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Cold-Water Immersion and Recovery from Exercise: Acute Benefits, Chronic Trade-Offs and Practical Application

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Abstract. Cold-water immersion (CWI) can be an effective post-exercise recovery tool, but its value depends on whether the priority is short-term readiness or long-term training adaptation. Systematic-review evidence suggests CWI can reduce delayed-onset muscle soreness and improve perceived recovery about 24 hours after strenuous exercise. It may also help restore muscular power after high-intensity or eccentric exercise and can be especially useful following exercise in hot environments. However, reduced soreness and improved readiness do not necessarily mean that maximal strength, muscle function, or physiological recovery are fully restored. Proposed mechanisms include reduced tissue temperature, cold-induced vasoconstriction, hydrostatic pressure, altered fluid distribution, and pain-relieving effects. These may reduce discomfort and help athletes feel more prepared for a subsequent session. The main drawback concerns immediate, repeated CWI after resistance training. Muscle hypertrophy and strength development depend on post-exercise muscle protein synthesis, cellular signaling, and tissue remodeling. Some intervention studies suggest that habitual immediate CWI may modestly blunt skeletal-muscle hypertrophy and potentially some strength and power adaptations. This concern is less clear for endurance training. When athletes face congested competition schedules, short recovery windows, or repeated training in heat, faster perceived recovery may outweigh possible long-term trade offs. Research remains limited by inconsistent immersion temperatures, durations, exercise protocols, participant characteristics, and outcome measures. Overall, CWI should be used strategically rather than routinely.It's most useful for rapid recovery, while people seeking maximal muscle growth should generally avoid immediate habitual CWI after resistance sessions and prioritize sleep, nutrition, progressive overload, and appropriate training load management.

Keywords: Cold-water immersion, post-exercise recovery, resistance training adaptation, muscle hypertrophy

1. Introduction

Cold-water immersion (CWI), commonly called an ice bath or cold plunge, is one of the most visible recovery practices in sport. Athletes may sit or stand in cold water after demanding training sessions, matches, races, or competitions in the hope of reducing soreness, fatigue, and improving readiness to perform again. The practice is used across endurance, team, and strength sports and has

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become increasingly common among recreational trainees. Its popularity is understandable: intense exercise can produce temporary reductions in strength and power, muscle soreness, heat strain, and a feeling of fatigue. When a second training session or competition is approaching, any intervention that makes an athlete feel more recovered will be attractive.

However, the usefulness of CWI depends on the outcome being prioritized. Recovery is not identical to adaptation. An athlete preparing for a tournament, stage race, or congested competition schedule may value readiness over the next 24 to 48 hours. In contrast, a person completing resistance training primarily to gain muscle mass and strength should care about the biological signals that turn repeated training sessions into long-term adaptation. Some of the same processes that produce temporary soreness and fatigue also participate in muscle remodeling, including muscle hypertrophy. Therefore, reducing the acute response to training is not automatically beneficial when repeated after every session.

The current literature supports a balanced conclusion. CWI can meaningfully improve certain markers of acute recovery, especially muscle soreness, and some measures of power after high-intensity exercise. Yet regular use of CWI immediately after resistance training may modestly reduce hypertrophic adaptation and may, in some circumstances, weaken strength-related gains. The purpose of this review is to evaluate CWI as an exercise recovery strategy by distinguishing acute recovery from chronic training adaptation, examining proposed mechanisms, identifying limitations in the evidence, and providing practical recommendations for athletes and recreational exercisers.

2. What is cold-water immersion

CWI refers to the immersion of part or the entire body in cold water after exercise. Most research protocols use water below 15°C, commonly about 10 to 15°C, for approximately 5 to 20 minutes. The lower limbs are often immersed after running, cycling, or lower-body-focused resistance training, while whole-body protocols typically submerge the torso and legs to around chest or waist level. Researchers vary the water temperature, depth, duration, timing after exercise, and whether immersion is continuous or intermittent. These differences matter because the actual thermal and hydrostatic stimulus can differ substantially between studies.

In practical settings, CWI is generally used soon after demanding exercise. Typical examples include a soccer player using an ice bath after a match, a cyclist cooling after a hard hot-weather tour stage, or a lifter using a cold plunge after a resistance session. The intervention is not intended to improve fitness directly from the immersion itself. Instead, its intention is to alter post-exercise symptoms and physiology in ways that may improve the athlete's ability or willingness to train or compete again. A useful distinction is between isolated use and chronic use. Acute use means using CWI after a single difficult event or occasionally during a short recovery window. Chronic use means applying CWI repeatedly across a training season, often after every or nearly every training session. The evidence suggests that these two use cases should not be judged by the same standard. A method can be useful for short-term readiness but undesirable when it repeatedly follows a training stimulus designed to produce muscle growth.

3. Acute exercise recovery

Hard exercise causes several short-term challenges. Repeated concentric contractions, eccentric exercise, sprinting, and prolonged racing can cause significant fatigue and elevations in markers associated with muscle damage. Exercise in hot conditions also elevates body temperature and cardiovascular strain. These responses are not uniform: the recovery profile after a hot endurance

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event differs from that after unfamiliar eccentric exercise or a heavy lower-body lifting session. Accordingly, CWI should not be expected to produce the same benefit in every situation. The strongest acute evidence is for perceptual outcomes. A systematic review and meta-analysis including 52 studies in physically active participants found that CWI after high-intensity exercise reduced muscle soreness 24 hours later and improved perceived recovery compared with passive recovery. The review also found improved muscular-power recovery 24 hours after both eccentric and high-intensity exercise [1]. These results support the practical observation that athletes often feel less sore and more prepared after cold immersion. Such outcomes are meaningful because perceptions of soreness and readiness can influence training quality, confidence, and willingness to perform another demanding session. The effect on objective performance is more selective. CWI improved muscular power at 24 hours and reduced serum creatine kinase after high-intensity exercise, but it did not significantly improve strength recovery after either eccentric or high-intensity exercise [1]. This distinction is important. Lower soreness or creatine kinase does not guarantee restored maximal strength, and an athlete should not equate feeling recovered with complete physiological recovery. Creatine kinase is also an imperfect proxy for damage or readiness because its response varies greatly across individuals and exercise types. The context of a recovery window is central. If an athlete must perform again within a day—for example, during a multi-day tournament, an intense training camp, or a stage race—CWI may offer a practical advantage by lowering discomfort and improving perceived readiness. In hot environments, immersion may have additional value because it can help reduce post-exercise thermal strain. CWI can improve recovery of endurance performance after exercise performed in warm conditions, although benefits are not equally evident in temperate conditions [1]. Cooling may therefore be especially relevant when high body temperature, rather than localized muscle soreness alone, is a major limiter of subsequent performance.

CWI should nevertheless be viewed as one component of recovery rather than a substitute for basic recovery behaviors. Rehydration, carbohydrate intake when glycogen restoration is needed, sufficient protein and total energy intake, sleep, sensible training-load management, and time remain foundational. An ice bath may make an athlete feel better, but it cannot compensate for inadequate fueling, sleep restriction, excessive training load, or illness. The magnitude of benefit from CWI also varies across people, exercise modes, and protocols, which means an individual-response approach is preferable to assuming that every athlete needs the same routine.

4. How CWI may work

Several mechanisms have been proposed to explain CWI's acute effects. The most direct is reduced tissue and body temperature. Cold water transfers heat more effectively than cold air, so immersion can lower skin and superficial tissue temperatures quickly. After hot exercise, this cooling may reduce thermal discomfort and assist the return toward thermal homeostasis. A second mechanism is cold-induced vasoconstriction, which can reduce local blood flow in immersed limbs. A third is hydrostatic pressure: immersion applies pressure to the limbs, which may influence fluid distribution and venous return. These effects occur simultaneously in water, making it difficult to determine how much of any observed benefit is due to temperature versus water pressure.

CWI may also reduce pain perception. Cold exposure can alter sensory nerve conduction and the experience of pain, which provides a plausible explanation for reductions in soreness even when structural muscle recovery is not fully restored. This analgesic effect can be useful in a short recovery window, but it also requires caution. Reduced soreness does not necessarily mean that an athlete is fully recovered or that the underlying mechanical fatigue has resolved. If reduced

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discomfort encourages an athlete to exceed sensible training load, CWI could indirectly contribute to poor decision-making. Inflammation is often described as the primary target of ice baths, but this explanation is too simple. Exercise-induced inflammation is not solely harmful; it is part of the coordinated response involved in repair and remodeling. In addition, the evidence that CWI consistently suppresses biological inflammatory markers more than comparison recovery methods is mixed. Local vasoconstriction, hydrostatic pressure, altered metabolic activity, and reduced limb blood flow are plausible contributors to acute responses, but findings for inflammatory and muscle-damage outcomes are inconsistent [2]. Thus, it is more accurate to say that CWI may alter several recovery-related pathways than to claim that it simply "removes inflammation." This uncertainty matters because mechanisms should not be confused with proven causal explanations. A lower skin temperature, lower soreness score, or altered blood marker does not by itself establish why performance recovered or why adaptation changed. Future research needs studies that compare cold water with thermoneutral water, compression alone, active recovery, and carefully matched sham conditions. Those designs can better separate the effects of cold, hydrostatic pressure, expectation, and post-exercise behavior.

5. Chronic use and training adaptation

The potential downside of CWI becomes most relevant when immersion is performed immediately after resistance exercise on a regular basis. Resistance training promotes hypertrophy through repeated bouts of mechanical tension and the subsequent molecular responses that support muscle protein synthesis, ribosomal biogenesis, satellite-cell activity, and tissue remodeling. These responses do not mean that all soreness or inflammation is necessary for growth; rather, they indicate that the post-exercise environment contributes to long-term adaptation. If CWI repeatedly blunts relevant anabolic signals, it could reduce the accumulated training response.

Evidence from a 12-week lower-body resistance-training intervention supports this concern. Resistance-trained young men who performed lower-limb CWI for 10 minutes at about 10°C beginning five minutes after training showed smaller gains in quadriceps muscle mass and several strength- and power-related measures than participants who completed low-intensity cycling as active recovery. The same research program reported attenuated signaling responses associated with muscle remodeling and reduced satellite-cell activity after acute post-exercise CWI [3]. The study does not imply that one ice bath eliminates gains, but it demonstrates that repeated, immediate cooling after every session can interfere with some desired resistance-training adaptations.

Whole-body immersion at 10°C for 15 minutes after resistance sessions attenuated type II muscle-fiber hypertrophy over seven weeks in previously untrained but recreationally active men [4]. In that study, differences in whole-body or regional lean mass assessed by dual-energy X-ray absorptiometry were not as clear, and maximal strength gains were partly maintained. This finding illustrates an important measurement issue: different assessment tools may capture different levels of adaptation. A muscle biopsy can detect fiber-specific changes, whereas dual-energy X-ray absorptiometry estimates lean mass at a broader regional or whole-body level. Therefore, apparently conflicting results may sometimes reflect what was measured rather than a complete disagreement about the physiological effect.

The most recent higher-level synthesis is consistent with a modest hypertrophy cost. A systematic review of eight interventions that combined post-exercise CWI with resistance training found that resistance training alone likely produced greater hypertrophic adaptation than resistance training combined with immediate CWI, with a comparative standardized mean difference of -0.22 [5]. The authors concluded that immediate CWI may attenuate hypertrophic changes in both trained and

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untrained adults. However, the evidence base was small, and the included studies were generally rated fair to poor in quality using a resistance-training-specific quality assessment [5]. The appropriate conclusion is therefore cautious rather than absolute. Regular immediate CWI is unlikely to be optimal when maximizing hypertrophy is the main goal, but the exact size of the penalty and the most important dose variables remain uncertain.

Strength outcomes are less consistent than hypertrophy outcomes. Smaller improvements in some strength measures have been observed when CWI was used after resistance training, and lower gains in several lower-body strength outcomes have also been reported [3, 6]. In contrast, dynamic one-repetition maximum strength was not clearly impaired despite reduced type II fiber hypertrophy in another intervention [4]. This is physiologically plausible because strength reflects not only muscle size but also neural adaptations, motor learning, coordination, tendon properties, and task specificity. A complex one-repetition maximum movement can improve substantially through skill and neural adaptations even when hypertrophy is somewhat blunted. Consequently, muscle size and strength should be evaluated as related but distinct outcomes.

A meta-analysis found a small overall attenuation of strength gains when CWI followed resistance training, but the result varied by cooling method [7]. Localized cooling of trained limbs was associated with an attenuation, whereas whole-body CWI did not show a statistically significant difference from control in the subgroup analysis [7]. These findings should be interpreted carefully because subgroups included few studies and protocols differed in temperature, timing, participant training history, exercise selection, and outcome testing. Still, they reinforce the practical principle that frequent immediate cooling should not be considered neutral by default in a hypertrophy- or strength-focused program.

The molecular literature provides biological plausibility for the chronic findings. CWI can attenuate anabolic signaling pathways, muscle protein synthesis, ribosome-biogenesis-related signaling, and satellite-cell responses after resistance exercise [2]. Repeated CWI has also been reported to alter the nuclear export and maturation of microRNAs associated with the regulation of post-exercise protein synthesis [8]. These results do not prove that any single molecular change directly causes lower muscle growth, because adaptation is regulated by interacting pathways. However, the pattern is consistent with the observed reduction in hypertrophy in longer intervention studies.

Endurance athletes require a more nuanced interpretation. Current evidence does not show the same clear adverse effect of post-exercise CWI on endurance-training adaptations as it does for resistance training. This does not mean that endurance athletes should automatically use CWI after every workout. If recovery demands are low and the athlete is in a normal development phase, the benefit of routine immersion may be small. However, in periods with closely spaced hard sessions, races, travel, high environmental heat, or competition, the priority may reasonably shift toward preserving short-term performance. For a cyclist, for example, CWI may make more sense after a hot multi-stage event or a high-priority race weekend than after every routine interval session in a long aerobic base block.

6. Limitations of the evidence

The evidence base has several limitations that prevent overly precise prescriptions. First, CWI protocols vary considerably. Studies have used water temperatures from approximately 10 to 15°C, exposures from 10 to 20 minutes, local or whole-body immersion, and different delays between exercise and immersion. The current hypertrophy literature largely examines cooling performed very

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soon after training and after every session. It cannot determine with confidence whether a warmer, shorter, delayed, or less frequent protocol would have the same long-term effects.

Second, studies use different forms of exercise. Some protocols involve full-body resistance programs, while others use isolated wrist-flexor, handgrip, leg-extension, or lower-body exercises. Exercise selection affects muscle mass recruited, systemic fatigue, and the relevance of strength tests. Results from a small-muscle handgrip model should not be generalized uncritically to a whole-body program used by athletes.

Third, measurement methods differ in sensitivity and meaning. Magnetic resonance imaging, computed tomography, and ultrasound provide more direct estimates of local muscle size than circumference or whole-body lean-mass estimates. Muscle biopsy permits fiber-level analysis but samples only a small site and can show considerable measurement variability. Panoramic B-mode ultrasound can validly and reliably assess changes in skeletal-muscle cross-sectional area when standardized procedures are used [9]. Well-designed future trials should therefore use direct imaging, consistent anatomical landmarks, trained operators, and preferably more than one measure of hypertrophy.

Fourth, many studies have small samples and include mostly young men. Seven of the eight studies in one hypertrophy meta-analysis included only male participants, with participants generally aged 20 to 26 years [5]. It remains unclear whether the effects are comparable in women, older adults, elite athletes, adolescents, or clinical populations. Sex, training status, energy availability, protein intake, and genetic variation could all influence adaptation.

Fifth, nutrition and total training load are not always tightly controlled. Protein and total energy intake influence resistance-training adaptations, while sleep and stress influence both recovery and performance [10]. Small randomized studies may not fully balance these variables between groups. If participants differ in diet, adherence, outside activity, or training effort, those factors can obscure or exaggerate the effect attributed to CWI.

Finally, expectancy effects are difficult to eliminate. Athletes often have strong beliefs about ice baths, and perceived recovery is partly subjective by definition. A reduction in soreness is still valuable if it improves comfort and readiness, but researchers should distinguish placebo-related perceptions from changes in objective performance or adaptation. Better placebo-controlled designs and transparent reporting of adverse events, adherence, immersion depth, water temperature, and actual timing relative to exercise would strengthen future evidence.

7. Practical recommendations

CWI should be periodized according to the athlete's immediate objective rather than applied reflexively after every hard session. For athletes prioritizing next-day or same-week performance, CWI can be reasonable after unusually demanding high-intensity exercise, competition, or hot-weather exercise. The evidence is strongest for reduced soreness and improved perceived recovery at approximately 24 hours, with possible benefits to power recovery [1]. A practical evidence-informed range is 10 to 15 minutes in water around 10 to 15°C, with immersion depth chosen according to the exercised muscles and comfort. Extremely cold or prolonged exposures are not necessary to assume a benefit, and they may add discomfort or safety concerns without clearly improving the outcome. For resistance trainees whose primary goal is hypertrophy, routine immediate CWI after lifting is difficult to justify. The accumulated literature indicates a potential small but meaningful reduction in muscle growth when CWI is applied immediately after every resistance session [3-5]. A lifter building muscle should generally prioritize post-exercise nutrition, adequate carbohydrate and protein intake, progressive overload, sleep, and appropriate programming

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instead. If CWI is desired for comfort, it may be more prudent to reserve it for exceptional circumstances, such as competition, an unusually high soreness burden, or a period where short-term performance is more important than maximizing hypertrophy. For athletes combining cycling or running with strength training, timing is especially important. Consider an endurance athlete who completes a heavy gym session in the morning and has a key cycling interval workout the next day. If maintaining next-day cycling quality is the priority, CWI after the strength session could be considered, but it may trade some long-term lifting adaptation for short-term readiness. If the athlete is in a strength-development phase, avoiding immediate CWI after the gym session and using lower-risk recovery strategies would better align with the goal. CWI could instead be reserved for high-priority endurance events or hot races, rather than being attached automatically to all workouts.

Basic safety also matters. Individuals with cardiovascular disease, uncontrolled hypertension, Raynaud's phenomenon, cold urticaria, impaired sensation, or other medical conditions should seek individualized clinical advice before using cold immersion. Athletes should avoid immersing alone, enter carefully to reduce the risk of a cold-shock response, stop if they experience chest pain, severe dizziness, numbness, or unusual shortness of breath, and rewarm gradually afterward. CWI is a performance-recovery tool, not a test of tolerance.

8. Conclusion

Cold-water immersion is best understood as a context-dependent recovery strategy. It can reduce muscle soreness and improve perceived recovery after demanding exercise, and it may aid short-term power recovery and thermal recovery in particular settings. These effects can be valuable when an athlete has limited time before another competition or high-quality training session. At the same time, short-term relief should not be confused with superior long-term adaptation. Frequent CWI immediately after resistance training may attenuate hypertrophy and may reduce some strength and power adaptations, although the size of these effects varies and the evidence base remains limited . For athletes seeking muscle growth, routine post-lifting ice baths are therefore not an evidence-based default. For athletes navigating congested competition schedules, hot conditions, or repeated bouts of high-intensity work, selective CWI may be a useful tool. The most defensible approach is strategic rather than habitual use. Match CWI to the performance calendar, recovery demands, environmental conditions, and training goal. Use it when short-term readiness is genuinely valuable and avoid making it an automatic post-resistance-training ritual when the objective is to maximize muscle and strength development.

References

[1] Moore, E., Fuller, J. T., Buckley, J. D., Saunders, S., Halson, S. L., Broatch, J. R., & Bellenger, C. R. (2022). Impact of cold-water immersion compared with passive recovery following a single bout of strenuous exercise on athletic performance in physically active participants: A systematic review with meta-analysis and meta-regression. *Sports Medicine, 52*(7), 1667–1688. https://doi.org/10.1007/s40279-022-01644-9

[2] Petersen, A. C., & Fyfe, J. J. (2021). Post-exercise cold water immersion effects on physiological adaptations to resistance training and the underlying mechanisms in skeletal muscle: A narrative review. *Frontiers in Sports and Active Living, 3*, 660291. https://doi.org/10.3389/fspor.2021.660291

[3] Roberts, L. A., Raastad, T., Markworth, J. F., Figueiredo, V. C., Egner, I. M., Shield, A., et al. (2015). Post-exercise cold water immersion attenuates acute anabolic signalling and long-term adaptations in muscle to strength training. *The Journal of Physiology, 593*(18), 4285–4301. https://doi.org/10.1113/JP270570

[4] Fyfe, J. J., Broatch, J. R., Trewin, A. J., Hanson, E. D., Argus, C. K., Garnham, A. P., et al. (2019). Cold water immersion attenuates hypertrophy but not strength gain following resistance training. *Journal of Applied Physiology, 127*(5), 1403–1415. https://doi.org/10.1152/japplphysiol.00325.2019

DOI: 10.54254/2753-8818/2026.38418

[5] Piñero, A., Burke, R., Augustin, F., Mohan, A. E., DeJesus, K., Sapuppo, M., et al. (2024). Throwing cold water on muscle growth: A systematic review with meta-analysis of the effects of postexercise cold water immersion on resistance training-induced hypertrophy. *European Journal of Sport Science, 24*(2), 177–189. https://doi.org/10.1002/ejsc.12074

[6] Fröhlich, M., Faude, O., Klein, M., Pieter, A., Emrich, E., & Meyer, T. (2014). Strength training adaptations after cold-water immersion. *Journal of Strength and Conditioning Research, 28*(9), 2628–2633. https://doi.org/10.1519/JSC.0000000000000434

[7] Malta, E. S., Dutra, Y. M., Broatch, J. R., Petersen, A. C., & Bishop, D. J. (2021). Effects of post-exercise cold water immersion on resistance training-induced gains in muscular strength: A systematic review and meta-analysis. *Sports Medicine, 51*, 2025–2039. https://doi.org/10.1007/s40279-021-01469-8

[8] D'Souza, R. F., Figueiredo, V. C., Markworth, J. F., Zeng, N., Hedges, C. P., Roberts, L. A., et al. (2023). Cold water immersion suppresses miRNA nuclear export and maturation after resistance exercise. *Physiological Reports, 11*(15), e15784. https://doi.org/10.14814/phy2.15784

[9] Ahtiainen, J. P., Hoffrén, M., Hulmi, J. J., Pietikäinen, M., Mero, A. A., Ahtiainen, M., & Häkkinen, K. (2010). Panoramic ultrasound is a valid method to measure changes in skeletal muscle cross-sectional area. *European Journal of Applied Physiology, 108*(2), 273–279. https://doi.org/10.1007/s00421-009-1206-6

[10] Fullagar, H. H. K., Skorski, S., Duffield, R., et al. (2015). Sleep and athletic performance: The effects of sleep loss on exercise performance, and physiological and cognitive responses to exercise. *Sports Medicine, 45*, 161–186. https://doi.org/10.1007/s40279-014-0260-0