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MINI-REVIEW

Neuromuscular fatigue management strategies in male semi-professional soccer players: a mini-review

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Abstract

This mini-review aims to examine fatigue management strategies that specifically target neuromuscular fatigue in soccer players. A literature search identified five studies involving male semi-professional players (mean age ranging from 21.8 ± 0.9 to 25 ± 3 years), all of which used a randomized crossover design. One study applied a real competitive match, while four used the Loughborough Intermittent Shuttle Test (LIST) to simulate match demands. Neuromuscular outcomes included maximal voluntary contraction (MVC), voluntary activation (VA), quadriceps potentiated twitch force ($Q_{tw,pot}$), and electromyography (EMG) parameters, including the root mean square (RMS) normalized to the maximal compound muscle action potential (M_{max}) (RMS/M_{max}). This review identifies five potential strategies for managing neuromuscular fatigue: cold water immersion (CWI), phase change material (PCM) garments, ischemic preconditioning (IPC), chronic beetroot juice supplementation (BEET), and acute acetaminophen ingestion (ACT). Preliminary results suggest that CWI and BEET may influence both central and peripheral components, whereas PCM, IPC, and ACT primarily affect markers associated with the central drive at specific assessment intervals. Implementing these strategies may accelerate neuromuscular recovery, attenuate fatigue onset, help maintain force production, and potentially optimize subsequent performance. This mini-review provides preliminary evidence-informed recommendations for the stakeholders in the soccer industry, from players to conditioning coaches, and highlights precautions regarding their potential misapplication or excessive use.

Keywords

Central fatigue; Peripheral fatigue; Therapy; Supplementation; Football

1. Introduction

Soccer is an intermittent high-intensity sport that places considerable physical, physiological, and cognitive demands on its players [1]. During a 90-minute match, athletes typically cover 10–13 km, with approximately 2–3 km performed at high intensity, including sprints, accelerations, decelerations, directional changes, and tackles [2]. These repeated explosive actions impose substantial strain on the neuromuscular system, frequently leading to neuromuscular fatigue that persists beyond the match [3].

Neuromuscular fatigue is defined as a transient reduction in the ability of the muscle to produce force [4]. The etiology of neuropathic pain is multifactorial, with contributions from both central and peripheral mechanisms. Central fatigue is characterized by a reduced capacity of the central nervous system to fully activate the skeletal muscles [5]. In contrast, peripheral fatigue results from disturbances at or distal to the neuromuscular junction, such as impaired excitation–contraction coupling, metabolite accumulation, and structural muscle damage [4]. Evidence from soccer-specific studies confirms that both central and peripheral factors contribute to the fatigue observed during and after competitive or simulated soccer match play [6–8]. Unlike field-based tests, such as countermovement jump height or subjective scales [9], electromyography (EMG) provides a more direct and mechanistic assessment of neuromuscular function, making it a powerful tool for uncovering subtle changes in neural drive and muscle activation that may otherwise remain undetected [10].

Several neuromuscular parameters are commonly assessed to investigate these processes. Maximal voluntary contraction (MVC) is widely used as a global measure of reductions in force-generating capacity [11, 12]. Voluntary activation (VA), derived from the twitch interpolation technique, reflects central motor drive, whereas quadriceps potentiated twitch force ($Q_{tw,pot}$) provides insight into peripheral contractile function [13, 14]. In addition, surface electromyography parameters, such as the root mean square (RMS) amplitude, are used to evaluate motor unit recruitment and the level of neural activation provided by the central nervous system (CNS) [15, 16]. The maximal compound muscle action potential (M_{max}) is frequently measured as an index of neuromuscular transmission integrity [17, 18]. Together, these parameters allow researchers to distinguish between central and peripheral contributions to fatigue and assess the dynamics of recovery.

Prolonged neuromuscular fatigue represents a critical post-match challenge for soccer players. Reductions in MVC, VA, and $Q_{tw,pot}$ have been reported to persist for up to 72 hours following competitive or simulated soccer match play [6, 8]. Given that congested fixture schedules frequently restrict recovery periods to approximately 72 hours, neuromuscular fatigue recovery often remains incomplete. Consequently, residual fatigue occurs in subsequent matches, impairing performance and increasing the risk of injuries [19]. For example, Dupont *et al.* [20] reported a higher injury incidence in professional players exposed to insufficient recovery between successive matches. Moreover, fatigue appears particularly detrimental in the final minutes of each half, a period often decisive for match outcomes [7, 21]. Collectively, these findings underscore the importance of addressing neuromuscular fatigue in soccer players.

Therefore, this mini-review aims to examine strategies applied either pre- or post-matches that specifically target the management of neuromuscular fatigue in soccer. Unlike broad recovery interventions that might address general soreness, our focus is exclusively on interventions with demonstrated efficacy in restoring muscle force-generating capacity and neural drive. By focusing on interventions with clear mechanistic benefits and robust scientific support, this review aims to provide practitioners with practical recommendations for optimizing neuromuscular recovery protocols in soccer.

2. Methods

2.1 Search strategy

A literature search was conducted up to 15 August 2025, in PubMed, Web of Science, and Scopus. The following key terms and Boolean combinations were used: "soccer" OR "football" AND "neuromuscular fatigue" OR "neuromuscular recovery" OR "post-match recovery" AND "electromyography" OR "MVC" OR "voluntary activation" OR "$Q_{tw,pot}$" OR "M_{max}".

2.2 Eligibility criteria

Studies were included if they: (i) investigated recovery strategies in soccer players, defined as interventions applied after a full 90-min match or an exercise protocol designed to replicate the physical and physiological demands of match play, such as The Loughborough Intermittent Shuttle Test (LIST); (ii) examined interventions applied either before exercise (to attenuate fatigue) or after exercise (to accelerate recovery); (iii) reported neuromuscular outcomes such as maximal voluntary contraction (MVC), VA, $Q_{tw,pot}$, and electromyography (EMG) parameters; and (iv) were published in peer-reviewed journals in English.

By stipulating these criteria, we ensured that the recovery strategies discussed in this review specifically targeted real-world soccer contexts and addressed neuromuscular fatigue induced by match play or validated simulations. Moreover, restricting the selection to peer-reviewed publications ensured that the evidence considered was derived from reputable scientific sources.

2.3 Study selection and synthesis

Fig. 1 illustrates the study selection process used in this review. Following database and reference list searches, 6011 records remained after duplicate removal and were screened by title and abstract, resulting in the exclusion of 5876 records. Of the 135 full-text articles assessed for eligibility, 130 were excluded for not meeting the inclusion criteria. Ultimately, five studies were included in this mini-review.

Titles and abstracts were screened independently by two reviewers (MB and OT), followed by a full-text review of potentially eligible articles. Any discrepancies regarding study eligibility were resolved through discussion or consultation with a third senior researcher. Data extraction (*e.g.*, population characteristics, intervention timing, and neuromuscular outcomes) was performed by one reviewer and verified by another. Given the narrative nature of this mini-review, no formal quality assessments were performed. Instead, emphasis has been placed on mechanistic studies with robust experimental designs (*e.g.*, randomized controlled trials, crossover trials, and repeated-measures protocols). Evidence was organized thematically to highlight recovery strategies with demonstrated effects on restoring force-generating capacity and neural activation in the affected muscles.

3. Results

All five studies included in this mini-review were conducted on male semi-professional soccer players, with mean ages ranging from 21 to 25 years. One study applied a real competitive match, whereas the remaining four used the Loughborough Intermittent Shuttle Test (LIST) to simulate match demands. All studies employed randomized crossover designs, with three using double-blinded procedures, as summarized in Table 1 (Ref. [7, 21–24]).

4. Discussion

This mini-review examined five recovery strategies for which preliminary evidence suggests potential benefits in mitigating neuromuscular fatigue in soccer players. By comparing their mechanisms, timing of application, and recovery outcomes (Fig. 2), we highlight the practical value of tailoring recovery protocols to the specific demands of post-match fatigue. It is important to distinguish between the strategies used for recovery (post-match) and those aimed at fatigue attenuation (pre-match). While CWI and PCM focus on post-exercise restoration, IPC and ACT modulate the internal environment prior to the onset of fatigue to preserve neuromuscular integrity during the match.

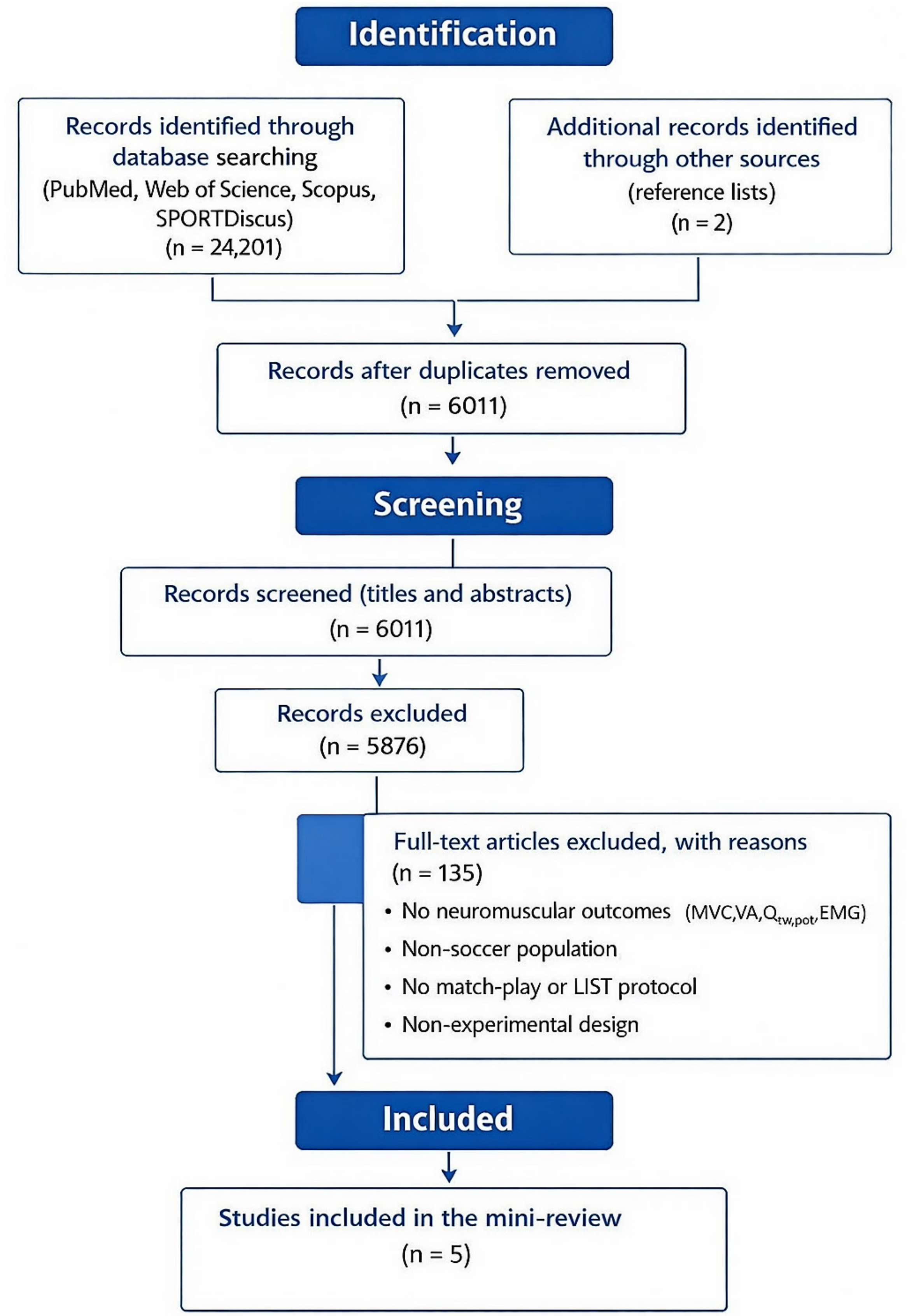

FIGURE 1. Flow diagram of the study selection for the mini-review. MVC: Maximal voluntary contraction; VA: Voluntary activation; $Q_{tw,pot}$: quadriceps potentiated twitch force; EMG: electromyography; LIST: Loughborough Intermittent Shuttle Test.

TABLE 1. Summary of the included studies on which recovery strategy recommendations are based in this mini-review.

Author (year)	Study design	Exercise protocol	Intervention	Participants	Playing level	Age	Neuromuscular measurements	Timing of fatigue assessments
Brownstein *et al.* [22]	Randomized crossover design	Competitive 90-min Soccer match-play	Wearing cooled phase change material garments	11 male Soccer players	Semi-professional (Level 8 of the English Soccer league)	22 ± 1 yr	MVC VA VA_{TMS} $Q_{tw,pot}$ EMG (RMS); TMS-evoked responses (MEP, M_{max}, CSP); Peripheral stimulation ($Q_{tw,pot}$)	Pre-exercise, 24, 48, 72 h post-match
Bouchiba *et al.* [23] (2022)	Randomized crossover design	Simulated Soccer match-play via the LIST	Cold water immersion	12 male Soccer players	Semi-professional (3rd Tunisian national league)	22.9 ± 0.9 yr	MVC VA $Q_{tw,pot}$ EMG (M_{max}, RMS and RMS/M_{max})	Pre-exercise, immediately, 24, 48, and 72 h post-LIST
Daab *et al.* [21] (2024)	Randomized double-blind crossover design	Simulated Soccer match-play via the LIST	Beetroot juice supplementation	13 male Soccer players	Semi-professional (League not specified)*	24 ± 3 yr	MVC VA $Q_{tw,pot}$ EMG (M_{max}, RMS and RMS/M_{max})	Pre-exercise, at half time and immediately post-LIST
Bouchiba *et al.* [24] (2025)	Randomized double-blind crossover design	Simulated Soccer match-play via the LIST	1-g acetaminophen ingestion	13 male Soccer players	Semi-professional (3rd Tunisian national league)	21.8 ± 0.9 yr	MVC VA $Q_{tw,pot}$ EMG (M_{max}, RMS and RMS/M_{max})	Pre-exercise, immediately, 24, 48, and 72 h post-LIST
Daab *et al.* [7] (2025)	Randomized double-blind crossover design	Simulated Soccer match-play via the LIST	Ischemic preconditioning	14 male Soccer players	Semi-professional (League not specified)	25 ± 3 yr	MVC VA $Q_{tw,pot}$ EMG (M_{max}, RMS and RMS/M_{max})	Pre-exercise, at half time and immediately post-LIST

LIST: Loughborough Intermittent Shuttle Test; MVC: Maximal Voluntary Contraction; VA: Voluntary Activation; VA_{TMS}*: Voluntary Activation assessed by Transcranial magnetic stimulation;* $Q_{tw,pot}$*: Quadriceps potentiated twitch force; EMG: Electromyography;* M_{max}*: maximal compound muscle action potential; RMS: Root Mean Square; MEP: motor evoked potential; TMS: Transcranial magnetic stimulation; RMS/*M_{max}*: Root Mean Square normalized to the maximal compound muscle action potential; CSP: Corticospinal Silent Period; *classified as semi-professional as per author statement.*

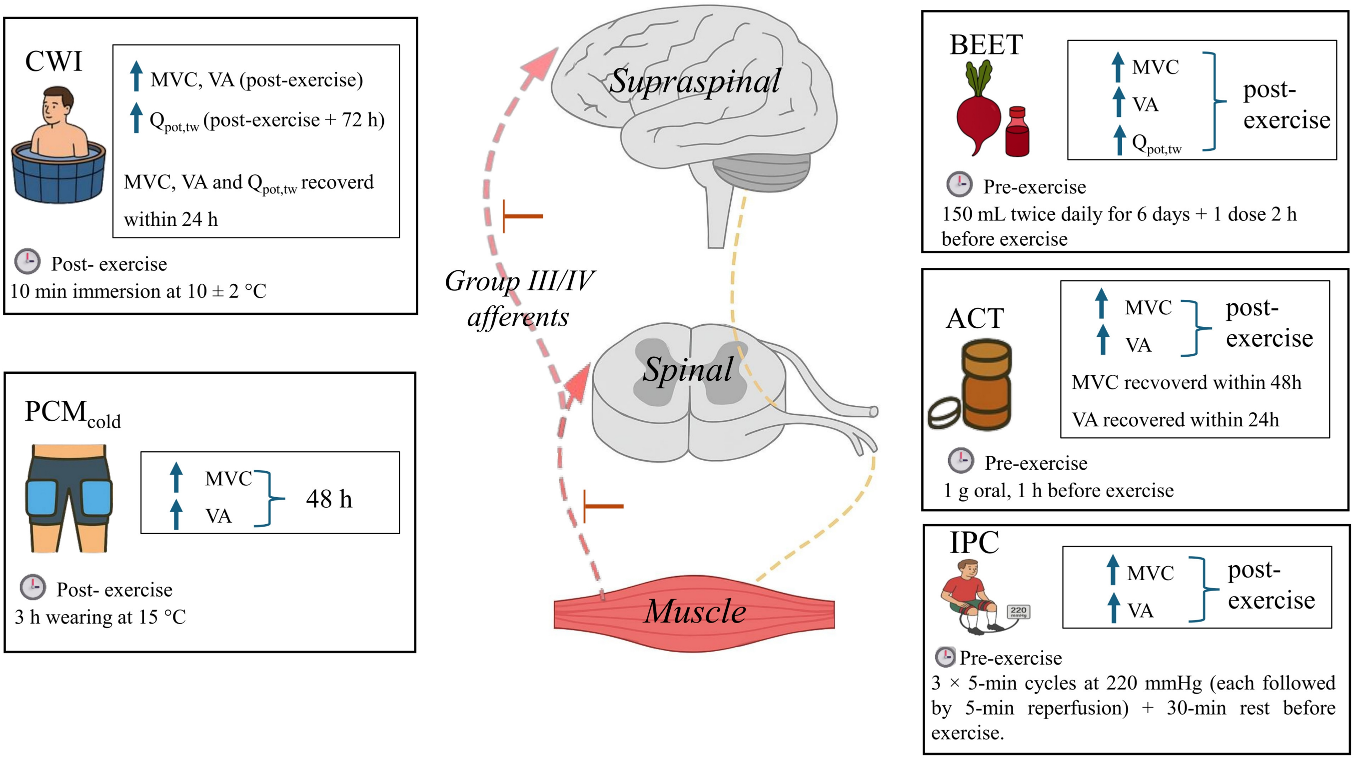

FIGURE 2. Summary of the five recommended evidence-based neuromuscular recovery strategies in soccer. CWI: cold water immersion; PCM$_{cold}$: phase change material cooled; IPC: ischemic preconditioning; BEET: beetroot juice supplementation; ACT: acute acetaminophen ingestion; MVC: maximal voluntary contraction; VA: voluntary activation; Q$_{pot,tw}$ is the same as Q$_{tw,pot}$, both representing quadriceps potentiated twitch force.

4.1 Identified neuromuscular fatigue management strategies

4.1.1 Cold water immersion (CWI)

Bouchiba *et al.* [23] investigated the effects of CWI in 12 semi-professional players after a 90-min simulated soccer match-play. In a randomized crossover design, athletes underwent 10 min of either CWI (10 ± 2 °C) or thermoneutral immersion (TWI, 28 ± 2 °C). Neuromuscular assessments showed that reductions in maximal voluntary contraction (MVC) and VA were attenuated post-exercise in the CWI condition, with both parameters fully restored within 24 h, whereas recovery in the TWI condition was delayed (VA by 48 h and MVC by 72 h). For Q$_{tw,pot}$, reductions were also attenuated post-exercise and at 72 h with CWI, whereas values remained depressed at 72 h under TWI.

The authors noted that M$_{max}$ and RMS/M$_{max}$ were unchanged, indicating preserved sarcolemmal excitability and neuromuscular transmission. The impairment of Q$_{tw,pot}$ was therefore attributed to excitation–contraction coupling disturbances, likely exacerbated by reactive oxygen and nitrogen species (ROS/RNS), which impair Ca^{2+} handling [4]. CWI may have accelerated recovery by attenuating ROS/RNS accumulation and inflammatory processes [25]. CWI also blunted central fatigue, as reflected in the faster restoration of VA. This was interpreted as a reduction in inhibitory feedback from group III/IV muscle afferents, which are activated by muscle damage, soreness, and oxidative stress [26–28]. Supporting this mechanism, plasma lactate dehydrogenase (LDH) was lower after CWI, suggesting reduced muscle disruption and thereby less afferent stimulation. The cooling effect of CWI may also have contributed, as hyperthermia has been associated with impaired central drive [29, 30].

It should be noted that these mechanistic interpretations remain speculative, as no direct markers of oxidative stress or afferent activity were assessed in the study.

Overall, these findings indicate that CWI expedites recovery of MVC by attenuating both peripheral (Q$_{tw,pot}$) and central (VA) fatigue. Nevertheless, whether the specific temperature and duration employed in this study represent an optimal recovery strategy remains uncertain. A recent meta-analysis by Wang *et al.* [31] examining the effects of different cold water immersion doses reported that medium-duration immersions (10–15 min) performed at either low (5–10 °C) or moderate (11–15 °C) temperatures were associated with improvements in performance recovery following acute exercise-induced muscle damage. However, these conclusions were derived from indirect comparisons across studies employing heterogeneous exercise models and were primarily based on indices such as jump performance rather than direct assessments of neuromuscular fatigue. To date, no study has directly compared the effects of different temperature–duration combinations on neuromuscular fatigue recovery in humans. Consequently, while commonly used protocols such as 10 min of immersion at ~10 °C appear effective, the current evidence does not allow conclusions regarding an optimal protocol for the recovery of neuromuscular fatigue.

4.1.2 Phase change material (PCM) garments

Brownstein *et al.* [22] investigated the effects of wearing phase change material (PCM) garments on post-match recovery in 11 semi-professional soccer players. In a randomized, crossover design, players wore either PCM cooled (PCM$_{cold}$, 15 °C) or ambient temperature (PCM$_{amb}$, >22 °C) for 3 h following match-play. A phase change material was applied to the quadriceps and hamstring muscle groups.

Recovery kinetics showed that both MVC and Q$_{tw,pot}$ remained depressed for up to 48 h and returned to baseline by 72 h, whereas VA recovered by 48 h in both conditions. M$_{max}$ was unchanged throughout, indicating preserved sarcolemmal excitability and neuromuscular transmission.

However, the authors reported that MVC and VA were higher at 48 h when players wore PCM$_{cold}$ compared with PCM$_{amb}$, whereas no differences were observed in Q$_{tw,pot}$, or M$_{max}$. This pattern suggests that PCM primarily acts on the central rather than peripheral mechanisms of neuromuscular fatigue. The improvement in VA was interpreted as a reduction in inflammation-induced inhibitory feedback from group III/IV muscle afferents, which are sensitive to nociceptive mediators such as bradykinin, histamine, and prostaglandin [32]. Attenuating this feedback would facilitate a greater descending motor drive, thereby supporting the recovery of MVC. In addition, cytokine-mediated effects on brain function have been proposed to contribute to prolonged reductions in VA [33, 34], and cryotherapy-based strategies, such as PCM, may partly mitigate these processes. Overall, the benefit of PCM was observed primarily at the 48-h mark for VA, suggesting a temporary preservation of the central drive rather than a global acceleration of all neuromuscular indices.

Overall, PCM garments appear to provide benefits for central aspects of neuromuscular recovery, as reflected in improvements in VA and MVC, with no effect on peripheral contractile function.

4.1.3 Ischemic preconditioning (IPC)

Daab *et al.* [7] investigated the effects of ischemic preconditioning (IPC) on neuromuscular fatigue during simulated soccer match-play in 14 semi-professional soccer players. After two familiarization visits, players completed two experimental sessions (IPC and placebo (PLA)) separated by 14 days in a randomized, crossover, placebo-controlled design. Each session began with three 5-min cycles of bilateral thigh cuff inflation at 220 mmHg in the IPC trial or 20 mmHg in the PLA trial, each followed by 5 min of reperfusion, conducted 30 min before the LIST. This was followed by a 30-min post-IPC rest period and a standardized 5-min warm-up. Each experimental session lasted ~185 min and included the intervention, rest, warm-up, 90 min of simulated soccer match play, and neuromuscular assessments performed at baseline, half-time (HT), and full-time (FT).

Following exercise, both MVC and VA decreased in IPC and placebo (PLA) conditions, but the attenuation of their decline with IPC indicated preservation of central neural drive. In contrast, Q$_{tw,pot}$, M$_{max}$, and RMS/M$_{max}$ were not affected by IPC, confirming that this strategy did not affect peripheral contractile function, sarcolemmal excitability, or neuromuscular transmission. Therefore, the mitigation of MVC decline was attributed primarily to VA preservation rather than peripheral mechanisms [35].

The authors attributed this effect to the modulation of group III/IV muscle afferents [36]. When activated by exercise-induced metabolites and inflammatory mediators, these afferents typically transmit inhibitory signals at the spinal level via presynaptic inhibition of Ia afferents and at supraspinal sites by reducing the descending motor drive to motoneuron pools [37–39]. The resulting outcome is a reduction in voluntary activation and an impairment in force production. IPC appeared to mitigate this inhibitory input, thereby preserving voluntary activation [36]. Although the precise supraspinal contributions remain unclear, recent studies have shown that IPC enhances VA and reduces central fatigue, even in isolated strength tasks, reinforcing its potential role in sustaining neural drive during fatiguing exercise [40].

Although no extended recovery assessments were conducted, the attenuation of VA immediately post-exercise suggests that IPC reduces the central load at the onset of recovery, supporting its potential as a strategy to accelerate the restoration of voluntary activation after simulated soccer match play.

4.1.4 Chronic beetroot juice supplementation

Daab *et al.* [21] evaluated the effects of chronic beetroot juice supplementation (BEET) on neuromuscular fatigue during and after simulated soccer match-play in 13 male semi-professional players. Using a randomized, double-blind, crossover design, participants consumed 150 mL of BEET (∼4 mmol nitrate per serving) or placebo (PLA) twice daily for 6 days and once more 2 h before the trial. BEET juice was prepared from natural beetroot without additives, whereas PLA was matched for taste and appearance.

Neuromuscular function was assessed using MVC, VA, Q$_{tw,pot}$, M$_{max}$, and RMS/M$_{max}$, measured pre-, during, and post-exercise. The authors noted that MVC, VA, and Q$_{tw,pot}$ declined following the LIST, but these reductions were consistently smaller in the BEET condition than in the PLA condition. In contrast, M$_{max}$ and RMS/M$_{max}$ remained unchanged in both trials, confirming preserved sarcolemmal excitability and neuromuscular transmission.

The attenuation of MVC decline could be explained by reduced impairment in both the peripheral and central mechanisms. On the peripheral side, nitrate-derived increases in nitric oxide (NO) may enhance blood flow to type II fibers [41], accelerate phosphocreatine resynthesis, and reduce metabolite accumulation [42]. NO has also been shown to improve Ca^{2+} handling in fast-twitch fibers [42], thereby sustaining excitation–contraction coupling and cross-bridge force production [43, 44], which could explain the smaller decline in Q$_{tw,pot}$. On the central side, higher VA values with BEET supplementation may reflect reduced inhibitory feedback from group III/IV afferents activated by exercise-induced metabolites, muscle damage, and inflammation [19, 23, 45]. Antioxidants and phytochemicals in beetroot, such as betalains [46], may further attenuate oxidative stress and inflammatory signaling [47].

Although no extended recovery assessments were conducted, the attenuation of MVC, VA, and $Q_{tw,pot}$ immediately post-exercise suggests that BEET supplementation reduces neuromuscular fatigue at the onset of recovery, supporting its potential as a nutritional strategy to accelerate post-match restoration.

4.1.5 Acetaminophen (paracetamol) ingestion

Bouchiba *et al.* [24] investigated the effects of acute acetaminophen (ACT) ingestion on neuromuscular recovery in semi-professional soccer players following simulated 90-min match play. In a randomized, double-blind, placebo-controlled crossover design, players ingested either 1 g of ACT or a placebo one hour before exercise. Neuromuscular assessments included MVC, VA, $Q_{tw,pot}$, M_{max}, and RMS/M_{max}, measured before, immediately after, and up to 72 h after the match.

In the placebo condition, MVC and VA were markedly reduced after exercise and required up to 72 h and 48 h, respectively, for complete recovery. With ACT, these reductions were attenuated post-exercise, and both parameters recovered approximately 24 h earlier than in the placebo condition. In contrast, no significant differences were observed between the conditions in $Q_{tw,pot}$, while M_{max} amplitude and RMS/M_{max} remained unchanged, confirming that the effects of ACT were confined to central rather than peripheral fatigue.

The authors suggested that the attenuation of the decrease in VA could be explained by the inhibition of cyclooxygenase, the enzyme responsible for prostaglandin synthesis [48]. Since prostaglandins increase during exercise-induced muscle damage and stimulate nociceptive group III/IV afferents [27, 49], their reduction through ACT ingestion may decrease afferent discharge. This would limit inhibitory feedback at both the spinal and supraspinal levels [37–39], thereby maintaining central motor command and enhancing muscle activation [50]. In addition, evidence indicates that ACT may increase corticospinal excitability [51], which could further support its central effects.

Overall, these findings indicate that acute ingestion of 1 g of ACT (1 h before the LIST protocol) attenuates the decrease in MVC and VA after exercise, with no effect on peripheral markers, highlighting its potential as a strategy to mitigate central fatigue in soccer players.

4.2 Potential risks of misapplication and excessive use

Although acute studies have demonstrated the effectiveness of CWI, PCM garments, ACT, IPC, and BEET supplementation, their long-term or repetitive use warrants caution. Overuse may blunt adaptations, induce tolerance, and pose health risks.

4.2.1 Cold water immersion (CWI)

Although CWI is widely adopted to accelerate neuromuscular fatigue recovery and reduce injury risk, caution is warranted regarding its chronic use. Evidence indicates that repeated immersion may blunt training adaptations by attenuating the activation of key proteins and satellite cells in skeletal muscle, thereby impairing muscle hypertrophy and strength development [52, 53]. In addition, Barnett [54] argued that inflammatory processes play a central role in muscle repair and adaptation, and given the anti-inflammatory effects of CWI, chronic suppression of inflammation may hinder long-term training benefits. Thus, CWI should be reserved for congested schedules or competition periods rather than being applied after every training session.

4.2.2 Acute acetaminophen ingestion (ACT)

Although its effects on neuromuscular recovery are evident, with acute ingestion of ACT (1 g, 1 h pre-exercise) accelerating the recovery of neuromuscular fatigue by attenuating central fatigue [24], chronic use of ACT may pose significant risks. The therapeutic use of acetaminophen is generally restricted to 1 g per dose every 4–6 h, with a maximum daily intake of 4 g in healthy adults [55]. Sustained use, even within these limits, may strain liver function and increase the risk of hepatotoxicity [56]. Furthermore, ACT's analgesic effect may blunt the perception of exercise-induced pain, potentially obscuring early signs of injury and encouraging athletes to continue playing despite musculoskeletal damage [57]. Overall, these risks suggest that ACT use in soccer should be carefully monitored. Accordingly, ACT should be restricted to occasional use in congested fixture periods or competitive contexts and not adopted as a long-term recovery strategy in soccer.

4.2.3 Beetroot juice supplementation (BEET)

Although chronic BEET supplementation may be effective, practitioners should be aware of the long-term metabolic effects of high nitrate intake. Current literature suggests that while short-term use is safe, adherence to the recommended dosages is vital to avoid potential adverse effects [58–61]. Accordingly, BEET may support recovery when applied strategically during periods of elevated training or competition. Coaches and practitioners should avoid chronic high-dose use and individualize dosing to remain within the acceptable daily intake (ADI) (3.7 mg·kg^{-1}·day^{-1}), ensuring safe and effective integration into recovery strategies.

4.2.4 Ischemic preconditioning (IPC)

Although IPC is generally considered safe, some precautions are necessary. Prolonged ischemia can induce edema, lysosome accumulation, and muscle fiber necrosis within 90 min [62], and repeated sessions may lead to diminishing effects compared with a single application [63]. To mitigate these risks, it has been established that most studies employ three or four 5-min cycles of ischemia and reperfusion at cuff pressures of 200–220 mmHg, a protocol shown to optimize blood flow, muscle oxygenation, and performance [64]. Therefore, soccer coaches should consider applying IPC strategically, aligning sessions with training or competition demands while avoiding unnecessary prolonged or repeated use.

4.2.5 Phase change material (PCM) garments

The risks associated with PCM cooling appear to be minor, and only a limited number of studies have specifically examined its safety in athletic contexts. Unlike repeated cold-water immersion, which has been linked to potential interference with long-term training adaptations, prolonged or repetitive use of PCM has not been shown to blunt adaptive responses [65]. Existing evidence suggests that PCM is a safe and practical recovery strategy when applied post-exercise, although further research is required to confirm its long-term safety and effectiveness in different sports settings.

4.3 Practical applications

Based on the results of the studies included, this mini-review outlines five recovery strategies that may accelerate recovery from neuromuscular fatigue in soccer (Fig. 2). Cold water immersion (CWI) expedites recovery of both central and peripheral fatigue when the lower limbs are immersed at ~10 °C for 10 min immediately after matches, restoring voluntary activation, maximal voluntary contraction, and quadriceps twitch within 24 h. Phase change material (PCM) garments (~15 °C) applied to the quadriceps and hamstrings for 3 h post-match enhance central recovery and force production by 48 h. Ischemic preconditioning (IPC) before match-play, using three 5-min cycles of thigh cuff inflation at 220 mmHg with reperfusion, reduces central fatigue and supports early recovery of voluntary activation immediately post-match. Chronic beetroot juice supplementation (150 mL twice daily for six days and once 2 h before play) attenuates both central and peripheral fatigue immediately post-match, while acute acetaminophen ingestion (1 g, 1 h before exercise) primarily mitigates central fatigue and accelerates recovery of voluntary activation and force output within 24 to 48 h post-match. Finally, practitioners should distinguish between preventative strategies (IPC 30 min prior; ACT 1 h prior and chronic BEET) aimed at attenuating the onset of neuromuscular fatigue and restorative strategies (CWI and PCM) applied post-match to accelerate the recovery of force-generating capacity.

4.4 Future directions

Future studies should extend the current findings by integrating match load variables (*e.g.*, external and internal load indices) with neuromuscular outcomes to better contextualize recovery responses. In addition, although simulated soccer match play offers experimental control, investigations conducted during official competitive matches are needed to account for the contextual and psychological demands that may influence fatigue and recovery. Research should also expand to other populations, including elite players, youth athletes, and female soccer players, as sex- and maturation-related differences in neuromuscular function may alter recovery mechanisms. Finally, future studies should explore additional or combined recovery strategies, such as thermotherapy, and examine dose–response relationships to optimize neuromuscular recovery.

4.5 Limitations

This mini-review has several limitations. First, the number of studies available on neuromuscular recovery in soccer is limited. Only five peer-reviewed studies met the strict inclusion criteria, reflecting the emerging nature of this research area rather than selective reporting of results. Consequently, the total sample size across studies was small and restricted to male semi-professional players, which limits the generalizability of the findings to other populations, such as elite professionals, female players, youth athletes, or amateur players. Second, although all the included studies employed robust experimental designs (randomized crossover or placebo-controlled protocols), most relied on simulated soccer match-play (LIST) rather than competitive matches, which may not fully capture the physiological, psychological, and contextual demands of real competition. Third, owing to the narrative nature of this mini-review and the limited number of eligible studies, no formal risk of bias or quality assessment was conducted. Fourth, although this review reports actionable implications, these recommendations are strictly based on the conclusions of the original studies and should be interpreted as preliminary. Larger longitudinal trials are required to confirm effectiveness, establish optimal dosing or timing, assess long-term safety, and determine whether these strategies translate into meaningful performance or injury-related outcomes in real-world soccer settings. Finally, future studies incorporating direct markers of ROS/RNS and afferent activity while systematically examining different water temperatures and immersion durations would help confirm the proposed mechanisms and further clarify dose–response relationships for neuromuscular fatigue recovery.

5. Conclusions

This mini-review highlights five recovery strategies for which current evidence, although preliminary, suggests potential benefits for neuromuscular fatigue recovery in soccer players: cold water immersion (CWI), phase change material garments (PCM_{cold}), ischemic preconditioning (IPC), chronic beetroot juice supplementation (BEET), and acute acetaminophen ingestion (ACT). Evidence indicates that CWI and BEET support both central and peripheral recovery, whereas PCM, IPC, and ACT primarily target central mechanisms. Timing is also crucial. Some interventions are applied post-match (CWI, PCM_{cold}), while others are applied pre-match (IPC, ACT) or over several days (BEET). The implementation of these strategies can help maintain voluntary activation and force production, optimize recovery, and potentially enhance subsequent performance. Further research is needed to replicate these findings, refine the protocols, and explore combined approaches to confirm the potential benefits of these strategies for neuromuscular fatigue recovery. However, as each strategy is represented by a single study in this specific population, these findings should be considered preliminary. Furthermore, as no formal meta-analysis was performed and the study designs varied, the efficacy of these strategies in professional league settings (where match density and travel fatigue are higher than those in the semi-professional cohorts studied) remains to be established.

AVAILABILITY OF DATA AND MATERIALS

Data sharing is not applicable to this article, as no datasets were generated or analyzed during the current study.

AUTHOR CONTRIBUTIONS

These should be presented as follows: MB and OT—designed the research; wrote the manuscript. MAB—conducted literature search. All authors analyzed the data. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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