

The low-temperature effect on sports regeneration

O efeito da baixa temperatura na regeneração esportiva

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Abstract

Introduction: Intense physical activity and increased exercise significantly reduce the body's adaptive capacity, negatively affect the recovery processes of athletes, and can significantly impair athletic performance. **Objective:** To identify how low temperatures can affect the regenerative processes in athletes, assess the effectiveness and feasibility of cold therapy in sports, and identify the key parameters that determine the effectiveness of the stated recovery method. **Methods:** A systematic review of studies related to the use of cold therapy in sports guided by the Cochrane Handbook for Systematic Reviews of Interventions, and reported through the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. The scientific material was selected by finding keywords and phrases, including "the effect of cold on athletes", "athletes' recovery", "cold therapy", etc. Following the selection criteria, only 30 studies were included. **Results:** Cold exposure has significant benefits for sports regeneration, including pain relief (100%), inflammation reduction (93%), and restoration of sprint capabilities (89%). However, its impact on muscle strength (33%), endurance (11%), and lactate reduction (8%) is more limited. It moderately improves the psycho-emotional state (65-75%). **Conclusion:** The use of low temperatures in sports has a beneficial effect on the recovery of sports performance for at least 24 hours after intense physical activity (training).

Keywords: Athlete. Cold therapy. Cooling. Physical activity. Thermoregulation.

Resumo

Introdução: *A atividade física intensa e o aumento do exercício reduzem significativamente a capacidade de adaptação do organismo, afetam negativamente os processos de recuperação dos atletas e podem prejudicar significativamente o desempenho atlético.* ***Objetivo:*** *Identificar como as baixas temperaturas podem afetar os processos regenerativos dos atletas, avaliar a eficácia e a viabilidade da terapia pelo frio no esorte e identificar os parâmetros-chave que determinam a eficácia do método de recuperação indicado.* ***Métodos:*** *Revisão sistemática de estudos relacionados com a utilização da terapia pelo frio no esporte, orientada pelo Manual Cochrane para Revisões Sistemáticas de Intervenções e reportada através dos* Preferred Reporting Items for Systematic Reviews and Meta-Analyses*. O material científico foi selecionado através da pesquisa de palavras-chave e frases, incluindo "o efeito do frio nos atletas", "recuperação dos atletas", "terapia pelo frio", etc. Seguindo os critérios de seleção, foram incluídos apenas 30 estudos.* ***Resultados:*** *A exposição ao frio tem benefícios significativos para a regeneração esportiva, incluindo o alívio da dor (100%), redução da inflamação (93%) e restauração das capacidades de sprint (89%). No entanto, o seu impacto na força muscular (33%), na resistência (11%) e na redução do lactato (8%) é mais limitado. Há uma melhora moderada sobre o estado psico-emocional (65-75%).* ***Conclusão:*** *A utilização de baixas temperaturas no esporte tem um efeito benéfico na recuperação do desempenho esportivo durante pelo menos 24 horas após uma atividade física intensa (treino).*

Palavras-chave: *Atleta. Terapia pelo frio. Arrefecimento. Atividade física. Termorregulação.*

Introduction

One of the most pressing problems for athletes today is overload and fatigue. When an athlete reaches a state of overtraining, certain changes occur in the body (in particular, metabolism changes). Therefore, when the interval between training sessions is short, the athlete is unable to recover, ensure normal muscle recovery, and maintain their performance. It is in this case that the problem of ensuring the fastest and most effective recovery of the body becomes relevant. It should be noted that incomplete or insufficient recovery of the body may cause the athlete difficulties in performing the usual exercises or other physical activity. As a result, this can lead to an increased risk of injury, deterioration of the athlete's performance, and the need for long-term muscle recovery.[1]

During high-intensity exercise, an athlete runs the risk of muscle damage or tearing. Therefore, to achieve maximum results during training without damaging the muscles, it is necessary to ensure the fastest possible recovery of the entire body and muscle tissue. Currently, there are many recovery strategies aimed at improving adaptive performance, accelerating the body's recovery processes after intense physical activity, and normalizing metabolic processes in both muscles and the entire body. However, to date, no officially registered method of athletes' recovery has been recognized as effective under a certain degree of load for a particular group of athletes.[2]

The use of cold (most often, immersion in cold water or simply the use of cold water) is a popular method for sports recovery. Bouzigon et al.[3] note that the use of cold or low temperatures can have a beneficial effect on muscle condition (reducing stiffness caused by overstrain), reducing fatigue and restoring sports performance to normal values. However, it is not specified which sports characteristics were restored, so it is inappropriate to judge the reliability of such data.

The effect of low temperatures on the body has long been used in sports medicine to relieve pain and suppress inflammation.[4] However, cold exposure is not limited and can affect other regenerative processes in athletes' bodies. Pawłowska et al.[5,6] monitored the inflammatory process in athletes immediately after training. The results of both studies showed that even a 3-minute cold exposure can significantly affect the level of inflammatory markers, minimizing the inflammatory process. Therefore, this method of regeneration is appropriate for use among athletes.

Poppendieck et al.[7] demonstrated that post-exercise cooling has a significant impact on athletes' ability to maintain speed performance, but the impact on strength and endurance is negligible. Klich et al.[8] exposed the trained lower limbs to a 5-minute cold bath (5 °C); the pain threshold of the participants became significantly higher compared to the values recorded immediately after training. In addition, the authors noted an improvement in sprinting performance among athletes.[8] The explanation for these results is the study by Kowalski and Lubkowska,[9] who found that under the influence of low temperatures (immediately after exercise), the decrease in lactate concentration in the athlete's body is slightly accelerated. Such data may indicate the effectiveness of the recovery method used.[9]

Another study shows that low temperatures do not have a beneficial effect on recovery, and cold only provides an analgesic effect.[10] In addition, the study noted that the use of low temperatures in the range of 11 to 15 °C during the first hour after exercise can significantly reduce muscle soreness and promote faster recovery. It should be noted that the temperature range may be individual, depending on the individual characteristics of each athlete. In general, the temperature range varies from 0 to 10-15 degrees.[10]

It is important to note that in addition to the use of cold as a way to improve athletes' condition, there are several different recovery strategies. These strategies include active recovery through light aerobic exercise, the use of compression garments to improve circulation, and proper nutrition to replenish glycogen stores and repair tissue. Hydrotherapy, massage, stretching, and flexibility exercises are also used to promote muscle relaxation and reduce soreness.

In addition, optimizing sleep, using foam massage and self-myofascial release, as well as mindfulness and relaxation techniques help manage stress and support the body's recovery processes. Electrotherapy methods such as TENS and EMS are used to reduce pain and improve blood circulation. Cryotherapy, intermittent pneumatic compression, and other recovery techniques such as cold exposure are also used to reduce inflammation and promote recovery.

To identify the mechanism of influence of low temperatures on the recovery process in athletes, the condition of athletes and their certain indicators (e.g., fatigue level, muscle strength, performance after performing high-intensity exercises, etc) and overall state was analysed. The research aims to analyze and evaluate the existing scientific data, focusing on the use of low temperatures to recover athletes after intense physical activity. That is, it is necessary to determine the degree of safety and effectiveness of this method for the recovery of athletes after intense physical activity.

Methods

This study is a systematic review on the use of cold therapy in sports is in line with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The study question in this research is: "How do low temperatures affect the regenerative processes in athletes, what is the effectiveness and feasibility of cold therapy in sports, and what are the key parameters that determine the effectiveness of this recovery method?"

Several search engines were used to find the necessary medical literature and research materials, including BASE, Google Scholar, and Semantic Scholar. The systematic search was also done in the following scientific databases: Medline (search conducted via PubMed), MedlinePlus, EMBASE, Scopus, and NCBI (National Centre for Biotechnological Information). It should be noted that this study included research materials from the last 20 years (i.e., from 2003 to 2023). The selected scientific material was aimed at substantiating the relevance of the use of cold therapy in sports, justifying the effectiveness of the use of low temperatures and explaining the mechanism of action of this method, substantiating the not yet fully studied practical aspects of the cold recovery method and explaining the specific changes that occur in the body under the influence of cold, identifying the effect on blood biochemical parameters (e.g., creatine kinase) and forming certain assumptions about the increase or decrease in the effectiveness of cold therapy.

The scientific material was selected by finding keywords and phrases, including: "cold in sports", "low temperatures in sports", "the effect of cold on athletes", "athletes' recovery", "sports regeneration", "cold therapy", "recovery in football players", "methods of athletes' recovery", "the effect of cold on muscles", "muscle recovery", etc. This study included only those scientific papers that contained information on the direct effect of cold on athletes, as well as containing a practical aspect of the use of low temperatures in sports (empirical research) or a theoretical description or meta-analysis and the presence of certain scientific hypotheses following the stated topic. It should be noted that the study could also include the sources listed in the references of the selected studies, as they fully or partially coincided with this topic. The search results were imported into EndNote and duplicates were removed. Two independent reviewers screened the titles, abstracts, and full texts against the inclusion criteria: (1) experimental studies involving cold exposure interventions for sports recovery, (2) participants were athletes or physically active adults, (3) outcome measures included indicators of sports performance, muscle damage, soreness, or inflammation. Review articles, conference abstracts, case studies, and non-English studies were excluded.

The risk of bias was assessed for the final included studies using the Cochrane Collaboration's tool, which examines sources of bias in randomized trials across areas like randomization, blinding, attrition, selective reporting, and other aspects.

Results and discussion

In line with the PRISMA flow diagram, a total of 127 studies were initially identified from Medline, MedlinePlus, EMBASE, Scopus, and NCBI databases for analysis (Figure 1). As the review progressed, duplicates were removed, resulting in 118 unique articles that were screened. Forty-three of these were immediately excluded due to reasons such as being off-topic, having methodological inconsistencies, or simply not fitting the scope of the review. This led to a closer inspection of 75 articles. The subsequent assessment of the remaining 75 full articles based on stricter eligibility criteria led to the exclusion of 45 more studies. The reasons for this further exclusion encompassed issues like lack of controls, outdated data, and non-peer-reviewed status.

Following the selection criteria, only 30 studies were chosen for systematic review and are presented in Table 1. It should be noted that the results of this study are limited, as the study did not consider the full range of sports performance (e.g., flexibility), and did not consider such individual factors as sleep time and quality, nutrition, etc. However, these factors can have a significant impact on the level of muscle damage and the outcome of recovery in general.

Thermoregulation is a key process for athletes during intense training. For a long time, sports medicine specialists have not been interested in the mechanism of action and certain features of thermoregulation that can fully affect an athlete during both training and recovery. It should be noted that thermoregulation affects not only the creation of thermal energy during exercise but also the relationship between overheating and cooling or heat and cold. In addition, thermoregulation has a direct impact on several sports' performance indicators.

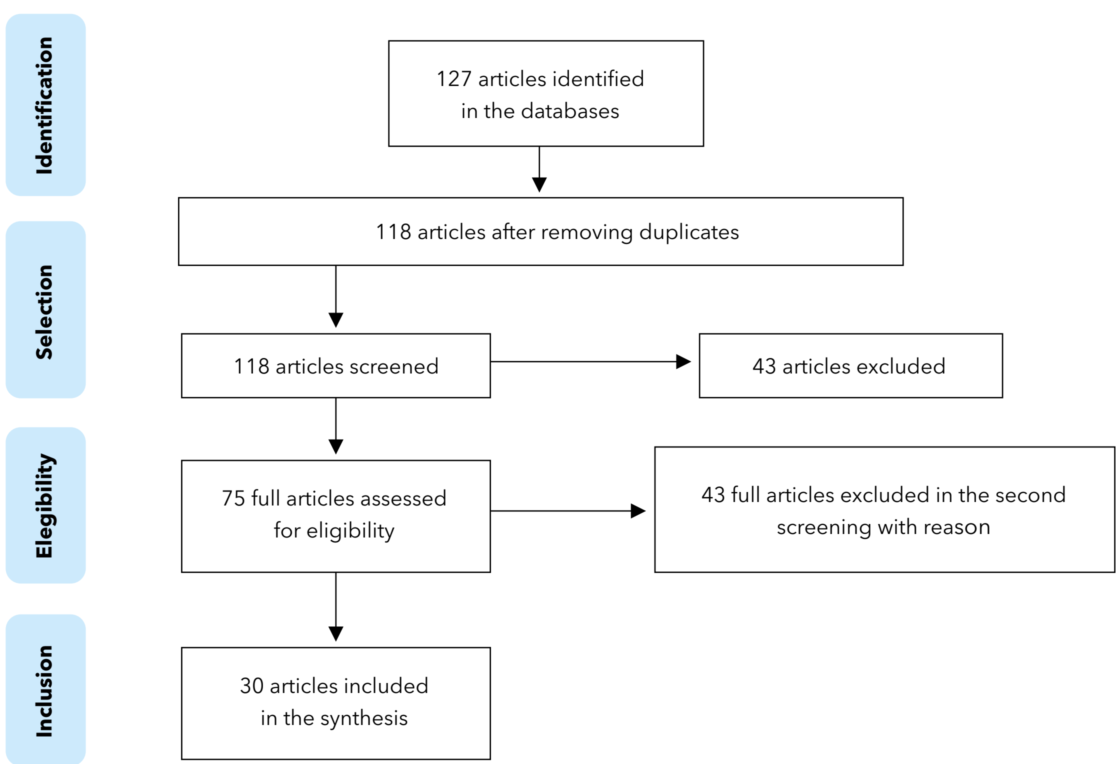

Figure 1 - Flowchart of study identification, assessment, exclusion, and inclusion.

Table 1 - Studies selected to integrate the systematic review

Article	Study methods	Results description
Lubkowska and Knyszyńska, 2023[2]	14 football players underwent PBC after a match. Thermographic analyses were performed before and after the treatment. Serum evaluations of CK, LDH, and AST were done before, directly after, and 24, 48, and 72h after the match.	Significant decrease in skin temperature in all analyzed areas post-PBC. Greatest temperature drops in thighs and smallest in the back and chest areas. Changes in CK and AST suggest a beneficial effect of PBC on post-workout regeneration.
Bouzigon et al., 2021[3]	Review paper on whole-body cryotherapy/ cryostimulation (WBC).	The application of cold or low temperatures can elicit favorable physiological adaptations in skeletal muscle tissue. Specifically, cryotherapy may improve muscle recovery, reduce exercise-induced muscle damage, and potentially enhance subsequent athletic performance.
Petersen and Fyfe, 2021[4]	Review on effects of post-exercise cold-water immersion (CWI) on physiological adaptations to resistance training and underlying mechanisms in skeletal muscle.	CWI can attenuate physiological adaptations to resistance training, but doesn't influence endurance training adaptations. CWI may hinder activation of anabolic signaling pathways and muscle protein synthesis.
Pawłowska et al., 2021[5]	22 male volunteers performed a 30 min submaximal aerobic exercise, followed by a 20 min rest at room temperature (RT-REST) or with a 3 min 8 °C water bath (CWI-REST). Blood samples were analyzed for various inflammatory markers.	IL-6, IL-10, and TNF-α levels and AAT activity increased significantly post-exercise. IL-6 was higher after CWI-REST than RT-REST. No changes in lysosomal enzymes were observed. Limited effect of 3 min CWI on post-exercise inflammatory markers.
Pawłowska et al., 2022[6]	45 male volunteers took part in two experiments: CWI (Experiment I) and a sauna bath (Experiment II). Blood samples were taken pre-exercise, post-exercise, and post-regeneration, analyzing indicators of inflammation and oxidative damage.	CWI was more effective than a sauna bath in reducing the post-exercise inflammatory response. A single sauna bath may cause proteolytic tissue damage. Disturbances were less pronounced in regular cold-water bath users.
Poppendieck et al., 2013[7]	Literature search of 21 randomized controlled trials addressing effects of cooling on performance recovery in trained athletes.	Largest average effect size for sprint performance. Effects most pronounced 96 h after exercise. Effects after endurance training larger than after strength-based exercise. Whole-body immersion more effective.
Klich et al., 2018[8]	12 elite sprint track cyclists studied after anaerobic power training. PPT measurements made on dominant leg at various times post-training.	PPT for anterior thigh muscles increased significantly 1 h after CWI. In posterior thigh muscles, PPT increased 1h and 12h after CWI.
Kowalski and Lubkowska, 2022[9]	Each participant performed an exercise test twice, once with a passive recovery period, and the second time with cold water immersion after exercise. Each time before the test, immediately after and at 3, 6 and 9 minutes after exercise, the concentration of lactate in the capillary blood was measured.	Faster reduction of lactate concentration with cold water immersion post-exercise. Suggests effectiveness in restoring physical fitness in post-exercise recovery.
Moore et al., 2022[10]	A systematic search was conducted in September 2021 using Medline, SPORTDiscus, Scopus, Web of Science, Cochrane Library, EmCare, and Embase databases. Studies were included if they were peer-reviewed and published in English, included participants who were involved in sport or deemed physically active, compared CWI with passive recovery methods following an acute bout of strenuous exercise and included athletic performance, athlete perception, and CK outcome measures. Studies were divided into two strenuous exercise subgroups: eccentric exercise and high-intensity exercise. Random effects meta-analyses were used to determine standardized mean differences (SMD) with 95% confidence intervals. Meta-regression analyses were completed with water temperature and exposure durations as continuous moderator variables.	CWI improved the recovery of muscular power 24 h after eccentric exercise (SMD 0.34 [95% CI 0.06-0.62]) and after high-intensity exercise (SMD 0.22 [95% CI 0.004-0.43]), and reduced serum CK (SMD - 0.85 [95% CI - 1.61 to - 0.08]) 24 h after high-intensity exercise. CWI also improved muscle soreness (SMD - 0.89 [95% CI - 1.48 to - 0.29]) and perceived feelings of recovery (SMD 0.66 [95% CI 0.29-1.03]) 24 h after high-intensity exercise. No significant influence on the recovery of strength performance following either eccentric or high-intensity exercise. Meta-regression indicated that shorter time and lower temperatures were related to the largest beneficial effects on serum CK (duration and temperature dose effects) and endurance performance (duration dose effects only) after high-intensity exercise.
Kruger et al., 2015[11]	11 endurance athletes tested with high-intensity running followed by rest with either 3 min of whole-body exposure to -110 °C or a placebo.	Difference in tlim between initial run and after recovery was lower with WBC. During post-recovery run, TSI was higher in WBC, while VO_2, HR, and RPE were lower.

Table 1 - Studies selected to integrate the systematic review (continued)

Article	Study methods	Results description
Egana et al., 2020[12]	Ten male team-sport players underwent 3 IST protocols separated by either passive rest, 5-min CWI, or 2.5-min CWI.	In the passive rest trial, total work and peak power were lower in the second half. This was not observed following CWI protocols. Tcore was lower in the second half after both CWI protocols.
Espeland et al., 2022[13]	Multiple database survey on effects of voluntary CWI in humans. 104 studies deemed relevant after filtering.	CWI seems to have protective effects against several diseases. Some studies indicate beneficial health effects from voluntary CWI. Conclusions are still debated.
Siqueira et al., 2018[14]	30 active males assigned to control or CWI group. CWI group had immersions post-exercise and every 24h for 72h. Multiple parameters assessed at various times post-EIMD.	Muscle thickness returned to baseline at 24h in CWI group and was lower than control. DOMS returned to baseline at 168h for CWI group. Greater CK peak in the control group. CWI attenuated muscle damage.
Xiao et al., 2023[15]	Systematic review and meta-analysis on the effect of CWI on fatigue recovery after high-intensity exercise. 20 studies included.	CWI significantly reduced DOMS and perceived exertion at 0h, lowered CMJ at 0h, reduced CK at 24h, and reduced lactate at 24 and 48h. No effect on CRP and IL-6. Cold water immersion recommended post-exercise.
Argus et al., 2017[16]	13 men underwent perceptual (fatigue, soreness) and performance measures (MVC of knee extensors, countermovement jumps) before and after training. Post-training, subjects underwent CWI, CWT, or passive sitting (CON) recovery strategies. Measures were reassessed immediately, 2h, and 4h post-recovery.	Peak torque during MVC and jump performance significantly decreased after resistance training in all conditions and remained depressed for 4h. Neither CWI nor CWT affected perceptual or performance measures over 4h.
Babak et al., 2021[17]	20 young men with no CWI experience had their output power and RSADec measured. After a simulated soccer test and blood sampling, they were immersed in 15°C water for 15 min. 24h later, tests were repeated. Subjects were then divided into CWI recovery and passive recovery groups. After four weeks, tests were repeated.	No significant effect of CWI on serum levels of AST and LDH before and after 4 weeks. No difference in power output and RSADec before and after cold water habituation.
Peiffer et al., 2010[18]	10 male cyclists did two bouts of 25-min cycling in hot conditions (35°C, 40% humidity) followed by a 4-km time trial. Bouts were separated by 15 min of seated recovery in the heat or with 5-min CWI. Rectal temperature, cycling economy, VO_2, average power output, and completion times were recorded.	CWI led to a significantly lower rectal temperature before the second bout until its end. Power output was significantly higher with CWI, resulting in a faster completion time. Economy and VO_2 were unaffected by CWI.
Hausswirth et al., 2011[19]	9 well-trained runners did 3 simulated trail runs on a treadmill designed to induce muscle damage. They tested three recovery modalities (WBC, FIR, PAS) in a random order. Muscle damage markers were recorded before, 1h, 24h, and 48h after exercise.	Muscle strength and perceived sensations recovered after the first WBC session, while recovery took 24 h with FIR and wasn't attained with PAS. No differences in plasma CK activity between conditions. WBC sessions within 48 h post-exercise enhanced recovery compared to FIR or PAS.
Kusuma et al., 2021[20]	30 elite athletes did 3 series x 3 sets x12 reps of 85-90%RM workout. Post-exercise, they underwent CWI, CWT, or SS recovery. Body temperature, lactate, cortisol, flexibility, muscle pain, depression, anxiety, and stress were measured.	CWI reduced lactate, cortisol, muscle pain, depression, anxiety, and stress. CWT maintained body temperature. SS increased flexibility. No significant difference in regeneration at 1st, 5th, 10th, and 15th minutes post-manipulation for all methods.
Panyakham et al., 2022[21]	16 male soccer players (18–25 years old) played a 90 min match with a 15-min halftime. They were divided into CG and CWI groups. Blood samples were taken to measure IL-6, creatine kinase, and lactic acid before the match, after the first half, after halftime, post-match, and 24 h post-match.	CWI during halftime decreased lactic acid levels and slowed down muscle fatigue. Muscle pain perception significantly decreased in the CG. No changes in IL-6, creatine kinase, and lactic acid between groups. CWI during halftime can be an alternative recovery method.
Poppendieck et al., 2020[22]	Randomized crossover design with 11 participants performing two 8-week training periods with cooling or passive sitting after each session. Measurements included leg press 1-repetition maximum, countermovement jump, leg circumference, and muscle thickness.	Cooling had small and negligible negative effects on 1-repetition maximum and countermovement jump immediately after training and moderate negative effects when comparing pre-training to follow-up. Cooling had a large negative effect on muscle thickness.

Table 1 - Studies selected to integrate the systematic review (continued)

Article	Study methods	Results description
Roberts et al., 2014[23]	Randomized crossover design with 10 physically active men performing high-intensity resistance exercise followed by either 10 min of cold water immersion (CWI) at 10°C or 10 min of active recovery (low-intensity cycling). Measurements included jump height, isometric squat strength, intramuscular temperature, venous blood samples for markers of metabolism, and muscle damage.	CWI did not enhance recovery of maximal muscle function but allowed participants to lift a greater load during submaximal muscle function test immediately after CWI compared to active recovery.
Pointon et al., 2012[24]	Ten male team-sport athletes performed intermittent-sprint exercise in the heat followed by either 20-min cold water immersion (CWI) or passive recovery. Measurements included neuromuscular function, muscle soreness, blood markers for muscle damage, core temperature, heart rate, and other physiological parameters.	CWI accelerated the reduction in thermal and cardiovascular load, improved maximal voluntary contraction (MVC), and central activation immediately and 2-h post-recovery. However, MVC 24h post-recovery was attenuated with CWI.
Abaïdia et al., 2017[25]	Ten physically active men performed eccentric exercise followed by either CWI (10 min at 10°C) or whole-body cryotherapy (WBC) (3 min at -110°C) recovery in a randomized crossover design. Measurements included strength, jump performance, soreness, and perception of recovery before and up to 72 hours after exercise.	CWI showed a moderate benefit for jump performance, reduced soreness at 48 hours, and enhanced perception of recovery at 24 hours post-exercise.
Higgins et al., 2017[26]	A systematic review and meta-analysis of 23 peer-reviewed articles (n = 606) examining hydrotherapy for recovery in team sports.	CWI was found to be beneficial for recovery at 24 hours and 72 hours, whereas contrast water therapy (CWT) was beneficial at 48 hours. Both CWI and CWT improved perceptions of fatigue, but neither was beneficial for perceptions of muscle soreness.
Bongers et al., 2017[27]	A comprehensive overview of current scientific knowledge on pre-cooling, per-cooling, and post-cooling techniques and their effectiveness in maintaining exercise performance in various ambient conditions.	The article discusses the effectiveness of cooling interventions, underlying physiological mechanisms, and practical considerations for the use of different cooling techniques to improve exercise performance in thermally stressful conditions.
Avsiyevich et al., 2013[28]	The study employed morpho-functional measurements and assessments to track the physical development and performance of male adolescents participating in powerlifting. It may have involved data collection and analysis of various physical attributes to tailor training plans based on biological development types.	Use of indices of biological development in training for powerlifting in male adolescents positively affects their results and allows for individualized training plans.
Aghyppo et al., 2021[29]	The research likely involved 40 secondary school students with mild to moderate musculoskeletal disorders. The study may have used a modified Romberg test to assess static balance before and after physical education sessions. The students were divided into groups and subjected to exercises and ball games, with data analysis to evaluate the effects on static balance.	Exercises and ball games in physical education improve the static balance of students with musculoskeletal disorders, especially those with congenital defects.
Fyfe et al., 2019[30]	The study involved 16 male participants who underwent resistance training for 7 weeks, with either CWI or passive recovery after each session. Data were collected on exercise performance, body composition, and molecular responses in skeletal muscle. Muscle fiber cross-sectional area and protein markers were measured, likely using biopsies and biochemical assays.	CWI blunted muscle fiber hypertrophy but not maximal strength after resistance training, suggesting that post-exercise CWI may affect muscle growth.
Getto and Golden, 2013[31]	The study involved 23 NCAA Division I athletes who were divided into three groups for different recovery interventions. Data on perceived muscular soreness, maximum vertical jump height, and 20-meter sprint time were likely collected before and after interventions. Statistical analysis, such as repeated measures ANOVA, was probably used to assess the impact of different recovery methods on the dependent measures.	The study found no significant differences in recovery of speed, power, or perceived soreness among cold-water immersion, active recovery, and passive recovery groups.

Following Krüger et al.,[11] such an indicator as sports endurance requires a lot of thermal energy, which contributes to a greater need for cooling the body to maintain the athlete's initial state. It is estimated that about 75% of the energy produced by the body during exercise cools the body, and 25% provides muscle activity.[12] It is worth noting that the longer the period of physical activity lasts, the more energy is required to maintain thermoregulation, which will ensure muscle function. However, the cooling process can reduce energy consumption to maintain muscle function, which will lead to athlete fatigue and disruption of metabolic and energy processes in the body. Cooling, or cold exposure, increases metabolic rate and energy expenditure as the body works to generate heat to maintain core temperature. It may benefit athletes aiming for weight management or increased calorie burn. However, cold exposure can negatively affect muscle performance, leading to reduced muscle contraction efficiency, power, flexibility, and strength.[10] The effects vary based on exposure duration, intensity, and individual responses. Balancing the advantages and limitations of cooling is crucial for optimizing athlete performance during training and competitions.

Currently, the use of low temperatures in sports is a fairly popular method for athletes' recovery. The effect of cold exposure implies a reduction in muscle pain, regulation of muscle tone (more frequent relaxation/ muscle relaxation), normalization of the humoral system, acceleration of regenerative processes (including muscle), and improvement of the athlete's psycho-emotional state. Another important fact is that low temperatures do not in any way disrupt physiological thermoregulation in the body.[2]

From a physiological point of view, the effect of cold on the human body requires a certain response, which is to maintain normal thermoregulation. Under the influence of low temperatures, the body will experience certain changes, including vasoconstriction, acute increase in peripheral blood flow, shivering, increased blood pressure, etc.[13] However, the present study examined the effect of cooling therapy on the changes that occur in the athlete's body after intense training during the recovery period.

Low temperatures can have significant effects on various physiological and biochemical processes in the human body. Cold exposure increases metabolic rate, leading to higher energy expenditure, while also causing vasoconstriction to conserve heat and maintain core body temperature. This response elevates heart rate and blood pressure, and the body activates thermoregulatory mechanisms like shivering and piloerection. Muscular performance may be negatively impacted, with reduced muscle contraction efficiency, strength, and flexibility.[1]

Moreover, cold exposure can influence the immune system, neurotransmitter release, hormonal changes, and blood chemistry. Short-term cold exposure might enhance certain immune responses and trigger the release of neurotransmitters like norepinephrine, affecting mood and cognitive functions. Changes in hormonal secretion, including cortisol and adrenaline, can also occur. Cellular responses are activated as the body adapts to the low-temperature environment.[2,3]

The method of exposure to low temperatures on the athlete's body is essential. Most often, cold water baths are used, where the temperature ranges from 0 to 10-15 degrees on average. However, the question of the depth of immersion is also important, as different degrees of immersion in cold water will have a completely different effect. Siqueira et al.[14] noted that immersion in cold water up to the level of the iliac crest (i.e., lower limbs only) is effective. This type of low-temperature exposure would be localized, as it would only affect the lower extremities. However, this method can be effective for track and field athletes, football players, and athletes who have at least some lower limb muscles involved in training (pelvic girdle muscles: gluteus maximus, psoas, and other muscles; thigh muscles: quadriceps; medial and posterior muscle groups; lower leg muscles the tibialis and peroneus muscles).

However, other studies have used other levels of submersion, including immersion in cold water to the level of the navel, the middle of the sternum, and the level of the shoulders.[15,16] Therefore, the choice of immersion depth should depend on the trained muscle area and the specifics of the sports activity. In this case, resistance will be exerted directly on the trained muscle, as well as on the areas nearby. Thus, it is likely to achieve maximum recovery.

In addition, individual characteristics are rarely considered, including the age and gender of the athlete, the level of sensitivity to temperature, the level of hardening, the presence of chronic cardiovascular and/ or respiratory diseases, the aspect of winter swimming, etc. It should be noted that previous researchers did not consider the aspect of individual characteristics of athletes, but this factor fully determines the effectiveness of cold therapy and its consequences. Therefore, in further studies, this factor must be addressed.

Babak et al.[17] highly recommend that football coaches consider the use of cold therapy for the recovery of athletes, as according to the researcher, the sprinting ability of players did not decrease (i.e., recovered) at all when low temperatures were used. Moreover, the authors note that the water temperature, the duration of stay in the water and the frequency of the procedure, as well as the intensity of the athletes' training, should be considered. Such data may indicate a purely individual effect of cold therapy on athletes. That is, for some athletes, one short session in the water will be enough, while for others, a 20-minute stay in cold water with short breaks will not be enough. Therefore, such criteria must also be addressed.

This study also examined the effect of low temperatures on aerobic exercise performance. A study by Peiffer et al.[18] showed that participants who used cold therapy had better results compared to participants without cold recovery. In addition, Hausswirth et al.[19] noted that this effect is achieved by reducing muscle pain. That is, the hypothesis is that vasoconstriction will contribute to a significant reduction of oedematous processes in the muscles so that the athlete will not have muscle pain. In addition, the effect on the nervous system will be important, as the feeling of fatigue will be suppressed, because of which the athlete will be able to perform aerobic exercises more effectively.

It should be noted that few previous researchers have examined in detail the effect of low temperatures on the normalization of the psychoemotional state of an athlete. It should also be noted that the psycho-emotional state of an athlete plays a significant role in sports results and achievements. That is, ordinary fatigue can significantly worsen an athlete's physical performance, thereby affecting the outcome of the competition (provided that frequent intense training is due to preparation for the competition). That is why the normalization of the psycho-emotional state is important in the recovery of athletes, and this indicator should be addressed.

However, Kusuma et al.[20] have noted that exposure to low temperatures stimulates cold receptors, which can lead to an antidepressant effect. The authors note that athletes (in particular, those who play professional sports and/or often participate in competitions) are prone to depression and the development of other psychological pathological conditions. It should be noted that depressive states can lead to the inability of an athlete to demonstrate the results achieved during the training period. Therefore, cold therapy may be promising in the prevention of depression in athletes. However, this hypothesis needs to be confirmed and additional studies conducted to investigate this indicator.

The effectiveness of cold therapy in athletes' recovery has been previously reported.[15] Sprinting performance, muscle strength, muscle pain, and certain blood biochemical parameters associated with injury (C-reactive protein, creatine kinase, interleukin-6, lipid hydroperoxide concentration) were evaluated. The results of the study showed that in athletes exposed to low temperatures after training, sprinting performance was restored 24 hours after intense exercise, and the level of creatine kinase in the blood was reduced. The researchers suggested that creatine kinase levels may indicate a reduction in muscle damage.[15] Another study came to similar conclusions.[21] The authors explain these results by the fact that metabolic processes in the muscles may not affect the level of tissue oxygen saturation, which is a key condition for adequate muscle recovery.

Following a study by Poppendieck et al.,[7] the favourable effect of low temperatures was noted only on sprinting performance. In addition, the authors note that cold had almost no or minimal effect on endurance, jumping height, and strength. Following Poppendieck et al.,[7] such results may indicate the effectiveness of cold exposure only under certain conditions (cooling of the whole body after performing sprinting exercises). However, the effect is sufficient to allow an athlete to recover, for example, before a competition. Therefore, for athletes participating in competitions, the use of low temperatures is appropriate and relevant.

In addition, Moore et al.[10] noted that sprinting performance recovered not only after 24 hours but also after 96 hours (i.e., long-term recovery of athletic performance). The study also noted that athletes recovered strength performance and decreased creatine kinase levels within 24-72 hours, as well as reduced muscle pain from 1 to 72 hours after cold exposure. Therefore, such data may indicate that low temperatures do indeed contribute to a faster recovery of various athletic qualities, including sprinting performance.

The effectiveness of cold therapy depends on several parameters, with temperature being a crucial factor. The effectiveness of cold therapy depends on the temperature applied, typically ranging from 0 to 15 degrees Celsius (32 to 59 degrees Fahrenheit), tailored to the individual's condition and treatment objectives.[15] The duration of cold therapy is crucial to avoid potential adverse effects like tissue damage or frostbite and can vary from a few minutes to up to 20-30 minutes. Various methods of application, such as ice packs, cold compresses, ice baths, or cryotherapy chambers, allow for different temperature control and distribution, while the frequency of sessions may vary depending on the specific condition being treated.[21] It is vital to consider an individual's tolerance and comfort level to ensure safe and effective cold therapy implementation.

It should also be realised that both the cooling process and cryotherapy can have different methods. These may include local application of cold, cold-water immersion and general cryotherapy itself, as shown in Table 2.

Table 2 - Comparison of cold therapy methods

Cold therapy method	Application area	Purpose	Temperature range
Local application of cold	Specific body area	Targeted relief for localized injuries	Varied, depending on method
Cold water immersion	Entire body or body part	Post-activity recovery, reduce muscle soreness	10 to 15 °C (50 to 59 °F)
General cryotherapy	Whole body	Reduce inflammation, muscle soreness, well-being	-110 to -166 °C (-166 °F)

Note: The temperature range for local application of cold varies depending on the specific method used, such as ice packs, cold compresses, or cooling gels, and may not have a fixed range. Source: compiled by the authors based on the study results.

To date, human studies have already been conducted to examine the effect of cold or low temperatures on muscle hypertrophy during exercise with or without weights. However, the results are mixed. Poppendieck et al.[22] demonstrated that cold significantly reduces muscle hypertrophy that occurs after exercise with a weight. In addition, the authors noted that none of the participants experienced an increase in muscle strength, which may also indicate the relaxing effect of cold therapy. Roberts et al.[23] also demonstrated a decrease in muscle hypertrophy and a decrease in muscle strength in leg press and knee extension (including isometric strength). However, there are also other results. A study by Moore et al.[10] demonstrated that cold exposure to athletes after high-intensity exercise had a beneficial effect on muscle strength recovery one day after training. In addition, hypertrophy hardly decreased.

It should be noted that such data could be obtained if the exercise was too intense in combination with insufficient exposure to cold (i.e., staying in cold water for a short time). Therefore, the ambiguity of the results is most likely due to insufficient cold exposure. However, there is a certain hypothesis about the lack of influence of cold on strength performance. Hausswirth et al.[19] suggested that cold therapy is not able to completely restrain the inflammatory process in muscle tissue. The author also noted that a decrease in impulse conduction can prevent an athlete from demonstrating maximum results during strength exercises. This hypothesis may be valid, but it needs to be confirmed and further research conducted.

Pointon et al. [24] have suggested that low temperatures do not affect muscle lactate concentrations. Therefore, this may lead to a significant inhibition in the production of the energy required for active muscle activity (this is due to impaired anaerobic glycolysis). This assumption is not yet confirmed, as there is a lot of data showing a significant reduction or complete disappearance of muscle pain, as well as a rapid recovery of muscle strength. However, the results of previous studies are mixed, so it is inappropriate to draw any conclusions. In addition, lactate levels depend on the intensity and time of training, and the process of its removal from the muscles can be affected by several individual characteristics (for example, the level of blood flow in the trained muscle, as well as the metabolic rate, which will affect the transport of lactate into the bloodstream and its transformation into pyruvate).

In addition, the method of applying low temperatures is essential, as the simplest cold exposure can be localized (applying ice directly to the area of an overstressed or even injured muscle), incomplete immersion of the body or only the extremities in cold water (usually from 5-6 to 15-16 degrees Celsius), or full cryotherapy. A study by Abaïdia et al.[25] has shown that regular exposure to cold water is more effective than cryotherapy. The author noted that immersion in 10 °C water had an effect within 24-48 hours. The effect was to restore sprinting performance and significantly reduce pain in the trained muscles. According to Higgins et al.,[26] the use of cold water immediately after intense training helps to reduce fatigue, muscle soreness, sprint performance, neuromuscular recovery, etc. However, the authors also emphasize the recovery methods use and note that cryotherapy is effective in reducing fatigue within 24 hours, and cold water within 72 hours. That is, conventional cold therapy is determined to be more effective than cryotherapy.

In general, the effect of low temperatures on the recovery of physiological and sports performance of athletes can be recognized as effective. Bongers et al.[27] highlighted mechanisms for pre- and per-cooling benefits, a neural safeguard mechanism to terminate exercise, cardiovascular and metabolic mechanisms, psychophysiological mechanisms, and thermoregulatory mechanisms. Table 3 shows the most common expected effects that should be achieved through cold exposure after athletes' training.

Table 3 - Effects of cold exposure on sports regeneration

Effect	Regeneration (%)
Inflammation reduction	93
Pain relief	100
Sprint capabilities restoration	89
Muscle strength restoration	33
Endurance restoration	11
Reduction of the concentration of lactate in the muscles	8
Improvement of psycho-emotional state	65-75

Note: Compiled by the authors based on the study results.

Following the Table 2, in all cases, there was a decrease in pain, and in almost all cases there was a decrease in the inflammatory process and restoration of sprinting characteristics. A lower frequency was observed in the recovery of the psycho-emotional state of athletes. In some cases, it was noted the restoration of muscle strength. Less frequently, recovery of endurance and a decrease in muscle lactate were observed.

In general, the existing and analysed research material on the effect of low temperatures on recovery performance in athletes suggests that this method is effective. Recovery after intense training is of great importance for athletes, especially when training every day or before competitions. Therefore, immersion in cold water promotes certain changes in the body, among which a significant reduction in swelling and pain in the muscles, as well as the restoration of the athlete's psycho-emotional state (reduction of fatigue), are key.

However, most of the studies reviewed had an uncertain risk of systematic error. As a result, the reliability of the results may also be uncertain. The researchers did not always indicate the temperature of the cold water used, the depth of immersion, or the time the athlete spent in the water. In addition, almost no studies reported data on individual or collective immersion. It is known that the individual use of cold therapy is more effective than the group method. This is due to the minimization of the placebo effect that participants can pass on to each other, as well as the athlete's focus on the recovery process (i.e., the result). It should also be noted that the individual use of the recovery method can contribute to a faster recovery of the psycho-emotional state, which can also contribute to a faster overall recovery of the body.

Therefore, to obtain more accurate data on the issues addressed in this study and to improve the methodological quality, it would be advisable to include even more randomized and controlled trials conducted individually with each athlete.

The use of low-temperature treatments for sports regeneration offers several advantages. It provides effective pain relief, reduces inflammation, and improves sprint performance. Additionally, athletes may experience psychological benefits, and swelling in muscles can be reduced, leading to faster recovery.[20,28] Low-temperature treatments are easy to apply through various methods, making them accessible and convenient for athletes.

However, there are considerations to keep in mind. The procedure may have a limited impact on restoring muscle strength and endurance, which could be a drawback for athletes focusing on those aspects. The lack of consensus on optimal protocols and individual variations in response require personalized approaches. There is also a need to be cautious about potential tissue damage with prolonged or extreme cold exposure.[1,2,29]

One of the results of this study was the effect of cold therapy on the sprint performance of athletes. However, there are also controversial points in this issue, as there is still no consensus on the time characteristics of this effect. Krüger et al.[11] note that the recovery of sprinting performance is observed directly after 24 hours. However, there are other opinions about the time frame of this effect. In their study, Fyfe et al.[30] stated that this effect is also observed 48 hours after exposure to low temperatures. Perhaps in the first case (24 hours), the minimum duration of the cold effect was meant. However, such data is only an assumption and will not affect the formation of further conclusions on this issue. In addition, it should be emphasized that there is no data on the methodology for testing sprint performance. It is reasonable to assume that the testing was carried out differently, and that is why the authors are so confident in their results, which are completely different.

Another controversial issue is the lack of data on the optimal time an athlete should spend in cold water to achieve at least a minimum result. In Egaña et al.[12] study, there was a short-term, but not a single cold exposure to the athlete's body (5 sets of 2 minutes, where the interval between sets was 2.5 minutes). However, Getto and Golden[31] noted that the short duration of the cold procedure may be ineffective in terms of muscle relaxation. In addition, incomplete recovery can provoke a deterioration in the athlete's general condition, as mentioned earlier.

It is also necessary to consider the effect of cold on reducing muscle pain. It is known that cold can suppress oedematous processes, reduce pain, and prevent the accumulation of metabolites.[24,32,33] In addition, low temperatures inhibit the production of the neurotransmitter acetylcholine, which also slows down the transmission of nerve impulses. As a result, muscle spasm is significantly reduced. Another important factor under the influence of low temperatures is vasoconstriction. This process also reduces swelling and pain.[15] According to Lateef,[34] when the body or limbs are immersed in cold water, hydrostatic pressure affects the body fluid in the area that is exposed. This is how the author explains the reduction of swelling in trained muscles, as well as the increase in the minute volume of blood circulation. In addition, the greater the depth of immersion, the greater the cardiac output. It is interesting to note that even with such significant changes in cardiovascular activity, energy expenditure remains at the baseline and does not increase.[15,35,36]

In addition, low temperatures have a mixed effect on muscle strength. It is worth noting that the concepts of "muscle strength" and "muscle power" need to be distinguished, as cold has almost no effect on muscle strength recovery, but power does, although not very pronounced.[37,38] Previous researchers have studied this issue in detail and tried to identify the mechanism of the cold's impact on the stated indicators. Babak et al.[17] also concluded that low temperatures could have a favourable effect on isometric strength, as it lacks such important factors as the muscle contraction and relaxation cycle. That is, isometric force is exerted exclusively by tension and depends on the degree of muscle stiffness. However, Kusuma et al.[20] state that a decrease in muscle stiffness can also lead to an increase in dynamic muscle strength (i.e., the strength that requires a contraction-relaxation cycle). Overall, that study demonstrates a slightly beneficial effect on athletes' strength performance. In addition, cold exposure will have a calming effect on the athlete's nervous system, which, in theory, can lead to improved dynamic strength performance.[39,40] However, there is currently insufficient research to generate definitive and unambiguous results on this issue.

In general, the results obtained are fully consistent with the findings of previous researchers. It is worth noting that the differences between the results obtained may be due to several factors, including temperature conditions, depth of immersion and time spent by the athlete in the water; methods of testing athletes (not all authors indicate how the effectiveness of cold exposure was tested), as well as the specifics of sports activities and individual characteristics of the athlete. However, to obtain more accurate data and formulate certain recommendations for improving the effectiveness of the use of low temperatures in sports, it is necessary to continue to conduct research with more accurate data. The study should indicate the specifics, intensity, time and conditions of training, the water temperature used, the depth of immersion and the time spent (in some cases, the number of repeated immersions), the age and gender of the participants and their general condition, the presence of chronic problems with cardiovascular diseases, such as coronary artery disease, hypertension, congestive heart failure, arrhythmias, valvular heart diseases, and cardiomyopathies. In addition, it would be worthwhile to include data on athletes' sleep time and nutritional status. The availability of such data would help to assess the effectiveness of the methods used to restore athletes' performance, as well as contribute to the development of new methods of sports regeneration.

Understanding the potential benefits of cold exposure for recovery can lead to optimized recovery strategies, injury management, and improved psychological well-being. Incorporating cold exposure in athletes' recovery routines may enhance overall performance and reduce fatigue, while individualizing protocols based on specific needs and responses. However, the lack of consensus on optimal parameters underscores the need for evidence-based practices and further research. By promoting effective recovery methods like cold exposure, practitioners can foster a recovery-focused culture, contributing to athletes' overall health and performance in the long term. Further research with controlled trials assessing individual athletes is needed to establish stronger evidence. Key limitations of current research include insufficient controlled studies, lack of statistical data, potential placebo effects, and inadequate accounting for confounding factors. Addressing these limitations in future studies will help develop a more comprehensive understanding of using cold exposure for sports recovery.

Conclusion

This systematic review aimed to evaluate the existing evidence on the use of cold exposure for sports recovery after intense physical activity. The results demonstrate that cold exposure can have beneficial effects on certain aspects of sports recovery, including reduced pain, inflammation, and enhanced sprint performance. However, the impacts on muscle strength, endurance, lactate clearance, and other measures are less conclusive.

Overall, the current body of evidence remains limited, with a lack of high-quality controlled trials. Many studies had uncertain risks of bias, insufficient controls, and inadequate reporting of key parameters like temperature, duration, and depth of cold exposure. There is also a lack of consensus on the optimal protocols for cold exposure to maximize recovery benefits.

Further randomized controlled trials are required to establish stronger evidence, focusing on individual recovery responses and accounting for potential confounding factors. Key limitations that need to be addressed include small sample sizes, potential placebo effects, lack of blinding, and insufficient statistical rigor. Developing standardized procedures and reporting will also enhance the quality of future research. In conclusion, cold exposure holds promise as an effective sports recovery aid, but current evidence is preliminary. High-quality research is needed to provide more definitive conclusions on the impacts of cold exposure on various recovery outcomes for athletes across sports modalities. Optimizing cold exposure protocols based on emerging evidence may help integrate this modality into recovery regimens to improve overall athletic performance.

Authors' contributions

All authors contributed equally in all stages of the study and approved its final version.

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