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CRYOTHERAPY MODALITIES IN PHYSICALLY ACTIVE INDIVIDUALS: EFFECTS ON RECOVERY, PERFORMANCE, AND PHYSIOLOGICAL HEALTH - A NARRATIVE REVIEW

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ABSTRACT

The aim of this narrative review was to analyze the impact of commonly used forms of cryotherapy - primarily cold-water immersion (CWI) and whole-body cryotherapy (WBC) - on post-exercise recovery, exercise capacity, and selected indicators of physiological health in physically active individuals. The review included publications, including meta-analyses, randomized trials, and experiments involving athletes and recreational exercisers, assessing short- and long-term effects. The available evidence indicates that CWI generally reduces post-workout muscle soreness and improves the subjective feeling of recovery, and in many studies also reduces the increase in markers of muscle damage, although this effect is not uniform and depends on the parameters of the intervention. WBC, on the other hand, has a stronger systemic anti-inflammatory and antioxidant effect, especially in multi-session protocols. Both the effectiveness and possible limitations of both modalities depend on the dose, temperature, immersion time, timing of application, and nature of the training load. All available data indicate that cryotherapy, when used properly and in accordance with safety standards, is a valuable tool for supporting sports recovery, while its impact on performance is mainly indirect, through reducing fatigue and accelerating the recovery of muscle function.

KEYWORDS

Cryotherapy, Cold-Water Immersion (CWI), Whole-Body Cryotherapy (WBC), Post-Exercise Recovery, Physiological Health

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Introduction

Cryotherapy, defined as the deliberate, short-term exposure of the body to very low temperatures, has been an integral part of wellness practices in sports and sports medicine for many decades. Its application has evolved from simple forms of local post-traumatic cooling to modern regenerative methods, including both cold-water immersion (CWI) and technologically advanced forms of whole-body cryotherapy (WBC). In recent years, there has been a dynamic increase in the popularity of both methods among competitive athletes and physically active individuals, due to the widespread belief in their impact on recovery, reduction of muscle pain, and potential stabilization of the inflammatory response after exercise (Allan et al., 2022). At the same time, a growing number of experimental studies and meta-analyses indicate that the body's response to cold is complex, dependent on the parameters of the intervention, and highly individual (Feng et al., 2024; Azevedo et al., 2022).

Contemporary literature emphasizes that CWI is one of the most commonly used cryotherapy methods due to its availability, low cost, and standardization potential. Meta-analyses confirm its effectiveness in reducing delayed onset muscle soreness (DOMS) and accelerating the recovery of selected muscle function parameters after exercise (Xiao et al., 2023). Network analysis has shown that the effectiveness of CWI depends on exposure parameters. Protocols lasting 10-15 minutes are the most effective time range, but the optimal temperature varies depending on the indicator analyzed: lower values (5-10°C) promote the reduction of muscle damage markers, while moderate temperatures (11-15°C) are more effective in alleviating post-workout muscle soreness. Both shorter and longer exposures are less effective (Wang et al., 2025). At the same time, not all studies confirm the full regenerative effect of CWI - in one study, no differences were observed compared to the control group in terms of DOMS, CK, or performance parameters, even though the intervention reduced swelling and cortisol profile (de Freitas et al., 2019).

WBC is a more advanced form of cryotherapy, based on short-term exposure to extremely low temperatures ranging from -110°C to -140°C. Physiological effects include a rapid decrease in skin

temperature, activation of the sympathetic nervous system, stimulation of the neuroendocrine axis, and modulation of the inflammatory and oxidative response (Lombardi et al., 2017). Studies indicate that multi-session protocols have a more pronounced systemic effect than single exposures. One study showed that cyclic whole-body cryostimulation lowers levels of pro-inflammatory markers such as IL-1β and CRP and reduces concentrations of reactive oxygen and nitrogen species, including H_2O_2 and NO (Zembron-Łacny et al., 2020). At the same time, oxidative stress parameters do not always show unidirectional changes - some studies have reported no significant differences in MDA levels or variable enzymatic response depending on the number of sessions and the training status of participants (Lombardi et al., 2017). In addition, repetitive WBC leads to adaptive molecular changes, including modulation of gene expression and markers associated with the control of inflammatory response and redox balance (Kusmierczyk et al., 2024b). In the context of functional recovery, studies indicate that WBC can support the return of muscle strength and reduce symptoms of muscle damage with appropriately planned, multi-session protocols, although these effects are highly dependent on the parameters of the treatment and the timing of its application - exposure immediately after exercise usually gives better results than delayed intervention (Haq et al., 2022b).

At the same time, there is an ongoing discussion about the differences between cryotherapy modalities. Systematic reviews indicate that different forms of cryostimulation (including CWI and WBC) often provide similar benefits in terms of reducing post-workout muscle soreness and certain markers of muscle damage, with individual techniques differing in their effect profiles and application goals (Feng et al., 2024). Comparative studies indicate that CWI has a stronger local effect - greater reduction in skin temperature and short-term changes in blood flow at the site of exposure - compared to air/partial treatments (PBC). In contrast, review literature and expert opinions indicate that WBC is more often associated with a broader profile of systemic effects, including autonomic modulation and neuroendocrine response (Hohenauer et al., 2018; Lombardi et al., 2017). At the same time, experts emphasize that the choice of modality should depend on the availability of infrastructure, the nature of the effort, recovery time, and the individual reactivity of the athlete (Bouzigon et al., 2021).

Increasing attention is also being paid to the timing of cryotherapy. Evidence indicates that both CWI and WBC differ in effectiveness depending on whether the intervention is applied immediately after exercise, with a delay, or repeatedly over several days. WBC applied immediately after exercise accelerates the recovery of muscle strength, while delayed exposure - e.g., 3-4 hours later - does not show such properties (Haq et al., 2022b). A similar importance of timing was observed in studies on WBC applied in the evening - although the timing of the intervention did not affect sleep quality, exposure closer to nighttime resulted in a more pronounced improvement in autonomic activity and thermoregulation during sleep (Arc-Chagnaud et al., 2024). Studies on multi-session protocols have shown that cumulative exposure can have an adaptive effect on the immune, oxidative, and endocrine systems (Kusmierczyk et al., 2024b; Zembron-Łacny et al., 2020).

From a safety perspective, the available data indicate that both CWI and properly performed WBC are associated with a low risk of serious adverse events, provided that these interventions are used in accordance with qualification procedures and exposure parameter control. It is also emphasized that many incidents reported in the literature involved procedures incorrectly classified as WBC - including, in particular, partial-body cryotherapy (PBC) - suggesting that the risk often stems from faulty equipment or failure to comply with treatment standards (Legrand et al., 2023). Studies on recreational exposures, such as winter swimming or cold water bathing, emphasize that health incidents are mainly due to non-compliance with safety rules rather than the method itself (Esperland et al., 2022; Cain et al., 2025).

Despite the large number of publications, there are still significant gaps in knowledge. Many studies do not include top-level athletes (Huang et al., 2024), the long-term effects of cryotherapy on training adaptation are rarely analyzed, and protocols vary in temperature, exposure time, and exercise characteristics, making it difficult to draw clear conclusions. Therefore, there is a need for a comprehensive review that synthetically assesses the effects of CWI and WBC in the context of post-exercise recovery, exercise capacity, and physiological health parameters.

Materials and methods

This review was developed as a narrative review, the aim of which was to collect, organize, and critically analyze current scientific evidence on the effects of cryotherapy, in particular cold-water immersion (CWI) and whole-body cryotherapy (WBC), on post-workout recovery, physical performance, and physiological responses in physically active individuals. The narrative nature of the study allowed for the inclusion of studies with diverse methodological designs and the integration of their results in a thematic approach.

The literature search was conducted in the PubMed database due to its wide range of publications in the field of exercise physiology and sports medicine. The search used a combination of terms related to cryotherapy and regeneration, including: "cryotherapy," "cold-water immersion," "whole-body cryotherapy," "cryostimulation," "post-exercise recovery," "muscle damage," and "athletic performance." The selection of keywords was planned to cover both clinical and experimental studies, as well as meta-analyses, review papers, and expert opinions. In order to increase the completeness of the material, the bibliographies of original and review publications were additionally analyzed.

Articles that met the following substantive criteria were included in the study:

(1) the subjects were physically active individuals or athletes;

(2) the intervention involved the use of CWI, WBC, or other forms of cryotherapy in the context of post-workout recovery;

(3) the publication was peer-reviewed and available in full text;

(4) the article contained data on physiological, neuromuscular, or subjective indicators of recovery.

Studies unrelated to physical exercise, case studies, non-peer-reviewed texts, and articles in which cryotherapy was not the main intervention were excluded.

The selection of material was carried out in stages and included analysis of titles, abstracts, and full texts. Each article was evaluated for relevance to the topic and suitability for narrative synthesis. Due to the purpose of the review, no formal risk of bias assessment was performed, but elements such as study type, participant group, cryotherapy protocol, and key results were considered.

The analysis was qualitative and consisted of identifying common patterns and discrepancies between studies. The results were organized thematically, covering, among other things, the effectiveness of CWI and WBC in reducing muscle damage, their impact on exercise parameters, inflammatory and oxidative markers, the importance of dose and exposure time, and current evidence on the safety of cryotherapy. This made it possible to present a broad, up-to-date, and consistent picture of the role of cryotherapy in sports practice.

Results

An analysis of twenty-four studies, including meta-analyses, controlled experiments, review papers, expert opinions, and translational studies, identified several key areas in which cryotherapy - especially cold-water immersion (CWI) and whole-body cryotherapy (WBC) - affects the post-workout recovery process, muscle system functioning, and the physiology of physically active individuals. The results include biochemical parameters, inflammatory markers, oxidative responses, neuromuscular, performance, and perceptual aspects. A detailed summary of the results is presented below.

1. Effects on muscle damage, soreness, and tissue-level recovery

Available studies indicate that the effect of cryotherapy - especially cold water immersion (CWI) - on post-exercise muscle soreness (DOMS) and tissue recovery is noticeable, although heterogeneous and largely dependent on the protocol used, the nature of the exercise, and the study population. A meta-analysis showed that CWI can reduce DOMS primarily in the first hours after exercise, while the effects observed after 24-48 hours are less consistent and depend on temperature, exposure time, and the intensity of muscle damage (Xiao et al., 2023). In studies involving soccer players, no significant differences were found between the CWI group and the control group in terms of DOMS, fatigue, muscle damage markers, or exercise readiness, indicating that the response to the intervention may depend on the specifics of the exercise and the characteristics of the study population (Farkhari Babak et al., 2021).

CWI also affects selected biomarkers of muscle damage. Meta-analyses indicate that appropriately selected protocols - especially those with a temperature of 5-10°C and a duration of 10-15 minutes - can reduce the post-exercise increase in creatine kinase (CK) within 24-72 hours after exercise, while both shorter (<10 minutes) and longer (>15 minutes) exposures are less effective (Wang et al., 2025; Xiao et al., 2023). At the same time, not all studies confirm significant differences between CWI and control conditions - in one experiment, no effect of CWI on CK levels was observed, despite a reduction in thigh swelling and hormonal changes (de Freitas et al., 2019).

Whole-body cryotherapy (WBC) does not directly reduce markers of muscle damage, such as CK or myoglobin, but it clearly modulates the course of the post-workout response. (Zembron-Łacny et al., 2020).

2. Effects on inflammation and systemic immune responses

Modulation of the inflammatory response is an important, albeit variable, element of cryotherapy. Research results indicate that CWI has mainly a local effect, leading to a decrease in tissue temperature and reduction of swelling, but its effect on systemic markers is limited. In a study involving volleyball athletes, regular use of CWI did not lead to significant changes in CRP, IL-6, or other inflammatory markers compared to the control group (de Freitas et al., 2019). These results suggest that the local effect of CWI does not necessarily translate into systemic modulation of the immune response.

Unlike CWI, WBC has a more pronounced systemic effect. Studies using multi-session protocols have observed a significant reduction in CRP, IL-1β, and IL-6, as well as an improvement in oxidative balance markers after a 10-day cryotherapy cycle (Zembron-Łacny et al., 2020). In addition, repeated exposure to extremely low temperatures has been shown to modulate the expression of genes associated with inflammatory processes and oxidative stress, indicating the adaptive nature of the immune response induced by WBC (Kusmierczyk et al., 2024b).

3. Oxidative stress and antioxidant capacity

The effect of cryotherapy on the oxidative-antioxidant balance depends on the method used and the duration of exposure.

In the case of CWI, the available data indicate that this intervention does not significantly affect markers of oxidative stress, such as lipid peroxidation (MDA) or advanced oxidation products of proteins (AOPP). In a study involving volleyball players, MDA and AOPP values did not differ between CWI and the control group, despite a several-day recovery protocol (de Freitas et al., 2019). These results suggest that CWI does not significantly modify the systemic oxidative response. In contrast, WBC has a more systemic effect. In a 14-session protocol, a significant reduction in markers of reactive oxygen and nitrogen species, such as H_2O_2 and NO (Zembron-Łacny et al., 2020), was observed, indicating a reduction in oxidative stress. Additionally, studies analyzing gene expression have found that repeated cryostimulation increases the expression of mRNA of antioxidant enzymes, especially SOD2 and GSS, suggesting an adaptive strengthening of defense mechanisms against free radicals (Kusmierczyk et al., 2024b).

4. Neuromuscular function and functional readiness

Experimental data indicate that cryotherapy may affect the rate of neuromuscular recovery, but the effects vary depending on the modality, type of exercise, and timing of the intervention.

CWI promotes faster normalization of selected muscle function parameters after eccentric exercise - improvements in isometric strength and sprint recovery after hamstring injury have been demonstrated (Huang & Chen, 2025). In sports, there is also an improvement in the perception of recovery and a reduction in fatigue in swimmers (Batista et al., 2024), although this does not always translate into improved neuromuscular indicators.

In the case of WBC, the body's response is more dependent on the timing of the intervention. Studies on interval and endurance exercise have shown that the use of WBC immediately after the end of a training session leads to faster recovery of strength and power within 24-48 hours, while delayed intervention (e.g., 3 hours) is less effective (Haq et al., 2022b). Similarly, among competitive rowers, multi-session WBC supported the restoration of neuromuscular function and improved training readiness (Huang et al., 2024). Importantly, the results do not confirm a temporary decline in function immediately after WBC - in a study comparing different cryotherapy models, WBC showed the smallest decline in jump height in the early stages of recovery (Qu et al., 2020).

In protocols involving repeated multi-day exercise, however, it has been shown that CWI does not always protect against cumulative power decline - in a study involving volleyball players, no differences were found between CWI and control in neuromuscular parameters, despite observed changes in edema and hormonal response (de Freitas et al., 2019).

5. Athletic performance outcomes

Available meta-analyses and synthetic reviews indicate that neither cold water immersion (CWI) nor whole-body cryostimulation (WBC) lead to a clear, direct improvement in key performance parameters - such as maximum strength, power, VO_2max, sprint speed, or jump height - beyond baseline values in the short term (Xiao et al., 2023; Feng et al., 2024; Azevedo et al., 2022). However, research findings indicate that cryotherapy may have an indirect effect by reducing DOMS, limiting fatigue symptoms, and stabilizing

selected physiological markers, which helps maintain training quality with high session frequency (Xiao et al., 2023; Feng et al., 2024).

Long-term data confirm these observations - in a 6-week strength-endurance program, regular WBC did not directly improve performance parameters, while not interfering with strength adaptation and body composition; the only deviation was the lack of improvement in explosive power (CMJ) observed exclusively in the WBC group (Haq et al., 2022a).

6. Psychological readiness, fatigue perception, and sleep

CWI does not improve perceived recovery indicators in a statistically significant way, but athletes report a clear preference for this method - 65% of swimmers reported feeling more recovered after CWI compared to other interventions (Batista et al., 2024).

WBC additionally modulates the autonomic nervous system. Studies have shown that WBC sessions performed in the evening improve sleep quality and stabilize nocturnal autonomic activity, which promotes deeper phases of recovery (Arc-Chagnaud et al., 2024).

7.Safety and tolerability

Available data indicate that properly conducted cryotherapy protocols have a favorable safety profile, provided that the rules of qualification and supervision are followed. In the case of WBC, a review of the literature showed that most of the reported adverse events are mild and transient (including headache, paresthesia, and chills), and more serious incidents are rare and most often co-occur with risk factors such as migraine, hypertension, or vascular disease. The authors emphasize that with proper qualification and adherence to contraindications, the risks associated with WBC remain at an acceptable level (Legrand et al., 2023).

CWI is also considered safe under controlled conditions, but exposure to cold water may be associated with an increased risk in people with cardiovascular disease, particularly due to cold shock, sudden hyperventilation, or the possibility of inducing arrhythmia. The analyses describe that most health incidents during cold bathing were due to non-compliance with safety rules rather than the method itself, which emphasizes the importance of proper qualification and supervision (Esperland et al., 2022).

Discussion

In this review, we have highlighted the multidimensional nature of cryotherapy effects in physically active individuals, with a particular focus on two commonly used modalities: cold-water immersion (CWI) and whole-body cryotherapy (WBC). We have combined evidence from meta-analyses, randomized controlled trials, and mechanistic studies, allowing us to draw nuanced practical conclusions and identify key research gaps.

1. Main findings and their interpretation

1.1 CWI: strong local effect at optimal dose

Available meta-analyses and network analysis indicate that cold water immersion (CWI) has a beneficial but condition-dependent effect on delayed onset muscle soreness (DOMS) and, in specific protocols, on biomarkers of muscle damage (e.g., CK). The meta-analysis shows that CWI reduces DOMS immediately after treatment, while the effect at 48 h is less consistent and depends on the temperature and exposure time used (Xiao et al., 2023). Network analysis showed that medium-length protocols (10-15 min) produce the best results: the MD-MT variant (10-15 min, 11-15°C) proved to be the most effective in alleviating DOMS, while the MD-LT variant (10-15 min, 5-10°C) performed best in terms of CK reduction and improvement of neuromuscular indicators (e.g., jump). At the same time, both shorter (<10 min) and longer (>15 min) exposures generally had a lesser effect, which emphasizes the importance of selecting the “dose” of CWI (Wang et al., 2025; Xiao et al., 2023). It should be added that in field studies (e.g., in volleyball players), CWI was not always found to be superior to the control in terms of DOMS or CK, which indicates the role of population specificity and protocol in determining the effect (de Freitas et al., 2019).

Available studies have shown that CWI causes a marked decrease in skin temperature and local hemodynamic changes, such as strong vasoconstriction and reduced skin blood flow, which may contribute to a reduction in swelling and subjective discomfort after exercise (Hohenauer et al., 2018). In practical applications, these changes may promote a subjective feeling of recovery, although they do not always translate into an improvement in objective functional parameters - in a study involving swimmers, no significant effect of CWI on exercise performance was reported (Batista et al., 2024), and among soccer players, no differences were found between CWI and the control group in DOMS, fatigue, or neuromuscular indicators (Farkhari Babak et al., 2021). These results emphasize that the response to CWI is variable and depends on the type of exercise, protocol, and characteristics of the study population.

1.2 WBC: systemic modulations and multi-session adaptations

WBC has a clearly more systemic effect than CWI. Studies on protocols involving multiple exposures have shown that repeated cryostimulation leads to a reduction in markers of inflammation and oxidative stress, including a reduction in H_2O_2 and NO (Zembron-Łacny et al., 2020), and to an increase in the expression of genes involved in the regulation of redox processes and inflammatory response, such as SOD2 and GSS (Kusmierczyk et al., 2024b). Review data confirm that these types of changes are particularly pronounced after series of several to a dozen or so sessions, suggesting an adaptive nature of the response to cold stimulation (Lombardi et al., 2017).

In practice, WBC may be useful as a more "systemic" intervention (anti-inflammatory treatment or support during start periods), while CWI is often preferred as a quick solution between training units.

1.3 No direct improvement in performance

Meta-analyses and empirical studies indicate that neither CWI nor WBC consistently increase exercise capacity (max. strength, sprint, jump, VO_2max) above baseline values in the short term (Xiao et al., 2023; Feng et al., 2024). However, indirect effects are important: reduced DOMS, improved perception of readiness, and faster restoration of biomarkers may enable higher quality and frequency of training on a weekly/monthly basis, which indirectly promotes training adaptation. This distinction is important for practitioners formulating recovery programs.

2. Contextualization of results in light of research diversity

2.1 Heterogeneity of protocols and populations

One of the key limitations of the literature is the heterogeneity of parameters (temperature, time, frequency), populations (recreational vs. competitive), and types of exercise. Meta-analyses attempt to synthesize the evidence, but discrepancies often arise from methodological differences (Azevedo et al., 2022; Chen et al., 2024). Better standardization of protocol reporting is needed to facilitate comparisons between studies.

2.2 Individual differences and training status

Training status, history of cold exposure, and other individual factors modify the response to cryotherapy. Unaccustomed individuals may respond more strongly to exposure with acute pro-inflammatory responses, while regular, repeated exposure promotes antioxidant and immunological adaptations (Kusmierczyk et al., 2024b; Esperland et al., 2022). Gender and age differences remain relatively understudied and require more analyses focused on women and young athletes (Batista et al., 2024).

2.3 Type of exercise as a moderator of the effect

The type of exercise significantly modulates the effect of cryotherapy. EIMD induced by eccentric exercise provides the largest "window" for observing therapeutic effects, while in endurance or submaximal tasks, the response may be weaker. Network analyses also indicate that different modalities work better for different outcomes (e.g., hydrotherapy vs. whole-body cryostimulation), hence the need to tailor interventions to the mechanism of injury (Chen et al., 2024; Wang et al., 2025).

3. Mechanisms: what happens after exposure to cold?

3.1 Vascular and metabolic mechanisms

CWI causes local vasoconstriction, reduced blood flow, and edema, which limits local inflammatory processes and contributes to faster resorption of tissue damage (Hohenauer et al., 2018). The hydrostatic effect of immersion further facilitates drainage. These mechanisms explain the observed rapid changes in pain perception and certain biomarkers.

3.2 Neuroendocrine and immunological responses

WBC induces immediate sympathetic-endocrine reactivity and, with repeated exposures, leads to further modifications of the immune system. Reviews and studies report changes in stress hormone levels (e.g., changes in cortisol and DHEA after multiple WBC sessions) and increased catecholamine secretion in response to exposure, indicating activation of the sympathetic-endocrine axis (Lombardi et al., 2017).

In addition, molecular studies indicate that repeated exposure to extremely low temperatures modifies the expression of genes involved in the regulation of oxidative stress and inflammatory response (e.g., increased expression of genes modulating antioxidant mechanisms and changes in inflammatory signaling regulators), which is consistent with the concept of adaptive adjustment of the immune system after a series of treatments. At the same time, the extent and direction of these effects depend on the parameters of the protocol (number of sessions, temperature, exposure time) and the training status of the participants (Kusmierczyk et al., 2024b).

3.3 Redox balance and myokines

Cryotherapy affects the redox balance and myokine profile (e.g., irisin), which may be important for metabolism and tissue regeneration. However, the link between changes in myokines and long-term training adaptation remains poorly documented and requires translational research (Lombardi et al., 2017).

4. Practical implications for coaches and practitioners

4.1 Prioritization of interventions

- Rapid recovery between sessions: CWI (10–15 min at 5–10°C) is useful for rapidly reducing DOMS and improving comfort, which may allow for more frequent training sessions (Wang et al., 2025; Xiao et al., 2023).

- Anti-inflammatory treatment and adaptations: multi-session WBC may support inflammatory regulation during periods of high load accumulation (Kusmierczyk et al., 2024b; Zembron-Łacny et al., 2020).

4.2 Personalization and monitoring

Interventions should be personalized - monitor subjective readiness, basic blood markers (e.g., CK) at selected points, and response to repeated treatments. The introduction of protocols documenting parameters (time, temperature, timing) will facilitate optimization in an individual context (Bouzigon et al., 2021; Legrand et al., 2023).

5. Summary of the discussion

In summary, evidence indicates that cryotherapy - both CWI and WBC - has potential applications in sports practice, but its use must be informed and tailored to the goal: CWI as a rapid tool for local recovery, WBC as part of a broader systemic strategy during periods of high load accumulation. Personalization, standardization of protocols, and further translational research are essential to fully exploit the potential of these interventions while minimizing risks and protecting training adaptations.

Strenghts and weaknesses of the research

Strengths

The literature review on cryotherapy in physically active individuals has several important strengths. First, in recent years, there has been an increase in the number of studies with robust methodologies, including meta-analyses, systematic reviews, and position papers, which improves the evidence base and allows for practical conclusions to be drawn (Azevedo et al., 2022; Xiao et al., 2023; Bouzigon et al., 2021).

Second, direct comparisons of different cryotherapy modalities (e.g., CWI vs. WBC/partial-body cryotherapy) and synthetic studies are available, allowing for an assessment of the relative benefits of each method and their mechanisms (Hohenauer et al., 2018; Qu et al., 2020; Feng et al., 2024).

Third, there is a growing number of studies conducted in athletic populations (including studies involving athletes and adolescents), which increases the clinical relevance of the results to training realities (Huang et al., 2024; Batista et al., 2024). In addition, the development of translational research on molecular and immunological mechanisms provides valuable explanations for the observed effects (Kusmierczyk et al., 2024b; Zembron-Łacny et al., 2020).

Finally, the literature often includes the analysis of key biomarkers (CK, IL-6, CRP, oxidative markers), which allows laboratory data to be combined with functional and subjective outcomes (Azevedo et al., 2022; Wang et al., 2025; Xiao et al., 2023).

Weaknesses

Despite progress, there are several significant limitations. The most important is the heterogeneity of protocols - differences in temperature, exposure time, immersion depth, and WBC chamber parameters make comparisons between studies difficult and limit the ability to formulate universal recommendations (Azevedo et al., 2022; Chen et al., 2024).

A second limitation is the often small sample sizes, especially in studies involving elite athletes, which reduces statistical power and limits generalizations (Huang et al., 2024; Qu et al., 2020).

The third problem is the short observation period in most studies - measurements up to 24–72 hours after the intervention predominate; there is a lack of studies evaluating the impact of cryotherapy on long-term training and seasonal adaptations (Haq et al., 2022b; Lombardi et al., 2017).

The fourth weakness is insufficient consideration of individual variability (gender, age, hormonal status, previous experience with cold). Although some studies address these issues, there is still a lack of sufficient research focused on women or young groups of athletes (Batista et al., 2024; Kusmierczyk et al., 2024a).

The fifth limitation is inconsistent reporting of intervention timing - many studies do not precisely document the time between the end of exercise and the application of cryotherapy, while timing is critical for effectiveness (Haq et al., 2022b; Arc-Chagnaud et al., 2024).

Finally, technological differences between WBC/PBC devices (chamber generations, air parameters, cooling dynamics) make it difficult to compare effects between centers and may contribute to intra- and inter-study variability in results (Legrand et al., 2023; Allan et al., 2022).

Future Directions

Despite significant progress in cryotherapy research, the current state of knowledge leaves a number of important questions that require further investigation. Based on the analyzed literature, several key research directions can be identified that will allow for a better understanding of the mechanisms of action of CWI and WBC, their impact on training adaptation, and ways to optimize the use of these interventions in sports practice.

1. Standardization of cryotherapy protocols

One of the main problems remains the heterogeneity of the protocols used, including temperature, exposure time, number of sessions, timing of application, and device parameters. The lack of standardization makes it difficult to compare studies and develop uniform recommendations. Future research should:

develop reference protocols for CWI and WBC,

compare parameters such as temperature, exposure time, session frequency, and timing of intervention under strictly controlled conditions,

conduct randomized trials with full reporting of protocols

Standardization will enable greater consistency in the literature and the creation of practical recommendations for various disciplines.

2. Research on the long-term effects of cryotherapy

Most available studies evaluate effects in the short term (24-72 hours after exercise). Few studies analyze the impact of cryotherapy on:

strength and endurance adaptation,

structural or molecular changes in tissues,

resistance to repeated muscle damage,

long-term functioning of the immune and endocrine systems,

training readiness on a micro- and macrocycle scale.

Studies of this type are extremely important because they can explain whether cryotherapy supports, remains neutral, or potentially inhibits training adaptations

3. Molecular mechanisms and individual reactivity

The literature points to significant molecular, immunological, and oxidative changes caused by repeated exposure to cold, including modulation of gene expression related to inflammatory response, oxidative stress, and cell adhesion, but their scope, stability, and impact on functional training outcomes remain poorly understood. Future research should include:

proteomic, metabolomic, and transcriptomic studies,

analysis of the role of myokines and cytokine interactions with the neurohormonal system,

exploration of genetic and environmental factors that differentiate the response,

identification of “responders” and “non-responders” profiles.

This will allow for the creation of more personalized and precise cryotherapy protocols.

4. Studies involving elite athletes, women, and young people

There is still a lack of sufficient studies involving:

top-level athletes

women, especially with analysis of the impact of the hormonal cycle

young athletes

older people who train regularly.

It is essential to include these populations as they may exhibit different physiological response profiles to cold exposure.

5. The impact of cryotherapy timing on exercise adaptation

The results of available studies indicate that the timing of the intervention is crucial for its effectiveness - immediate interventions may produce different effects than delayed ones.

Future work should systematically compare:

immediate vs. delayed cryotherapy,

interventions used between sets vs. interventions used after a full day of training,
cryotherapy used in the evening vs. in the morning,
peri-exercise cryotherapy (pre- vs. post-workout).

This will allow for a better determination of when cryotherapy supports recovery and when it may affect the adaptability of loads.

6. Safety and technological standards

Although studies show that WBC is generally safe when participants are properly qualified, there are still gaps in knowledge regarding:

the effects of very low temperatures on people with subclinical vascular or metabolic disorders,
differences in response depending on the design and technical parameters of cryogenic chambers,
potential long-term effects of frequent exposure to extreme cold,
safety in populations of young athletes and women.

It is also necessary to standardize WBC equipment and exposure parameters, as emphasized by historical analyses of the development of cryotherapy technologies.

7. Modality comparisons and integration with other recovery strategies

Future research should develop direct comparisons of different forms of cryotherapy ("head-to-head"):
CWI vs. WBC vs. PBC vs. hydrotherapy
comparisons depending on the type of exercise (eccentric, interval, endurance).
In addition, it is necessary to analyze potential synergies with other recovery strategies:
- active recovery,
- compression therapies,
- massage,
- supplementation and nutrition,
- sleep optimization, which already shows a correlation with the use of cryostimulation.

Integrating methods may prove more effective than using one form in isolation.

8. Translational research and practical recovery models

Research is needed that:
reflects realistic conditions of club micro- and macrocycles,
analyzes the logistics of implementing cryotherapy (time, costs, equipment availability),
assess the impact of interventions on seasonal training readiness and start regeneration,
combine objective indicators (power, HRV, biomarkers) with subjective perceptions of fatigue and readiness (RPE, POMS).

Translational research is crucial for the creation of practical decision-making tools and implementation models in sport.

Conclusions

This review indicates that cryotherapy - in particular cold-water immersion (CWI) and whole-body cryotherapy (WBC) - is an important element of recovery strategies used by physically active individuals. The most consistently confirmed effect of CWI is the reduction of delayed onset muscle soreness (DOMS) and improvement in the subjective feeling of recovery, as demonstrated in numerous meta-analyses and experimental studies. Some studies have also observed faster normalization of certain biomarkers, although the results in this area are varied and depend on temperature, exposure time, and exercise intensity. WBC, on the other hand, has a stronger systemic effect, including modulation of inflammatory, oxidative, and neurohormonal responses, especially in multi-session protocols. These changes include, among others, a reduction in pro-inflammatory markers, an improvement in the antioxidant profile, and adaptations at the level of gene expression. During periods of high load accumulation, this can support physiological stability and training readiness.

Although neither modality leads to an immediate improvement in exercise capacity above baseline, both can indirectly support the maintenance of training quality by reducing pain, fatigue, and the negative effects of intense exercise. In sports practice, this means not so much an increase in performance in the short term, but rather the creation of conditions conducive to the effective implementation of subsequent training units and maintaining high availability for work.

The choice between CWI and WBC should depend on the nature of the effort, the time available for recovery, the expected physiological response, and the individual reactivity of the athlete. Current literature clearly emphasizes that there is no single universal cryotherapy protocol - the effectiveness of the intervention

depends on the parameters of the treatment, the timing in relation to the effort, as well as the level of training and individual characteristics of the user. This requires a personalized approach and integration with other wellness strategies, such as sleep, nutrition, compression, and active recovery.

In summary, cryotherapy remains a valuable tool to aid recovery in sports, but its effectiveness depends on conscious, precise, and individualized use. Deepening our knowledge of its mechanisms of action and developing detailed, practical recommendations will allow us to fully exploit its potential as an element of training support and health protection for athletes in the future.

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