts et al. demonstrated smaller increases in satellite-cell markers after CWI [9]. Satellite cells contribute additional myonuclei to growing fibers and are therefore relevant to sustained hypertrophy.

These mechanisms should not be interpreted as fully independent. Cooling alters tissue temperature, perfusion, metabolism and cellular signaling simultaneously. The chronic phenotype probably reflects the cumulative interaction of several small effects repeated after numerous training sessions.

Endurance-training adaptations

The effects of CWI following endurance exercise differ substantially from those following resistance training.

Acute cooling can increase the expression of genes and signaling proteins related to mitochondrial biogenesis, including PGC-1α, AMPK and p38 MAPK [13,29]. Joo et al. also demonstrated augmented expression of PGC-1α and vascular endothelial growth factor following cold exposure, supporting a potential role in mitochondrial and angiogenic signaling [30].

However, enhanced molecular signaling does not guarantee a superior training outcome.

Broatch et al. examined six weeks of sprint-interval training followed by CWI at approximately 10°C for 15 min. Peak aerobic power, VO_2peak, mitochondrial respiration and 2-km cycling performance improved with training, but CWI neither enhanced nor impaired these adaptations [14].

Similarly, Aguiar et al. reported increased mitochondrial markers without a clear additional performance benefit following high-intensity interval training combined with CWI [31].

Halson et al. studied competitive cyclists and found that hydrotherapy did not produce a clear global suppression of training adaptation and may have supported selected performance measures during intensive training [16].

These findings contrast with earlier work by Yamane et al., which suggested attenuation of some endurance, strength and vascular adaptations after regular post-exercise cooling [17]. Differences in protocol, local versus more extensive cooling, participant characteristics and training program may explain some of the discrepancy.

The current balance of evidence therefore suggests that repeated post-exercise CWI is generally adaptation-neutral for endurance training, with possible enhancement of molecular markers but no consistent demonstration of superior long-term endurance performance.

Team-sport and congested competition environments

Laboratory training studies do not fully reproduce the decision-making environment of elite sport.

During tournaments, congested fixture schedules or intensive training camps, the athlete's immediate objective may not be to maximize molecular adaptation to each session. Instead, the priority may be preservation of neuromuscular performance, sleep, subjective readiness and tolerance of the next training or competition exposure.

Under these conditions, the recovery benefits of CWI may outweigh theoretical losses in adaptation. Applied studies in team-sport athletes have generally not demonstrated dramatic chronic performance impairment, and in some cases regular immersion has facilitated maintenance of performance during periods of high workload.

Therefore, the appropriateness of CWI depends not simply on exercise modality but on the position of the session within the training calendar.

Table 1. Summary of the principal acute effects of post-exercise cold-water immersion

Outcome	Overall effect of CWI	Interpretation
Delayed-onset muscle soreness	Small-to-moderate reduction, particularly within 24–48 h	One of the most consistent benefits
Perceived recovery/fatigue	Generally improved	Expectancy/placebo contributes to effect
Maximal strength	Usually no meaningful acceleration of recovery	Subjective improvement does not equal force recovery
Explosive power	Can be impaired immediately; selected benefit at ~24 h	Avoid immediately before sprint/jump/power tasks
Creatine kinase	Sometimes reduced at 24–48 h	Limited value as an isolated surrogate of muscle recovery
Inflammatory markers	Inconsistent	No evidence of a uniform systemic anti-inflammatory effect
Muscle oxygenation/perfusion	Altered, but response is region- and temperature-dependent	Physiological change does not ensure better performance
Autonomic recovery	Parasympathetic recovery may be accelerated	Potentially useful after high cardiovascular/thermal stress
Heat removal	Clearly enhanced	Particularly relevant in hot environments

Source: authors' synthesis based on references 3–8, 19–25.

Table 2. Effects of repeated CWI on long-term training adaptation

Training outcome	Direction of evidence	Practical interpretation
Muscle hypertrophy	Attenuated	Avoid routine immediate CWI during hypertrophy-focused blocks
Muscle protein synthesis	Reduced	Strong mechanistic support for interference with anabolic adaptation
mTOR-related signaling	Frequently attenuated	Supports biological plausibility of reduced hypertrophy
Satellite-cell response	Attenuated in key mechanistic studies	May contribute to reduced long-term muscle growth
Strength development	Small average attenuation; individual studies mixed	More uncertain than hypertrophy effect
Mitochondrial signaling	Neutral or sometimes enhanced	Different response from resistance pathways
VO_2peak/endurance performance	Usually preserved	No convincing evidence of chronic impairment in most modern studies
Angiogenic/microvascular signaling	Potentially enhanced	Performance significance remains uncertain

Source: authors' synthesis based on references 9–18 and 26–31.

DISCUSSION

The recovery–adaptation paradox

The central finding of this review is that acute recovery and chronic adaptation must be treated as separate outcomes.

CWI can make an athlete feel better and may improve selected performance variables during the following day while simultaneously reducing some of the cellular responses required for

maximizing hypertrophy. These observations are not contradictory. They represent different biological timescales and different definitions of success.

Acute recovery research generally asks whether an athlete is less sore or performs better hours to days after one bout of exercise. Training-adaptation research asks whether repeated alteration of the recovery environment changes the phenotype produced over several weeks or months. A recovery intervention can therefore be successful according to the first definition and undesirable according to the second.

This concept is increasingly recognized in contemporary reviews [18,32–35].

When is CWI most useful?

The strongest rationale for CWI exists when the value of rapid recovery exceeds the value of maximizing adaptation from the immediately preceding session.

Examples include tournaments, multiple matches within several days, intensive training camps, twice-daily training, qualification events and exercise performed in hot environments. In these contexts, reduction of thermal strain, soreness and perceived fatigue may allow the athlete to maintain training or competition quality.

A second reasonable application is after unusually damaging or unaccustomed exercise when severe soreness is likely to interfere with subsequent essential training.

Conversely, routine immersion after every session is difficult to justify. If a resistance session is specifically designed to stimulate muscle growth, routinely suppressing parts of the anabolic response is inconsistent with the training objective.

CWI during hypertrophy- and strength-focused training

During blocks designed primarily to maximize hypertrophy, immediate post-exercise CWI should generally be avoided.

This recommendation is supported by direct longitudinal evidence, muscle-protein-synthesis measurements and meta-analysis. The evidence is particularly convincing for muscle hypertrophy.

The effect on strength is smaller and more heterogeneous. Strength involves neural learning, motor coordination, tendon properties and muscle size, making it less directly dependent on

hypertrophic signaling. This may explain why some studies demonstrate attenuated muscle-fiber growth despite similar 1RM improvements.

It has been proposed that delaying CWI for several hours could preserve more of the early anabolic signaling window while retaining later recovery benefits. This strategy is physiologically plausible, but direct longitudinal evidence defining a safe delay period remains insufficient. Recommendations such as delaying CWI by six or eight hours should therefore be considered pragmatic hypotheses rather than firmly established thresholds.

CWI during endurance training

Routine avoidance of CWI is less defensible in endurance athletes.

Most contemporary evidence suggests that endurance adaptations remain intact when CWI is regularly performed after training. Some molecular pathways involved in mitochondrial biogenesis and vascular remodeling may even be augmented by cold exposure [13,29,30].

Nevertheless, increased PGC-1α expression should not be interpreted as proof that CWI enhances endurance performance. Training studies generally demonstrate similar rather than superior improvements in VO_2peak and time-trial performance.

Accordingly, CWI may be used more freely during endurance-focused training when athletes value recovery, particularly under high thermal strain or congested workload. It should not, however, be marketed as an established method for enhancing mitochondrial or endurance adaptation.

Placebo and expectancy effects

One of the most important methodological problems in CWI research is participant blinding.

An athlete immediately knows whether the water is cold. Expectations regarding the effectiveness of an ice bath can therefore influence soreness ratings, readiness and even subsequent performance. Sham-controlled experiments demonstrate that this contribution can be substantial [19,20].

The placebo component does not necessarily make CWI clinically useless. In applied sport, subjective readiness is itself relevant. However, mechanistic claims should not be based solely on unblinded changes in perceived soreness.

Future trials should incorporate expectancy assessment, credible sham interventions where possible and standardized information given to participants.

Methodological limitations of the current literature

Several limitations reduce certainty.

First, sample sizes are generally small. Many experiments include fewer than 20 participants, making results susceptible to sampling variability.

Second, the literature is dominated by young men. This substantially limits external validity.

Third, interventions are heterogeneous. Water temperatures range from extremely cold to moderately cool conditions, exposure duration ranges from several minutes to 20 min or more, and immersion depth varies from isolated limbs to neck-level immersion.

Fourth, exercise protocols differ widely. Findings from eccentric muscle-damage models cannot automatically be extrapolated to professional football, endurance competition or conventional resistance training.

Fifth, recovery is assessed using outcomes with different biological significance. Soreness, CK, muscle temperature, jump height and maximal strength should not be regarded as interchangeable markers.

Sixth, long-term adaptation studies are comparatively scarce and usually last only 4–12 weeks. Effects across a full competitive season remain much less certain.

Finally, adverse-event reporting is inconsistent. Typical sport CWI protocols appear well tolerated by screened healthy athletes, but cold exposure produces acute sympathetic, ventilatory and vascular responses. Greater caution is warranted in individuals with known cardiovascular disease, cold hypersensitivity, Raynaud-type conditions, impaired sensation or other medical contraindications.

Integration with recent literature from Quality in Sport

Recent publications in *Quality in Sport* broadly support the conclusions derived from higher-level international evidence.

Poręba et al. concluded that CWI is useful for acute regeneration but should be strategically periodized because routine use following resistance training may interfere with hypertrophic and strength adaptation [32].

Bakuła et al. similarly emphasized reductions in soreness and perceived fatigue while noting inconsistent objective and long-term effects and the gap between scientific evidence and commercial claims surrounding cryotherapy [33].

Starzyk et al., reviewing interventions for DOMS, described cryotherapy as providing short-term analgesic benefits while potentially blunting hypertrophic adaptation [34].

Roczyński et al. likewise concluded that subjective benefits are more reproducible than objective performance improvements and emphasized the need to individualize CWI according to training goals [35].

These publications are therefore consistent with, rather than contradictory to, the broader international evidence base.

Practical periodization

The practical question should be framed as: “What is the primary objective during the next 24–72 h and during the current training block?”

If competition or another high-priority session is imminent, reducing soreness, heat load and perceived fatigue may take precedence over maximizing adaptation from one training session. CWI is reasonable in this situation.

If no important performance is scheduled and the current mesocycle is designed to maximize muscle hypertrophy or strength adaptation, routine immediate CWI is difficult to justify.

If the primary stimulus is endurance training, the risk of impaired chronic adaptation appears considerably smaller, allowing more flexible use.

The same athlete may therefore appropriately use CWI frequently during a tournament, rarely during an off-season hypertrophy block and selectively during endurance-heavy phases [36–38].

Table 3. Goal-oriented recommendations for the use of post-exercise CWI

Training/competition context	Suggested approach	Rationale
Tournament or congested competition schedule	Consider CWI	Rapid recovery is a higher priority than maximizing adaptation from each bout
Two demanding sessions on the same/next day	Consider selectively	May reduce soreness and perceived fatigue; allow adequate rewarming before power exercise
Exercise/competition in heat	Consider CWI	Strong thermoregulatory rationale
Hypertrophy-focused resistance block	Avoid routine immediate use	Evidence for attenuated protein synthesis and hypertrophy
Maximal-strength development	Use sparingly	Possible small attenuation of strength gains
Endurance-focused block	Can be used selectively	Aerobic adaptations generally preserved
Easy/recovery training	Usually unnecessary	Limited additional benefit
Immediately before sprint/jump/power task	Avoid	Residual cooling can impair explosive performance

Source: authors' synthesis of the evidence reviewed.

SUMMARY

Cold-water immersion is an effective but highly context-dependent recovery intervention.

The most consistent acute benefits are reductions in perceived muscle soreness and fatigue. Selected improvements in next-day muscular power are also supported, particularly after high-intensity exercise. In contrast, maximal strength recovery, inflammatory markers and other objective outcomes show smaller or inconsistent responses.

CWI should not be performed immediately before a subsequent explosive effort because residual muscle cooling can transiently impair jump, sprint and dynamic force performance.

The principal long-term concern involves resistance training. Repeated immediate CWI can reduce muscle protein synthesis, anabolic signaling, ribosomal responses and satellite-cell activity and is associated with smaller increases in muscle-fiber size and overall hypertrophy. Meta-analytic evidence suggests that strength development may also be modestly attenuated.

The evidence for endurance training is materially different. Regular CWI generally does not impair aerobic training adaptations and may enhance selected molecular markers associated with mitochondrial biogenesis and vascular remodeling. However, these molecular effects have not been shown consistently to improve long-term endurance performance beyond that achieved by training alone.

The most rational approach is therefore periodized rather than habitual use. CWI is particularly appropriate during congested competition schedules, periods of high thermal strain and situations in which short-term readiness is more important than maximizing adaptation from an individual training session. Routine immediate CWI should be minimized during hypertrophy-focused resistance training.

There is no universally optimal protocol. Approximately 10–15°C for 10–15 min represents a practical evidence-informed range, but the appropriate dose depends on exercise modality, body composition, immersion depth, recovery interval and the athlete's primary objective.

Future research should include larger samples, female athletes, elite populations, standardized assessment of expectancy effects, objective tissue-temperature measurements and longer longitudinal interventions. Particular attention should be directed toward identifying whether delayed or periodized CWI can preserve acute recovery benefits without compromising resistance-training adaptation.

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

Funding Statement

The article did not receive any funding.

Institutional Review Board Statement

Not Applicable.

Informed Consent Statement

Not Applicable

Conflict Of Interest

Authors declare no conflict of interest.

ChatGPT was used during manuscript preparation to support language refinement and formatting. The authors critically reviewed and edited the text and assumed full responsibility for the content of the article.

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