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Cold Comfort: Does Chronic Post-Exercise Cold-Water Immersion Blunt Long-Term Training Adaptations?

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Abstract

Background: High-intensity exercise commonly causes exercise-induced muscle damage (EIMD), neuromuscular fatigue, and delayed-onset muscle soreness (DOMS). While cold-water immersion (CWI) is widely used for recovery, its physiological benefits remain debated. Specifically, the extent to which psychological expectations dictate recovery, and the risk that routine ice baths might interfere with long-term performance gains remain unanswered.

Aim: To evaluate the acute and chronic effects of CWI on post-exercise neuromuscular recovery, muscle damage markers, subjective soreness, and long-term training adaptations in active populations.

Methods: A literature search was conducted in PubMed (2021–2026). Twelve clinical trials meeting the inclusion criteria were selected and analyzed.

Results: CWI did not consistently outperform passive rest or placebo in restoring maximal strength, jump height, or sprint performance following intense exercise. The reduction in DOMS after CWI appeared largely driven by expectancy-based placebo mechanisms rather than physiological tissue repair. However, CWI demonstrated specific benefits, including more effective restoration of parasympathetic autonomic modulation and reduced thermoregulatory stress. Chronic CWI application did not meaningfully alter $\text{VO}_{2\text{max}}$, body composition, or intramuscular adaptive signalling, though repeated exposure elevated heat shock protein-72 (HSP-72) concentrations.

Conclusions: Routine CWI offers no clear physiological advantages over passive rest for restoring performance. Perceived recovery benefits appear to be mediated by psychological expectation. Implementation of CWI should therefore be individualised, accounting for the athlete's competitive schedule, personal beliefs, and specific performance objectives.

Keywords: Cold-water immersion (CWI); Exercise-induced muscle damage (EIMD); Delayed-onset muscle soreness (DOMS); Post-exercise recover; Neuromuscular fatigue; Training adaptations; Athletes

1. Introduction

Contemporary high-intensity athletic disciplines, including team-based sports such as football and rugby, endurance modalities such as distance running and competitive swimming, and resistance-based training, subject athletes to substantial mechanical and metabolic strain. These strenuous activities frequently result in exercise-induced muscle damage (EIMD), which is characterized by myofibrillar microtrauma, an elevated systemic inflammatory response, increased blood concentrations of markers like creatine kinase (CK), and delayed-onset muscle soreness (DOMS) [7,17]. Consequently, athletes experience a transient state of neuromuscular fatigue, manifested by a decline in maximal voluntary isometric contraction (MVIC) and impaired explosive force generation [15,17]. Depending on the extent of tissue disruption, such impairments may persist across several days, carrying meaningful implications for performance maintenance and injury vulnerability in subsequent training or competitive contexts [21].

As competitive schedules in both elite and amateur sport continue to intensify, optimizing post-exercise recovery to restore homeostasis following competition or intensive training has become a central concern within applied sports science [5,18]. Within this context, a key distinction should be drawn between two separate applications of hydrotherapy. The first involves supporting the repair of damaged muscle tissue over multiple days following strenuous exercise — primarily through peripheral vasoconstriction and suppression of cellular metabolic activity, which attenuate the acute inflammatory response, restrict oedema formation, and limit secondary muscle damage [7,17]. The second involves quickly lowering body temperature between consecutive matches in tournaments played in hot environments [18]. Additionally, CWI facilitates cardiovascular recovery by improving cardiac vagal modulation and parasympathetic nervous system activity [5].

Despite these proposed mechanisms, the actual efficacy of CWI in restoring neuromuscular function remains a subject of considerable scientific debate. Concurrently, hot-water immersion (HWI) is frequently investigated alongside CWI as an alternative thermal strategy [6,7,17,21]. Unlike CWI, HWI promotes blood vessel dilation and improved local circulation, which supports the removal of metabolic products and offers a different pathway to tissue recovery [7,17]. While some studies show that cooling accelerates muscle recovery and reduces soreness, many controlled trials find no meaningful physiological advantage over thermoneutral immersion, active recovery, or simple passive rest [6,7].

Furthermore, growing evidence suggests that habitual CWI may interfere with long-term training adaptations. Specifically, CWI can blunt myofibrillar protein synthesis, suppress

anabolic signaling, and impair satellite cell activation, which are crucial for muscle hypertrophy and strength gains [14,16]. Notably, the harmful effects of chronic CWI on resistance-training adaptations have been well-documented in the literature. In contrast, its influence on endurance performance, cardiorespiratory efficiency ($\text{VO}_{2\text{max}}$), and HIIT adaptations remains far less certain, with recent findings suggesting no clear interference with aerobic intramuscular signaling. [11]. In the short term, cooling the muscles can temporarily reduce their ability to contract efficiently. This may briefly impair explosive power and the speed at which force is produced during high-intensity efforts performed shortly after the intervention [15,17].

Evaluating CWI is further complicated by psychological factors. Recent studies suggest that the perceived benefits of CWI, especially regarding muscle soreness, might be largely driven by the placebo effect rather than actual physiological tissue repair [6,12]. An athlete's expectations can significantly reduce perceived pain, even without any objective physiological improvement [2]. The response to water immersion also varies between individuals, depending on several factors that interact with one another. These include body composition (particularly the insulation provided by subcutaneous fat), biological sex, and the specific metabolic demands of the preceding exercise [8,19,21]. Taken together, these points highlight the need for well-designed studies that combine objective physiological and neuromuscular measures with carefully controlled assessments of how athletes perceive their own recovery.

Therefore, the purpose of this literature review is to critically examine the current scientific evidence regarding the capacity of routine post-exercise cold-water immersion to blunt long-term training adaptations. The focus was particularly on chronic intramuscular adjustments, physiological versus psychological recovery outcomes, and individual variability across diverse athletic populations compared to passive rest or alternative recovery strategies.

2. Materials & Methods

A comprehensive literature search was conducted in accordance with PRISMA guidelines using the PubMed database to identify studies examining cold-water immersion as a post-exercise recovery strategy across various athletic disciplines. The search includes publications from January 2021 to June 2026, employing the following keywords: *cold-water immersion*, *hydrotherapy*, *cryotherapy*, *sports*, and *athletes*. Studies were considered eligible for inclusion if they met the following criteria: a controlled design comparing CWI against a placebo intervention or passive rest condition, full-text availability in English, and classification as a clinical trial. Studies were excluded if they lacked a control condition, involved non-athletic or clinical populations, or did not report objective performance outcomes. Following the initial screening of titles and abstracts, 12 studies satisfied all inclusion criteria and were subsequently incorporated into this review.

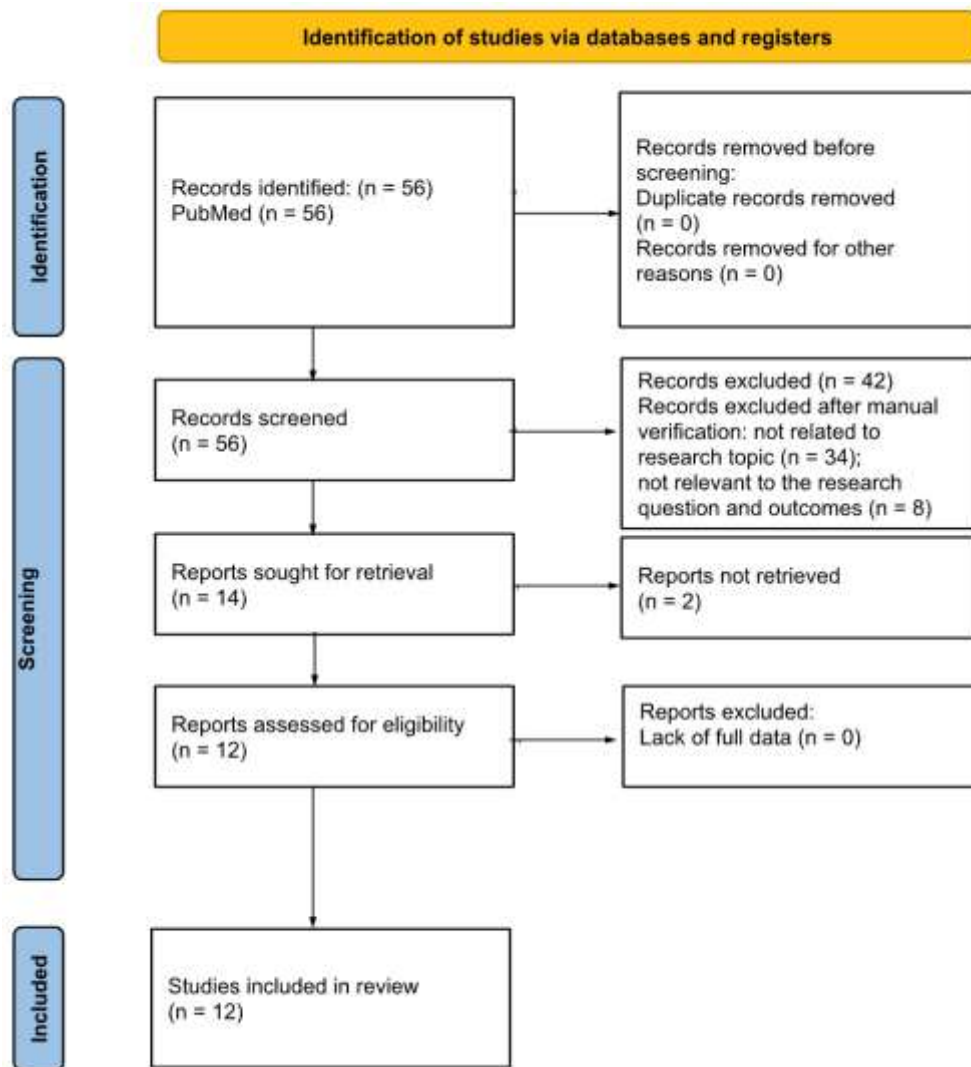


Figure 1. PRISMA flowchart for screening search results.

3. Results

3.1. Acute Neuromuscular Recovery and Performance Restoration

The impact of cold-water immersion (CWI) on short-term recovery (within 24-72 hours post-exercise) remains highly debated, with outcomes largely depending on fatigue levels and the type of performance test used. A large body of controlled clinical trials shows no objective physiological advantage of CWI over traditional rest or placebo protocols [6]. For instance, acute CWI (10°C for 10 minutes) right after a simulated soccer match did not provide any extra benefits for restoring muscle strength, countermovement jump (CMJ) height, or sprint speed compared to a sham laser placebo group [6]. Studies at the level of isolated muscle groups demonstrate corroborating evidence [15]. Richards et al. showed that after a fatiguing protocol of the ankle dorsiflexors, a 10-minute cold bath at 10°C did not accelerate the recovery of maximal voluntary contraction (MVC) torque compared to room-temperature passive rest [15].

Interestingly, they noted that torque recovery under high-frequency electrical stimulation (50 Hz) was slightly delayed up to 3 hours post-CWI [15].

A similar lack of physical benefit has been observed across diverse sports. For competitive adolescent swimmers, a one-week CWI protocol (14°C) applied between resistance training and swim sessions had no impact on 100-meter sprint times or upper and lower body power [1]. For well-trained runners, CWI did not induce any meaningful changes in running economy or spatial-temporal stride biomechanics 24 and 48 hours after an exhaustive run [4]. Likewise, in healthy women experiencing exercise-induced muscle damage (EIMD), neither CWI nor hot-water immersion (HWI) accelerated the recovery of objective mechanical performance over a 72-hour period [21].

On the other hand, some evidence suggests that cooling deeply fatigued tissues might temporarily impair certain aspects of dynamic force [17]. Sautillet et al. demonstrated that after a demanding protocol designed to damage the quadriceps femoris, CWI (11°C) failed to limit the drop in the late-phase rate of force development (RFD 100–200 ms) [17]. Crucially, HWI (41°C) successfully mitigated this decline, suggesting that maintaining or increasing muscle temperature helps preserve contractility and explosive strength soon after a damaging bout [17]. A notable exception showing a positive effect of CWI involves eccentric-induced hamstring damage in women [8]. Huang and Chen observed that a 5-day repeated CWI protocol (14°C for 14 minutes) significantly accelerated the recovery of isometric MVC and improved the straight leg raise (SLR) range of motion [8].

3.2. Psychobiological Mediators and the Placebo Effect

One of the most consistent findings in recent hydrotherapy research is that subjective relief and reductions in delayed-onset muscle soreness (DOMS) frequently do not align with biological tissue repair. Instead, these perceived benefits appear to be largely driven by psychological factors and the placebo effect. Key data supporting this stems from a study where semi-professional soccer players completed the exhaustive Loughborough Intermittent Shuttle Test (LIST) and were assigned to CWI, passive rest, or a placebo group given a supposedly advanced recovery drink. Markers of muscle damage, such as blood creatine kinase (CK) activity, increased identically across all three conditions. Moreover, the inflammatory marker C-reactive protein (CRP) rose significantly at 24 hours in both the rest and CWI groups, but not in the placebo beverage group. Despite the lack of physiological advantages from cooling, DOMS scores were significantly lower in both the CWI and placebo groups compared to the rest group. This strongly indicates that post-CWI pain reduction is driven by an athlete's expectations (expectancy-driven placebo) and belief in the method [12].

A similar mechanism was revealed by Gustafsson et al., who compared CWI and HWI with a pure placebo treatment using a turned-off laser device (sham laser), presenting it to the athletes as a cutting-edge recovery therapy. The study showed that neither hot nor cold water baths provided any statistical or practical advantage over the sham laser for both subjective fatigue and objective physical performance [6]. Similarly, adolescent swimmers reported no differences in subjective well-being, leg heaviness, or fatigue between CWI and a thermoneutral water immersion (TWI) control, which served as an environmental placebo. However, the athletes expressed a clear dislike for sitting on a chair for passive recovery,

showing a deep-rooted cultural belief that water immersion after training is essential, regardless of its actual temperature [1].

3.3. Chronic Training Adaptations and Intramuscular Signaling

While the negative impact of CWI on resistance training adaptations is well-documented, recent studies have focused on verifying whether regular cooling also impairs endurance adaptations (HIIT) and mixed sports performance. For aerobic and interval training, long-term cooling appears to be neutral. Malta et al. evaluated a 5-week HIIT block combined with regular CWI after every session. Muscle biopsies revealed that chronic CWI did not alter markers of intramuscular adaptation: the tissue's inflammatory profile (IL-6, TNF- α , IL-10), the satellite cell pool size, and PGC-1 α (the key protein for mitochondrial biogenesis) remained unaffected compared to the control group. Consequently, regular ice baths neither impair nor improve gains in cardiorespiratory fitness (VO₂max) or endurance running performance [11]. This long-term neutrality was also confirmed by Gustafsson et al., who had elite soccer players use CWI or HWI regularly over a 15-week competitive season. At the end of the protocol, chronic adaptations were nearly identical between the CWI, HWI, and sham laser placebo groups [6].

Interesting biochemical data emerged from a study on academy rugby players. Fasting morning blood samples collected during a 12-week resistance training program showed that repeated hydrotherapy modifies systemic signals depending on water temperature. Chronic CWI led to a distinct increase in resting concentrations of heat shock protein-72 (HSP-72), reflecting a clear protective adaptation of the thermoregulatory system to repeated cold stress. In contrast, chronic HWI raised growth factors like PDGF-BB and IGF-1, suggesting that heat, rather than cold, activates systemic anabolic and regenerative pathways [7].

3.4. Autonomic and Thermoregulatory Modulations

If CWI does not reliably repair muscle structure or speed up mechanical strength recovery, its widespread use can be explained by acute modulations of the autonomic nervous system and thermoregulation. Dutra et al. showed that while CWI (11°C) and HWI (41°C) did not alter neuromuscular fatigue after continuous and intermittent runs, both methods profoundly impacted the cardiovascular system. Specifically, CWI enhanced cardiac vagal modulation improving heart rate variability 2 hours post-exercise, whereas HWI effectively reduced the oxygen consumption rate (VO₂) during subsequent submaximal brief runs. Both hot and cold water improved vastus lateralis muscle activation during maximal voluntary contractions [5]. Another key benefit is the reduction of thermal strain. In a tournament setting where rugby sevens matches were played in hot environments, a 15-minute CWI protocol (11.6°C) between two demanding matches on the same day dramatically lowered core body temperature, skin temperature, and overall thermal strain. In these situations, CWI serves as an acute rescue tool for the thermoregulatory system, preventing overheating and allowing athletes to self-regulate pacing strategies in subsequent bouts [18]. Local hemodynamic changes are also highly pronounced. Wellauer et al. used near-infrared spectroscopy (NIRS) to confirm that immediately after exiting cold water, women experience a sharp, sustained drop in muscle

oxygen saturation (SmO₂) caused by strong vasoconstriction, a response that completely differs from HWI or control conditions [21].

3.5. Athlete-Specific Factors Modulating Hydrotherapy Efficacy

Analyzing the collective data reveals that the effectiveness of water immersion shows substantial inter-individual variability. Applying a uniform recovery protocol to all athletes regardless of individual differences represents a notable methodological limitation. First, biological sex and subcutaneous fat thickness dictate how heat is transferred, with body fat acting as a powerful thermal insulator. In women exposed to an identical muscle-damaging protocol, acute cooling provided no acceleration in DOMS or CK recovery [21]. However, when the cooling protocol (14°C) was extended over 5 consecutive days for eccentric hamstring damage, healthy women showed rapid recovery of strength and a decrease in plasma myoglobin concentrations. This indicates that the duration of the protocol and the specific muscle group targeted determine whether a female athlete responds positively to cryotherapy [8].

Second, body mass and the sport modality matter significantly. In heavily built rugby players whose resistance training causes substantial structural cell disruption, both chronic CWI and HWI successfully lowered post-exercise creatine kinase (CK) leakage into the bloodstream. This suggests that in athletes with large muscle masses and high baseline structural damage, the hydrostatic pressure of water—regardless of temperature—might help stabilize muscle membranes [7].

Finally, adolescent populations show entirely different characteristics. In teenage competitive swimmers, applying CWI did not modify physical recovery parameters or pain perception. This underscores that in young athletes, whose natural baseline for homeostatic recovery is already highly efficient, aggressive thermal interventions like ice baths may be completely unnecessary, serving primarily to build psychological comfort and satisfy personal preferences [1].

Table 1: Characteristics of included studies: Study group, type of training, CWI protocol, analyzed parameters and main outcomes.

Author	Study group	Type of training	CWI protocol	Analyzed parameters	Outcomes
Gustafsson J (2025)	N=40 males; CWI=13, Placebo=13, HWI=14	Part I: Simulated soccer match (SSM); Part II: 15-week soccer training	10 min at 10°C, immersed to iliac crest, approx. 45 min post-SSM	Submaximal aerobic test (HR, RPE, lactate), 20m sprint, CMJ height/power, knee extension MVIC, TTE, body composition	CWI was not more effective than placebo for physical performance recovery or long-term training adaptations in soccer players
Horgan (2024)	B N=18 male Super Rugby players; CWI=17, HWI=15, Control=17	Twice weekly resistance exercise over 12 weeks	15 min at 15.1°C, whole-body immersion to neck, 15 min post-exercise	Blood markers: CK, myoglobin, cytokines (IL-1ra, IL-1b, IL-4, IL-6, IL-8, IL-10, IL-17a, TNF- α), growth factors (IGF-1, IGFBP-3, PDGF-BB), HSP-72, testosterone, cortisol	CWI reduced CK (trivial effect) and increased HSP-72 compared to HWI. No significant effects on hormones or pro-inflammatory cytokines
Dutra (2025)	Y Study 1: N=12 males; Study 2: N=10 males. Crossover: CWI, PWI (Placebo), HWI, CON	Continuous running at vRCP (Study 1) and high-intensity intermittent running (Study 2)	15 min at 11.4°C, immersed to xiphoid process, 20 min post-exercise	Neuromuscular function (iMVC, VA, electrical stimulation twitches, EMG), CMJ, heart rate variability (RMSSD), mood state, cardiorespiratory (VO ₂ , RER), RPE, pain	CWI increased cardiac vagal modulation at 2h post-exercise and enhanced EMG activation after intermittent running, but didn't improve peak force or mood
Malta (2026)	E N=16 males; CWI=9, Control=7	5 weeks of HIIT (3 sessions/week)	15 min at 11.2°C, immersed to waist, immediately post-exercise	Muscle biopsies (satellite cell pool, PAX-7, PGC-1 α , IL-6, IL-10, TNF α), VO ₂ max,	CWI did not influence training-induced changes in satellite cell pool, muscle inflammation, PGC-1 α , VO ₂ max,

						constant work- rate test (TTF)	or running performance
Richards (2025)	A	N=12 (10 males, 2 females). Crossover: CWI vs. Room Temperature	High-intensity interval dorsiflexion/pla ntarflexion (6 sets x 30-s all- out)	10 min at 10°C, single leg immersion, immediately post-exercise	Neuromuscular function (MVC torque, VA, 10/50 Hz torque, 10:50 ratio, RTD, HRT), intramuscular temperature, next-day performance	CWI was not effective in accelerating the recovery of low- frequency force depression (PLFFD) or enhancing next- day performance	
Nasser (2023)	N	N=12 male soccer players. Crossover: CWI, Placebo (beverage), Rest	Loughborough Intermittent Shuttle Test (LIST)	15 min at 11.3°C, immersed to sternum, 5– 10 min post- LIST	CK, CRP, Uric Acid, DOMS (VAS), SJ, CMJ, 10m/20m sprint, RSA, Belief Questionnaire	CWI improved jumping and RSA recovery and reduced DOMS; however, benefits were similar to placebo, suggesting a placebo effect	
Wellauer (2025)	V	N=30 females; CWI=10, HWI=10, Control=10	Muscle- damaging protocol (5 x 20 drop-jumps)	10 min at 10°C, immersed to sternum, twice (0 and 120 min post- exercise)	Muscle oxygen saturation (SmO2), Tcore, Tskin, HR, MVIC, muscle swelling (ultrasound), DOMS, serum CK	CWI significantly reduced Tskin and SmO2 acutely, but did not improve subjective (DOMS) or objective recovery (MVIC, CK) over 72h	
Skein (2025)	M	N=10 males; CWI=5, Control=5	Simulated rugby sevens (intermittent- sprint protocol)	15 min at 11.6°C, applied after the first ISP bout	HR, Tcore, Tskin, thermal sensation (TS), RPE, 15m sprint time, vertical jump height, distance covered	CWI reduced thermal and cardiovascular stress but negatively affected initial high- intensity performance (sprints/jumps) due to muscle cooling	

Batista (2024)	N	N=20 (12 males, 8 females); CWI=19, TWI (placebo)=16, Passive=16	Resistance land-based training and swim training	12 min at 14°C, 3 times/week immediately post-resistance training	100m freestyle time, FINA points, flexibility (sit-and-reach), power, shoulder proprioception, well-being, pain, tiredness	Repeated CWI did not significantly impact swim or functional performance; athletes reported a preference for CWI over passive recovery
Huang (2025)	Y	N=18 females; CWI=9, Control=9	Maximal eccentric contraction (EC) exercise (hamstrings)	14 min at 14°C, applied at 1, 25, 49, 73, and 97 h post-exercise	Maximal voluntary isometric contraction (MVC), DOMS, straight leg raise (SLR), plasma myoglobin (Mb)	Five consecutive days of CWI significantly enhanced recovery by increasing MVC, reducing DOMS, and lowering plasma myoglobin levels
Duñabeitia (2022)	I	N=48 males; CWI=16, Massage=16, Control=16	Exhaustive interval running session	10 min at 10°C, applied 1 hour post-treadmill test	Running economy (RE), ground contact time, swing time, step length, stride angle, stride height, stride frequency	CWI did not significantly improve running economy or biomechanics compared to control; massage was more effective than CWI
Sautillet (2024)	B	N=30 males; CWI=10, HWI=10, Control=10	Individualized eccentric exercise (EIMD protocol)	11 min at 11°C, within 30 min post-EIMD	Peak torque (Tpeak), late-phase rate of force development (RFD100-200), pressure pain threshold (PPT), surface EMG (sEMG)	CWI mitigated maximal strength loss (Tpeak) but did not improve explosive strength (RFD) or soreness compared to HWI

Abbreviations: **CK** - Creatine kinase **CMJ** - Countermovement jump **CON** - Control group **CRP** - C-reactive protein **CWI** - Cold-water immersion **DOMS** - Delayed-onset muscle soreness **EC** - Eccentric contraction **EIMD** - Exercise-induced muscle damage **EMG** - Electromyography **FINA** - Fédération Internationale de Natation (International Swimming Federation) **HIIT** - High-intensity interval training **HR** - Heart rate **HRT** - Half relaxation time **HSP-72** - Heat shock protein 72 **HWI** - Hot-water immersion **IGF-1** - Insulin-like growth factor 1 **IGFBP-3** - Insulin-like growth factor-binding protein 3 **IL** - Interleukin (e.g., IL-1ra, IL-1b, IL-4, IL-6, IL-8, IL-10, IL-17a) **iMVC** - Maximal voluntary isometric contraction **ISP** - Intermittent-sprint protocol **LIST** - Loughborough Intermittent Shuttle Test **Mb** - Myoglobin **MVC** - Maximal voluntary contraction **MVIC** - Maximal voluntary isometric contraction **PAX-7** - Paired box 7 **PDGF-BB** - Platelet-derived growth factor-BB **PGC-1 α** - Peroxisome proliferator-activated receptor- γ coactivator 1- α **PLFFD** - Prolonged low-frequency force depression **PPT** - Pressure pain threshold **PWI** - Placebo water immersion **RE** - Running economy **RER** - Respiratory exchange ratio **RFD** - Rate of force development (e.g., RFD100-200) **RMSSD** - Root mean square of successive R-R interval differences **RPE** - Rating of perceived exertion **RSA** - Repeated sprint ability **RTD** - Rate of torque development **sEMG** - Surface electromyography **SJ** - Squat jump **SLR** - Straight leg raise **SmO₂** - Muscle oxygen saturation **SSM** - Simulated soccer match **Tcore** - Core temperature **TNF- α** - Tumour necrosis factor alpha **Tpeak** - Peak torque **TS** - Thermal sensation **Tskin** - Skin temperature **TTE** - Time to exhaustion **TTF** - Time to task failure **TWI** -

Table 1. Summary of the literature review about CWI

4. Discussion

4.1 Acute Neuromuscular Recovery and Performance Restoration

The efficacy of CWI in restoring neuromuscular function remains highly contested. Recent evidence demonstrates that CWI often fails to outperform passive rest or placebo treatments in restoring maximal voluntary contraction (MVC), jump height, or sprint performance following intense exercise [1,6]. These findings align with earlier literature in soccer players [10] and marathon runners [22], suggesting that performance gains are frequently marginal. Mechanistically, aggressive cooling may be counterproductive. Richards et al. reported impaired contractile efficiency following CWI, supporting the "mind over matter" framework proposed by Wilson et al. [15,22]. Although CWI is commonly assumed to reduce pain sensitivity, evidence suggests it may actually fail to restore pressure pain thresholds, while also impairing muscle mechanics and delaying the late-phase rate of force development (RFD) [17]. On the other hand, hot-water immersion (HWI) may be a superior modality for preserving dynamic power output and explosive strength through mechanisms such as the upregulation of heat shock proteins and modulated immunoinflammatory responses [17,20].

4.2 Psychobiological Mediators and the Placebo Effect

Subjective recovery following CWI often fails to reflect actual physiological repair. Growing evidence indicates that the perceived alleviation of DOMS following hydrotherapy is substantially mediated by expectancy-driven placebo mechanisms rather than biological change [6,12]. These results are consistent with earlier work by Broatch et al., which showed that immersion in thermoneutral water, when paired with a "recovery scent," was equally effective in reducing pain as traditional cold water immersion [2]. Findings in adolescent swimmers further reinforce this, showing no differences in subjective fatigue and pain indices between CWI and a thermoneutral water placebo immersion [1].

4.3 Chronic Training Adaptations and Intramuscular Signaling

The impact of chronic CWI on training adaptations appears modality-dependent. While regular cooling may blunt anabolic pathways following resistance exercise [14,16], Malta et al. report that CWI does not impede endurance or HIIT-related adaptations, such as PGC-1 α signaling and *VO2max* improvements [11]. This aligns with earlier evidence showing that post-exercise cooling can actually enhance mitochondrial biogenesis markers [9]. Furthermore, Horgan et al. highlight distinct molecular profiles depending on water temperature: CWI upregulates stress-tolerance markers (HSP-72), whereas HWI might better stimulate systemic anabolic factors like IGF-1. Importantly, neither modality negatively alters long-term body composition [7].

4.4 Autonomic and Thermoregulatory Modulations

CWI and HWI serve distinct roles in cardiovascular recovery. Dutra et al. demonstrated that exclusively CWI (11°C) significantly accelerates the return of parasympathetic autonomic modulation (HRV) two hours post-exercise, whereas HWI does not yield this response. Consequently, the authors suggest distinct applications: CWI is recommended for enhancing HRV and sympathetic withdrawal, while HWI is more suited for accelerating cardiorespiratory recovery [5]. These findings expand on earlier work by Buchheit et al., who reported beneficial effects of cooling on autonomic reactivation following intense bouts [3]. Furthermore, in high-heat tournament settings, CWI acts as a critical intervention for reducing core temperature and internal thermal strain, serving as a specialized thermoregulatory rescue tool rather than a generic recovery strategy [18].

4.5 Athlete-Specific Factors Modulating Hydrotherapy Efficacy

The effectiveness of CWI is highly individualized, with outcomes dependent on athlete-specific factors. While single-session protocols often fail to enhance recovery in women [21], repeated multi-day exposure may yield substantial functional recovery and attenuate muscle damage markers [8]. Body composition is a significant confounding factor, as subcutaneous fat thickness acts as an insulator, reducing cold penetration to deep tissue [19]. Muscle mass also matters like in heavy rugby players, hydrostatic pressure, independent of water temperature, has been shown to reduce muscle damage markers such as creatine kinase (CK), whereas water temperature plays a critical role in modulating systemic inflammatory markers [7]. Conversely, adolescent athletes with superior natural homeostatic recovery mechanisms may derive no functional benefit from cold-water therapy [1].

4.6 Limitations

Despite the valuable insights provided by the current body of literature, several methodological limitations across the analyzed studies must be acknowledged. Firstly, the majority of the trials were conducted on relatively small sample sizes, often constrained by recruitment challenges and the rigorous demands of the experimental designs [6,11,12,18]. This insufficient statistical power may mask small but potentially meaningful physiological effects of hydrotherapy. Moreover, there is considerable heterogeneity regarding the populations investigated, the studies included a wide spectrum of participants, ranging from elite academy rugby players and semi-professional soccer players to competitive adolescent swimmers, well-trained runners, and recreationally active men and women [1,4,7,12,21]. This diversity in training age, biological sex, and body composition significantly influences individual thermoregulatory responses to water immersion, complicating the formulation of universal recovery guidelines. Furthermore, the exercise protocols used to induce fatigue or exercise-induced muscle damage (EIMD) varied drastically across the research, encompassing simulated matches, high-intensity interval training (HIIT), exhaustive continuous running, and isolated maximal eccentric contractions [6,8,11,15,18]. Additionally, the cold-water immersion (CWI) protocols

themselves lacked standardization; immersion temperatures ranged from 10°C to 15°C, durations varied between 10 and 15 minutes, and the depth of immersion differed substantially (e.g., whole-body, waist-level, or single-limb immersion) [1,6,15,17]. Finally, the overall volume of literature directly comparing CWI, HWI, and strictly controlled placebo interventions within athletic cohorts remains relatively small, highlighting the need for future large-scale trials to validate these findings [1,6,12].

5. Conclusions

The routine application of cold-water immersion (CWI) or hot-water immersion (HWI) does not consistently yield meaningful advantages in restoring objective neuromuscular performance when compared with passive rest or placebo treatments. The available evidence indicates that the perceived reduction in muscle soreness (DOMS) following hydrotherapy is largely mediated by psychological expectancy and placebo mechanisms, rather than accelerated biological tissue repair. Nevertheless, specific temperature-dependent effects may be selectively applied in practice. CWI demonstrates comparatively greater effectiveness in reducing thermoregulatory strain and accelerating parasympathetic reactivation, whereas HWI appears more beneficial for preserving muscle contractility and restoring late-phase rate of force development (RFD) following exercise-induced muscle damage and reducing cardiorespiratory demand during subsequent submaximal efforts. From a chronic perspective, regular water immersion does not appear to meaningfully impair adaptations to high-intensity interval or field-sport training. However, the two modalities engage divergent molecular pathways - cold exposure promoting cellular stress tolerance via elevated HSP-72, and heat exposure upregulating systemic anabolic growth factors - distinctions that may carry practical implications for periodised training programmes. Accordingly, recovery interventions should transition away from uniform prescription towards strictly individualised implementation, guided by exercise demands, biological sex, body composition, and the athlete's personal beliefs and expectations.

Disclosure

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