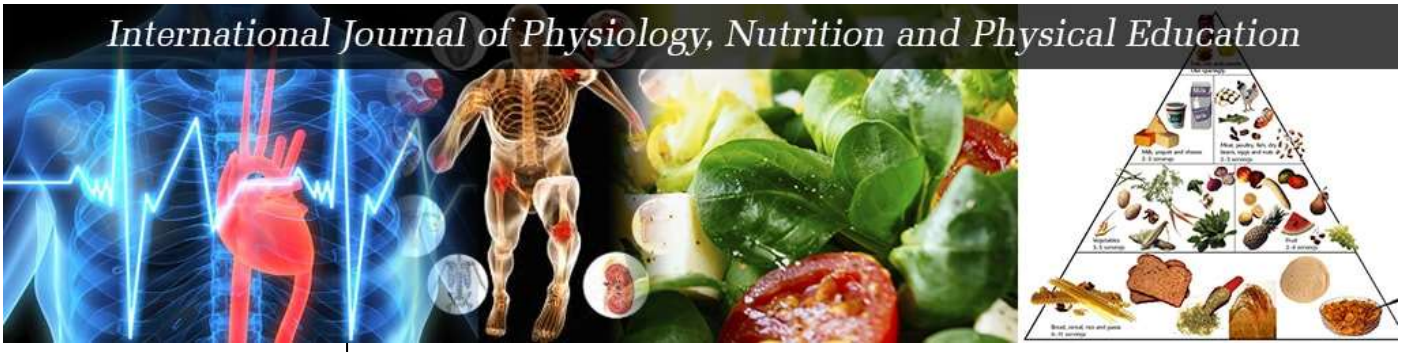

ISSN: 2456-0057
IJPNPE 2025; 10(1): 293-300

www.journalofsports.com
Received: 21-03-2025
Accepted: 25-04-2025

Harshita Shah
Ramaiah University of Applied Sciences, New BEL Road, Bengaluru, Karnataka, India

Madhusudhan Nayak C
Assistant Professor,
MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Aishwarya V Patil
Assistant Professor,
MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Chennappa Gurikar
Assistant Professor,
MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Poornima DS
Assistant Professor,
MS Ramaiah University of Applied Sciences, Bengaluru, Karnataka, India

Corresponding Author:
Harshita Shah
Ramaiah University of Applied Sciences, New BEL Road, Bengaluru, Karnataka, India

Nutritional approaches for reducing exercise-induced muscle damage and delayed onset muscle soreness: A comprehensive review

Harshita Shah, Madhusudhan Nayak C, Aishwarya V Patil, Chennappa Gurikar and Poornima DS

Abstract
Exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS) are common outcomes following unaccustomed or strenuous physical activity, particularly those involving eccentric muscle contractions. These phenomena can impair subsequent performance, reduce training quality, and hinder athletic progression. Emerging evidence highlights the potential role of targeted nutritional strategies in attenuating muscle damage, reducing soreness, and accelerating recovery. This review provides a comprehensive synthesis of current literature on nutritional interventions aimed at mitigating EIMD and DOMS. We explore the mechanistic roles and practical applications of macronutrients (protein, branched-chain amino acids, carbohydrates, and omega-3 fatty acids), micronutrients (vitamin D, magnesium, and zinc), and bioactive compounds (polyphenols, curcumin, ginger, and green tea catechins). Additionally, the efficacy of supplementation strategies such as creatine, glutamine, and beta-hydroxy beta-methylbutyrate (HMB) is discussed, along with the importance of hydration and electrolyte balance. Considerations of nutrient timing, dosage, and population-specific responses are also addressed. By integrating mechanistic insights with applied recommendations, this review offers evidence-based guidelines for athletes, coaches, and practitioners seeking to optimize recovery and enhance performance through nutrition. Future research directions are proposed to refine and personalize these nutritional approaches for diverse athletic populations.

Keywords: Exercise-induced muscle damage, delayed onset muscle soreness, nutritional strategies

Introduction
Exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS) are well-recognized physiological consequences of unaccustomed or strenuous physical activity, particularly exercises emphasizing eccentric muscle contractions, plyometric movements, or high mechanical loading (Proske & Morgan, 2001) [28]. EIMD manifests as microtrauma within the contractile and connective tissues of skeletal muscle, leading to a cascade of secondary inflammatory, immune, and oxidative responses that compromise muscle function (Peake *et al*., 2017) [25]. Typically, symptoms of DOMS — including tenderness, stiffness, swelling, and reduced range of motion — peak between 24 to 72 hours' post-exercise, potentially impairing subsequent training quality, delaying performance recovery, and increasing susceptibility to injury (Owens *et al*., 2019) [24].
Mechanistically, the initiation of EIMD begins with disruption to sarcomere structures and excitation-contraction coupling impairments, particularly in type II muscle fibers, which are more susceptible to mechanical stress (Proske & Morgan, 2001) [28]. Following the initial mechanical insult, an inflammatory response is triggered, characterized by infiltration of neutrophils and macrophages, cytokine release (e.g., interleukin-6, tumor necrosis factor-alpha), and heightened oxidative stress via reactive oxygen species (ROS) production (Peake *et al*., 2017) [25]. These secondary processes exacerbate membrane permeability, calcium dysregulation, and subsequent proteolytic enzyme activity, compounding tissue damage and amplifying sensations of soreness and stiffness (Howatson & Van Someren, 2008) [9]. While this sequence of events is integral to muscle adaptation and remodeling, excessive or poorly managed muscle damage can attenuate force-generating capacity and hinder training progression, particularly in athletes undergoing high training volumes or competition

schedules (Owens *et al*., 2019) [24].

Given the multifactorial nature of EIMD and DOMS, researchers and practitioners have explored various recovery modalities to attenuate their magnitude and accelerate functional restoration. Non-nutritional strategies — such as cryotherapy, massage, compression garments, and low-intensity active recovery — have demonstrated variable efficacy in modulating soreness, inflammation, and muscle performance (Dupuy *et al*., 2018) [7]. However, nutritional interventions have emerged as an accessible, scalable, and often synergistic approach to support muscle recovery and enhance resilience to future exercise stress (Jäger *et al*., 2017) [12]. Nutrition can influence several aspects of the EIMD and recovery process, including inflammatory signaling, oxidative balance, immune modulation, muscle protein turnover, and glycogen replenishment.

Accumulating evidence suggests that specific macronutrients, micronutrients, and functional bioactive compounds exert beneficial effects in mitigating muscle damage and soreness. For instance, protein and branched-chain amino acids (BCAAs) support muscle protein synthesis and membrane repair, while omega-3 fatty acids (EPA/DHA) modulate inflammation and cellular signaling (Jäger *et al*., 2017; Owens *et al*., 2019) [12, 24]. Polyphenol-rich foods such as tart cherry juice, pomegranate extract, and blueberries have demonstrated antioxidant and anti-inflammatory properties that may accelerate recovery and attenuate DOMS (Sousa *et al*., 2014) [34]. Additionally, compounds like curcumin, ginger, creatine, and beta-hydroxy beta-methylbutyrate (HMB) have been investigated for their roles in reducing muscle membrane disruption, modulating immune responses, and enhancing tissue regeneration (Howatson & Van Someren, 2008) [9].

Despite promising findings, inconsistencies in study designs, supplementation protocols, populations, and exercise models pose challenges in drawing definitive conclusions. Furthermore, factors such as nutrient timing, dosing, and combined interventions require further investigation to optimize recovery strategies across diverse athletic populations.

The purpose of this review is to comprehensively synthesize current evidence on nutritional interventions aimed at reducing exercise-induced muscle damage and delayed onset muscle soreness. This paper will examine mechanistic insights and practical applications of macronutrients, micronutrients, and functional bioactive compounds. Moreover, considerations of nutrient timing, population-specific responses, and emerging evidence will be discussed, with the goal of offering evidence-based recommendations for athletes, coaches, and sports nutrition practitioners seeking to enhance recovery and maintain training quality.

Nutritional mechanisms of action for attenuating EIMD and DOMS

Inflammation is a central component of the secondary muscle damage cascade following the initial mechanical disruption of muscle fibers during exercise. The acute inflammatory response is characterized by infiltration of neutrophils and macrophages into the damaged tissue, which contributes to cytokine release, such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-α), and exacerbation of tissue disruption (Peake *et al*., 2017) [25]. Nutritional strategies that modulate inflammation have the potential to mitigate the extent of secondary damage and accelerate recovery. Omega-3 polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), have demonstrated anti-inflammatory effects through several mechanisms. These include reducing the production of pro-inflammatory cytokines, altering membrane phospholipid composition, and increasing the synthesis of resolvins and protectins—specialized pro-resolving lipid mediators that aid in resolving inflammation (Philpott *et al*., 2018) [27]. Supplementation with omega-3s has been shown to reduce muscle soreness and markers of inflammation after exercise, likely contributing to improved recovery outcomes (Tinsley *et al*., 2016) [35]. Similarly, polyphenol-rich foods such as tart cherry juice, pomegranate extract, and curcumin (from turmeric) have demonstrated anti-inflammatory properties by inhibiting cyclooxygenase enzymes, reducing cytokine production, and modulating nuclear factor kappa B (NF-κB) signaling pathways (McLeay *et al*., 2012; McFarlin *et al*., 2016) [18, 17].

Oxidative stress, induced by the generation of reactive oxygen species (ROS) during strenuous exercise, is another key factor exacerbating muscle damage and inflammation. Excess ROS can impair cell membranes, proteins, and DNA, prolonging tissue damage and delaying recovery (Peake *et al*., 2017) [25]. Antioxidant-rich nutrients and compounds, such as vitamins C and E, polyphenols, and carotenoids, have been investigated for their ability to attenuate oxidative damage. For example, consumption of tart cherry juice and pomegranate extract, which are rich in anthocyanins and ellagitannins respectively, has been associated with reduced oxidative markers and improved muscle function recovery (Bell *et al*., 2014; Trombold *et al*., 2011) [1, 37]. However, it is important to note that excessive antioxidant supplementation, particularly with high-dose isolated vitamins, may blunt beneficial exercise-induced adaptations by impairing endogenous antioxidant signaling pathways (Merry & Ristow, 2016) [19]. Therefore, dietary strategies emphasizing whole-food sources of antioxidants or moderate supplementation may offer a more balanced approach.

Another critical mechanism for attenuating EIMD and DOMS is the modulation of muscle protein synthesis and repair. Muscle damage disrupts the sarcomeric structure and impairs excitation-contraction coupling, necessitating efficient protein turnover and membrane repair to restore muscle integrity (Owens *et al*., 2019) [24]. Dietary protein, especially sources rich in essential amino acids and leucine, plays a pivotal role in stimulating muscle protein synthesis via activation of the mechanistic target of rapamycin (mTOR) pathway (Jäger *et al*., 2017) [12]. Consuming protein post-exercise, typically in the range of 20-40 grams depending on body weight and exercise intensity, has been shown to enhance recovery, preserve lean mass, and support muscle remodeling (Morton *et al*., 2018) [20]. Branched-chain amino acids (BCAAs) supplementation, particularly leucine, may further contribute to reducing markers of muscle damage and soreness, although evidence on its independent efficacy remains mixed (Jackman *et al*., 2010) [11].

In addition to supporting muscle protein turnover, certain nutrients influence immune function and cellular recovery processes critical for resolving muscle damage. Glutamine, the most abundant amino acid in the body, serves as a substrate for immune cells and has been suggested to support immune resilience during periods of high physical stress (Walsh *et al*., 2011) [39]. Although direct evidence for glutamine's role in attenuating EIMD is limited, its immunomodulatory properties may aid overall recovery. Vitamin D, through its role in regulating immune cell activity and muscle function, has also been linked to improved

recovery and reduced susceptibility to musculoskeletal injuries (Owens *et al*., 2015) [23]. Furthermore, creatine supplementation has shown promise in supporting muscle cell membrane integrity and satellite cell activity, which may facilitate muscle regeneration following damage (Branch, 2003) [3].

Collectively, these nutritional strategies target multiple biological pathways—modulating inflammation, mitigating oxidative stress, supporting muscle protein synthesis, and enhancing immune function—which together can reduce the severity of exercise-induced muscle damage and delayed onset muscle soreness. An integrative nutritional approach, incorporating these evidence-based nutrients and bioactive compounds, holds considerable potential for optimizing recovery in athletic and physically active populations.

Nutritional strategies to mitigate EIMD and DOMS

Nutritional strategies play a pivotal role in attenuating exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS) by supporting muscle repair, modulating inflammation, replenishing energy stores, and optimizing cellular recovery processes. Interventions involving macronutrients, micronutrients, bioactive compounds, and dietary supplements have demonstrated promising effects in accelerating post-exercise recovery and minimizing muscle damage markers.

Adequate dietary protein intake is fundamental for stimulating muscle protein synthesis (MPS), facilitating tissue repair, and preserving lean mass following strenuous exercise. Protein ingestion, particularly rich in essential amino acids and leucine, enhances MPS by activating the mechanistic target of rapamycin (mTOR) signaling pathway, a key regulator of muscle hypertrophy and repair (Jäger *et al*., 2017) [12]. Consuming high-quality protein (approximately 20-40 g per meal) within the post-exercise anabolic window is widely recommended to optimize recovery (Morton *et al*., 2018) [20].

In addition to whole protein sources, branched-chain amino acids (BCAAs) — leucine, isoleucine, and valine — have been extensively studied for their role in reducing muscle soreness and improving functional recovery. BCAA supplementation may attenuate muscle damage by reducing exercise-induced increases in creatine kinase and lactate dehydrogenase, although findings on its efficacy remain equivocal (Jackman *et al*., 2010) [11]. Emerging evidence also highlights the potential benefits of collagen peptides for connective tissue health and joint recovery. Collagen supplementation, when combined with vitamin C, may stimulate collagen synthesis, benefiting tendons, ligaments, and cartilage, thereby supporting structural recovery in physically active individuals (Shaw *et al*., 2017) [31].

Carbohydrates play a central role in replenishing muscle glycogen stores, a key determinant of exercise performance and recovery. Post-exercise carbohydrate ingestion restores glycogen levels and promotes an anabolic hormonal environment by stimulating insulin secretion, which facilitates glucose and amino acid uptake into muscle cells (Ivy, 2004) [10]. In endurance and high-intensity sports, adequate carbohydrate intake is critical for maintaining muscle function and delaying fatigue during subsequent exercise bouts. Additionally, carbohydrates can modulate immune function by attenuating post-exercise increases in stress hormones (e.g., cortisol) and reducing circulating pro-inflammatory cytokines, which are implicated in impaired immune surveillance and muscle recovery (Nieman, 1998) [22]. Consuming 1.0-1.2 g/kg of carbohydrates immediately post-exercise is generally recommended for optimal glycogen resynthesis (Jäger *et al*., 2017) [12].

Omega-3 fatty acids, particularly EPA and DHA, possess potent anti-inflammatory properties that may benefit exercise recovery. These fatty acids are incorporated into cell membranes, altering membrane fluidity and signaling, and are precursors to resolvins and protectins that actively resolve inflammation (Philpott *et al*., 2018) [27]. Omega-3 supplementation has been shown to reduce muscle soreness, inflammatory cytokine production, and muscle stiffness following eccentric exercise, thereby potentially accelerating muscle recovery (Tinsley *et al*., 2016) [35]. A daily intake of 2-3 g of combined EPA and DHA is often recommended to elicit these effects.

Micronutrients also contribute significantly to muscle repair and recovery. Vitamin D, through its role in modulating calcium homeostasis and immune function, has been linked to muscle regeneration and reduced susceptibility to musculoskeletal injuries (Owens *et al*., 2015) [23]. Deficiency in vitamin D can impair muscle strength and delay recovery processes. Magnesium plays a critical role in energy metabolism, neuromuscular function, and protein synthesis, making it an essential nutrient for physically active individuals (Volpe, 2015) [38]. Similarly, zinc is involved in tissue repair, antioxidant defense, and immune function, and inadequate zinc status may compromise muscle recovery and wound healing (Mossink, 2020) [21].

In addition to nutrients, bioactive compounds and functional foods rich in polyphenols have demonstrated potential for attenuating EIMD and DOMS. Tart cherry juice, pomegranate extract, and blueberries are rich in anthocyanins and ellagitannins, which exert antioxidant and anti-inflammatory effects by scavenging reactive oxygen species and modulating cytokine production (Bell *et al*., 2014; Trombold *et al*., 2011) [1, 37]. Regular consumption of these polyphenol-rich foods has been associated with reduced muscle soreness, decreased oxidative stress markers, and improved muscle function recovery. Curcumin, the bioactive compound in turmeric, and ginger have shown analgesic and anti-inflammatory properties through inhibition of cyclooxygenase enzymes and NF-κB signaling (McFarlin *et al*., 2016) [17]. Supplementation with curcumin has been linked to reductions in muscle damage biomarkers and perceived soreness following exercise. Green tea extract, rich in catechins such as epigallocatechin gallate (EGCG), exhibits similar antioxidant and anti-inflammatory actions that may contribute to enhanced recovery and reduced oxidative stress (Kavitha *et al*., 2013) [14].

Supplementation strategies involving compounds such as creatine monohydrate, glutamine, and beta-hydroxy beta-methylbutyrate (HMB) offer additional avenues to support muscle recovery. Creatine enhances phosphocreatine stores, supporting energy availability during high-intensity exercise, and has been implicated in promoting muscle cell membrane stability and satellite cell activation, which can aid in muscle regeneration post-damage (Branch, 2003) [3]. Glutamine, a key substrate for immune cells, may support immune function during intense training periods, although its direct effect on EIMD mitigation is less established (Walsh *et al*., 2011) [39]. HMB, a leucine metabolite, has been shown to reduce muscle protein breakdown and improve recovery markers, particularly during novel or high-volume resistance training (Wilson *et al*., 2014).

Together, these nutritional strategies offer a multifaceted approach to mitigating EIMD and DOMS. Integrating macronutrient and micronutrient interventions, alongside

bioactive compounds, targeted supplements, and hydration practices, provides an evidence-based foundation to optimize muscle recovery and enhance athletic performance.

Hydration and electrolyte balance

Hydration and electrolyte balance are fundamental components in optimizing muscle function and accelerating recovery following exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS). Dehydration, even as little as a 2% reduction in body weight from fluid loss, can impair physiological function, reduce endurance capacity, and increase the perception of fatigue (Sawka *et al*., 2007) [29]. During prolonged or intense exercise, significant fluid and electrolyte losses can occur through sweat, particularly in hot or humid environments. The depletion of water and key electrolytes—sodium, potassium, calcium, and magnesium—compromises plasma volume, reduces blood flow to muscles, and impairs thermoregulation, all of which can exacerbate muscle cramping and delay recovery processes (Maughan & Shirreffs, 2010) [15].

Rehydration strategies after exercise are critical to restoring fluid balance and supporting cellular functions necessary for muscle repair. Optimal rehydration not only involves water replacement but also requires appropriate electrolyte replenishment, particularly sodium, which aids in fluid retention and promotes rapid restoration of extracellular fluid volume (Shirreffs & Sawka, 2011) [32]. The addition of sodium to rehydration beverages enhances plasma osmolality, stimulating thirst and reducing urine output, both of which facilitate better fluid retention and rehydration efficiency (Maughan *et al*., 2016) [16]. Potassium plays a complementary role by aiding intracellular fluid restoration and supporting neuromuscular function, crucial in minimizing muscle weakness and cramping during the recovery phase (Casa *et al*., 2000) [5].

Electrolyte imbalances post-exercise can adversely affect muscle contractility and increase the risk of muscle dysfunction. Sodium loss, in particular, is associated with exercise-associated muscle cramps (EAMC), which are more prevalent during endurance events or prolonged training sessions (Bergeron, 2008) [2]. Ensuring sufficient sodium intake—via food or electrolyte-containing beverages—can mitigate these risks and promote optimal muscle relaxation and contraction cycles. Magnesium, an essential cofactor in ATP synthesis and neuromuscular transmission, also plays a role in modulating muscle excitability and protein synthesis (Volpe, 2015) [38]. Inadequate magnesium status has been linked to increased oxidative stress, impaired glucose metabolism, and prolonged muscle soreness, further highlighting the importance of maintaining electrolyte balance.

Incorporating beverages that contain carbohydrates along with electrolytes, such as sports drinks, can further enhance recovery by supporting glycogen resynthesis and stimulating insulin release, which facilitates nutrient uptake into muscle cells (Ivy, 2004) [10]. The synergistic effects of carbohydrates and electrolytes optimize both energy replenishment and fluid restoration, creating a favorable environment for muscle repair and reducing the physiological strain associated with EIMD and DOMS.

Overall, maintaining proper hydration status and electrolyte balance before, during, and after exercise is essential not only for preserving performance but also for expediting recovery and mitigating muscle damage. An individualized hydration strategy, accounting for sweat rate, exercise duration, environmental conditions, and electrolyte losses, can help optimize recovery outcomes in athletes and physically active individuals.

Timing and doseage of nutritional interventions

The timing and dosing of nutritional interventions play a pivotal role in mitigating exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS), with evidence suggesting that the strategic provision of nutrients around exercise sessions can optimize recovery and enhance adaptive responses. Pre-exercise nutrition focuses on priming the body's metabolic environment to sustain performance and reduce muscle catabolism. Consuming protein or amino acid-containing meals approximately 1-2 hours before exercise has been shown to elevate circulating amino acid levels, promoting muscle protein synthesis and potentially reducing muscle damage during exercise bouts (Tipton *et al*., 2001) [36]. Additionally, carbohydrate ingestion prior to exercise supports glycogen stores, preserves muscle energy availability, and attenuates the rise in cortisol levels, thereby minimizing proteolysis and inflammation (Ivy, 2004) [10].

Intra-exercise nutrition strategies, while less common for shorter sessions, can be relevant during prolonged or high-intensity endurance activities where extended muscle loading may exacerbate muscle damage and immune perturbations. The consumption of carbohydrates and electrolytes during exercise not only maintains blood glucose concentrations but also mitigates the decline in immune function and reduces markers of inflammation post-exercise (Nieman, 1998) [22]. Emerging evidence also suggests that branched-chain amino acid (BCAA) supplementation during exercise may reduce muscle soreness and muscle damage biomarkers, although the magnitude of these effects may depend on exercise type and duration (Jackman *et al*., 2010) [11].

Post-exercise nutritional interventions are perhaps the most extensively studied in the context of recovery. Prompt intake of protein and carbohydrates immediately following exercise has consistently been shown to stimulate muscle protein synthesis, replenish glycogen stores, and attenuate markers of muscle damage and soreness (Jäger *et al*., 2017) [12]. The "anabolic window," traditionally considered to exist within 30 to 60 minutes' post-exercise, represents a critical period where nutrient delivery is most effective in supporting tissue repair and adaptation, although recent evidence suggests that this window may be broader, especially in individuals who have consumed protein pre-exercise (Schoenfeld *et al*., 2013) [30]. Consuming approximately 20-40 grams of high-quality protein with a balanced profile of essential amino acids shortly after training appears to maximize muscle protein synthesis and support recovery (Morton *et al*., 2018) [20]. Carbohydrate ingestion post-exercise at a rate of approximately 1.0-1.2 g/kg/hour enhances muscle glycogen repletion, particularly when consumed in the immediate hours following exhaustive endurance exercise (Ivy, 2004) [10].

Beyond acute interventions, chronic or sustained supplementation strategies may confer additive or distinct benefits in attenuating EIMD and DOMS. For instance, the regular intake of omega-3 fatty acids (EPA/DHA) over several weeks has been shown to reduce markers of inflammation and muscle soreness following eccentric exercise, likely due to the incorporation of these fatty acids into cell membranes, modulating inflammatory responses (Philpott *et al*., 2018) [27]. Similarly, chronic supplementation of creatine monohydrate has demonstrated protective effects on muscle membrane integrity and improved recovery

following resistance exercise through enhanced phosphocreatine resynthesis and cellular hydration (Branch, 2003) [3]. Other bioactive compounds such as curcumin, polyphenols (e.g., tart cherry, pomegranate), and vitamin D may also require sustained dosing over days or weeks to exert measurable anti-inflammatory or antioxidant effects that mitigate muscle damage (Bell *et al*., 2014; Owens *et al*., 2015) [1, 23].

The efficacy of these interventions is influenced not only by the timing but also by the dosage and duration of supplementation. Insufficient dosing may yield suboptimal effects, while excessively high intakes can increase the risk of adverse outcomes or diminish returns. Therefore, tailoring nutrient type, dose, and timing to the specific exercise modality, individual characteristics, and training status is essential to maximize recovery benefits and reduce EIMD and DOMS.

Population specific considerations

The efficacy and requirements of nutritional strategies aimed at mitigating exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS) can vary significantly across different populations, influenced by factors such as training status, exercise modality, age, and sex. Trained and untrained individuals exhibit distinct physiological and adaptive responses to exercise-induced stress. Untrained individuals often experience greater degrees of muscle damage, inflammation, and soreness following novel or high-intensity exercise due to a lack of repeated bout effect (RBE)—an adaptive phenomenon where prior exposure to eccentric or strenuous exercise confers protective adaptations against subsequent muscle damage (McHugh, 2003). Consequently, untrained individuals may benefit more acutely from nutritional interventions such as protein, branched-chain amino acids (BCAAs), and antioxidant-rich foods during the early stages of training to attenuate soreness and accelerate recovery (Jackman *et al*., 2010) [11]. Conversely, trained athletes may require less aggressive intervention due to their enhanced muscle repair capacity and attenuated inflammatory responses, although strategic supplementation can still optimize recovery and sustain high training loads (Owens *et al*., 2019) [24].

Exercise modality further influences the nature and extent of muscle damage and, consequently, nutritional needs. Resistance training, particularly with eccentric overload, results in localized muscle fiber disruption and increased muscle protein turnover, warranting emphasis on protein-rich interventions to stimulate muscle protein synthesis and repair (Morton *et al*., 2018) [20]. Nutrients such as creatine monohydrate and collagen peptides may provide additional support by enhancing muscle and connective tissue recovery in resistance-trained populations (Jäger *et al*., 2017) [12]. In contrast, endurance exercise—especially prolonged or high-intensity sessions—induces systemic metabolic stress, oxidative damage, and immune perturbations due to sustained energy expenditure and repetitive muscle contractions. Here, strategies emphasizing carbohydrate replenishment, antioxidant intake (e.g., polyphenols), and omega-3 fatty acids may be more beneficial in supporting glycogen resynthesis, reducing oxidative stress, and modulating inflammation (Nieman *et al*., 2010; Philpott *et al*., 2018) [22, 27]. Age-related factors also play a crucial role in modulating recovery responses. Older adults experience anabolic resistance, characterized by a blunted muscle protein synthetic response to exercise and protein intake, necessitating higher protein doses (~40 grams) or leucine-enriched protein sources to overcome this barrier and support muscle repair (Burd *et al*., 2013) [4]. Furthermore, age-associated declines in antioxidant defenses and immune function may heighten susceptibility to prolonged inflammation and muscle soreness, making antioxidant-rich and anti-inflammatory nutrients (e.g., vitamin D, omega-3 fatty acids) particularly relevant in aging populations (Owens *et al*., 2015) [23]. Sex-based differences, although less extensively studied, also merit consideration. Estrogen has been shown to exert protective effects against muscle damage via membrane stabilization and anti-inflammatory properties, potentially leading to reduced markers of EIMD in females compared to males (Enns & Tiidus, 2010) [8]. However, hormonal fluctuations across the menstrual cycle can influence recovery capacity and nutrient metabolism, indicating that female athletes may benefit from tailored nutritional strategies based on cycle phase and training load (Smith-Ryan *et al*., 2021) [33].

Taken together, these population-specific considerations underscore the importance of individualized nutrition strategies in sports recovery. A nuanced understanding of how factors such as training history, exercise type, age, and sex modulate physiological responses to muscle damage can guide more effective and targeted nutritional interventions, ultimately optimizing recovery outcomes across diverse athletic populations.

Limitations and future research direction

Despite substantial progress in understanding nutritional strategies to mitigate exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS), several limitations in the current body of evidence restrict the ability to draw definitive conclusions and formulate universal guidelines. A primary methodological limitation across many studies is the heterogeneity in study designs, participant characteristics, exercise protocols, and outcome measures. Variability in sample sizes, ranging from small cohorts to underpowered trials, reduces statistical robustness and generalizability of findings (Owens *et al*., 2019) [24]. Moreover, inconsistencies in dosing regimens, timing of nutrient ingestion, and the form of supplements used (e.g., whole food vs. isolate) create challenges in comparing results and establishing standardized recommendations (Jäger *et al*., 2017) [12]. There is also a reliance on surrogate biomarkers such as creatine kinase (CK), interleukin-6 (IL-6), and subjective soreness ratings, which, while informative, may not fully capture the complex physiological processes involved in muscle recovery or translate directly into functional performance outcomes (Peake *et al*., 2017) [25].

Furthermore, many studies predominantly focus on acute interventions and short-term outcomes, often neglecting the long-term implications of chronic supplementation and its potential cumulative benefits or risks. The majority of existing research has been conducted in young, healthy, male populations, limiting the extrapolation of findings to other groups such as females, older adults, and clinical populations with compromised muscle function (Smith-Ryan *et al*., 2021) [33]. Another notable gap is the limited understanding of nutrient-nutrient and nutrient-exercise interactions. The combined effects of multiple dietary components—such as protein, polyphenols, and omega-3 fatty acids—on recovery processes remain underexplored, as most interventions are assessed in isolation (Philpott *et al*., 2018) [27]. Additionally, individual variability in genetics, gut microbiota, and metabolic responses to supplementation is rarely accounted

for, despite evidence indicating that personalized nutrition strategies could optimize recovery outcomes (Jones *et al*., 2020) [13].

Emerging areas for future research offer promising avenues to address these limitations. There is a growing need for well-designed, randomized controlled trials (RCTs) with larger, more diverse populations and longer follow-up periods to evaluate both acute and chronic effects of nutritional interventions. Advanced biomarker analyses—including proteomics, metabolomics, and microbiome profiling—can provide deeper mechanistic insights into how nutrients modulate recovery at a molecular and systemic level (Petersen *et al*., 2017) [26]. Moreover, interdisciplinary approaches that integrate nutrition with other recovery modalities (e.g., sleep, cold therapy, and mechanical interventions) may yield more comprehensive strategies for optimizing muscle repair and performance. The exploration of novel bioactive compounds, such as emerging phytochemicals, functional peptides, and nutrigenomics-based supplements, also represents a fertile area for investigation. Finally, research emphasizing personalized nutrition, leveraging artificial intelligence and big data analytics to tailor interventions based on individual characteristics, holds considerable potential to advance the precision and efficacy of recovery strategies (de Toro-Martín *et al*., 2017) [6].

In sum, while current evidence provides a solid foundation, addressing methodological inconsistencies and broadening research scope through innovative and inclusive studies will be critical to refining nutritional recommendations for mitigating EIMD and DOMS effectively across diverse athletic and clinical populations.

Conclusion

In summary, exercise-induced muscle damage (EIMD) and delayed onset muscle soreness (DOMS) are inevitable consequences of unaccustomed or intense physical activity, particularly activities with eccentric muscle actions. While these physiological responses play an integral role in muscular adaptation and remodeling, excessive or prolonged damage can impair performance and delay recovery. The evidence reviewed underscores the critical role of nutrition in modulating these recovery processes and mitigating the adverse effects of muscle damage. Key takeaways include the importance of macronutrients—especially adequate protein intake and amino acid supplementation—for stimulating muscle protein synthesis and repair, as well as the utility of carbohydrates for glycogen replenishment and immune modulation. Omega-3 fatty acids demonstrate promising anti-inflammatory properties, and various micronutrients such as vitamin D, magnesium, and zinc contribute to muscle function and recovery. In addition, bioactive compounds such as polyphenols, curcumin, ginger, and green tea catechins offer antioxidant and anti-inflammatory support, while ergogenic supplements like creatine, glutamine, and HMB have demonstrated potential benefits in promoting muscle repair and reducing soreness.

Effective integration of these nutritional strategies also hinges on optimizing the timing, dosing, and combination of interventions relative to exercise. Pre-, intra-, and post-exercise nutrition windows present unique opportunities to enhance recovery, and both acute and chronic supplementation strategies can be leveraged based on individual training demands. Importantly, considerations of athlete characteristics—such as training status, exercise modality, age, and sex—further guide tailored nutritional interventions for optimal results. Despite notable advancements, current evidence gaps highlight the need for more rigorous and inclusive research to refine recommendations and explore emerging interventions.

Ultimately, nutrition serves as a powerful and modifiable factor in recovery paradigms. When integrated thoughtfully alongside other recovery modalities and individualized to the athlete, targeted nutritional strategies can accelerate muscle repair, attenuate soreness, and enhance subsequent performance capacity. Continued research and application of evidence-based nutritional practices will ensure that athletes, both recreational and elite, maximize their recovery potential and sustain long-term training adaptations.

References

1. Bell PG, Walshe IH, Davison GW, Stevenson E, Howatson G. Montmorency cherries reduce the oxidative stress and inflammatory responses to repeated days high-intensity stochastic cycling. Nutrients. 2014;6(2):829-843. https://doi.org/10.3390/nu6020829
2. Bergeron MF. Muscle cramps during exercise—is it fatigue or electrolyte deficit? Current Sports Medicine Reports. 2008;7(4):S50-S55. https://doi.org/10.1249/JSR.0b013e31817ef417
3. Branch JD. Effect of creatine supplementation on body composition and performance: A meta-analysis. International Journal of Sport Nutrition and Exercise Metabolism. 2003;13(2):198-226. https://doi.org/10.1123/ijsnem.13.2.198
4. Burd NA, Gorissen SH, van Loon LJ. Anabolic resistance of muscle protein synthesis with aging. Exercise and Sport Sciences Reviews. 2013;41(3):169-173. https://doi.org/10.1097/JES.0b013e318292f3d5
5. Casa DJ, Armstrong LE, Hillman SK, Montain SJ, Reiff RV, Rich BS, *et al*. National Athletic Trainers' Association position statement: Fluid replacement for athletes. Journal of Athletic Training. 2000;35(2):212-224.
6. de Toro-Martín J, Arsenault BJ, Després JP, Vohl MC. Precision nutrition: A review of personalized nutritional approaches for the prevention and management of metabolic syndrome. Nutrients. 2017;9(8):913. https://doi.org/10.3390/nu9080913
7. Dupuy O, Douzi W, Theurot D, Bosquet L, Dugué B. An evidence-based approach for choosing post-exercise recovery techniques to reduce markers of muscle damage, soreness, fatigue, and inflammation: A systematic review with meta-analysis. Frontiers in Physiology. 2018;9:403. https://doi.org/10.3389/fphys.2018.00403
8. Enns DL, Tiidus PM. The influence of estrogen on skeletal muscle: Sex matters. Sports Medicine. 2010;40(1):41-58. https://doi.org/10.2165/11319760-000000000-00000
9. Howatson G, Van Someren KA. The prevention and treatment of exercise-induced muscle damage. Sports Medicine. 2008;38(6):483-503. https://doi.org/10.2165/00007256-200838060-00004
10. Ivy JL. Regulation of muscle glycogen repletion, muscle protein synthesis and repair following exercise. Journal of Sports Science & Medicine. 2004;3(3):131-138.
11. Jackman SR, Witard OC, Jeukendrup AE, Tipton KD. Branched-chain amino acid ingestion can ameliorate soreness from eccentric exercise. Medicine & Science in Sports & Exercise. 2010;42(5):962-970.

https://doi.org/10.1249/MSS.0b013e3181c1b798
12. Jäger R, Kerksick CM, Campbell BI, Cribb PJ, Wells SD, Skwiat TM, *et al*. International Society of Sports Nutrition position stand: Protein and exercise. Journal of the International Society of Sports Nutrition. 2017;14(1):20. https://doi.org/10.1186/s12970-017-0177-8
13. Jones ML, Tomaro-Duchesneau C, Prakash S. The gut microbiome, probiotics, and their potential role in muscle recovery and sports performance. Journal of Applied Microbiology. 2020;128(6):1626-1642. https://doi.org/10.1111/jam.14589
14. Kavitha K, Kowshik J, Kishore TK, Baba AB. Green tea catechins alleviate oxidative stress-mediated cellular toxicity in the murine macrophage cell line RAW 264.7. Food and Chemical Toxicology. 2013;62:814-822. https://doi.org/10.1016/j.fct.2013.10.015
15. Maughan RJ, Shirreffs SM. Dehydration and rehydration in competitive sport. Scandinavian Journal of Medicine & Science in Sports. 2010;20(S3):40-47. https://doi.org/10.1111/j.1600-0838.2010.01207.x
16. Maughan RJ, Watson P, Cordery PA, Walsh NP, Oliver SJ, Dolci A, *et al*. A randomized trial to assess the potential of different beverages to affect hydration status: Development of a beverage hydration index. American Journal of Clinical Nutrition. 2016;103(3):717-723. https://doi.org/10.3945/ajcn.115.114769
17. McFarlin BK, Venable AS, Henning AL, Sampson JN, Pennel K, Vingren JL, Hill DW. Reduced inflammatory and muscle damage biomarkers following oral supplementation with bioavailable curcumin. BBA Clinical. 2016;5:72-78. https://doi.org/10.1016/j.bbacli.2016.02.003
18. McLeay Y, Barnes MJ, Mundel T, Hurst SM, Hurst RD, Stannard SR. Effect of New Zealand blueberry consumption on recovery from eccentric exercise-induced muscle damage. Journal of the International Society of Sports Nutrition. 2012;9(1):19. https://doi.org/10.1186/1550-2783-9-19
19. Merry TL, Ristow M. Do antioxidant supplements interfere with skeletal muscle adaptation to exercise training? Journal of Physiology. 2016;594(18):5135-5147. https://doi.org/10.1113/JP270654
20. Morton RW, Murphy KT, McKellar SR, Schoenfeld BJ, Henselmans M, Helms E, *et al*. A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. British Journal of Sports Medicine. 2018;52(6):376-384. https://doi.org/10.1136/bjsports-2017-097608
21. Mossink JP. Zinc and the immune system: The biological basis of altered resistance to infection. American Journal of Clinical Nutrition. 1990;51(2):225-227. https://doi.org/10.1093/ajcn/51.2.225
22. Nieman DC. Influence of carbohydrate on the immune response to intensive, prolonged exercise. Exercise Immunology Review. 1998;4:64-76.
23. Owens DJ, Sharples AP, Polydorou I, Alwan N, Donovan T, Tang J, *et al*. A systems-based investigation into vitamin D and skeletal muscle repair, regeneration, and hypertrophy. American Journal of Physiology-Endocrinology and Metabolism. 2015;309(12):E1019-E1031. https://doi.org/10.1152/ajpendo.00375.2015
24. Owens DJ, Twist C, Cobley JN, Howatson G, Close GL. Exercise-induced muscle damage: What is it, what causes it and what are the nutritional solutions? European Journal of Sport Science. 2019;19(1):71-85. https://doi.org/10.1080/17461391.2018.1505953
25. Peake JM, Neubauer O, Della Gatta PA, Nosaka K. Muscle damage and inflammation during recovery from exercise. Journal of Applied Physiology. 2017;122(3):559-570. https://doi.org/10.1152/japplphysiol.00971.2016
26. Petersen LM, Bautista EJ, Nguyen H, Hanson BM, Chen L, Lek SH, Sodergren E. Community characteristics of the gut microbiomes of competitive cyclists. Microbiome. 2017;5(1):98. https://doi.org/10.1186/s40168-017-0310-4
27. Philpott JD, Donnelly C, Walshe IH, Bell PG. Omega-3 polyunsaturated fatty acids augment the adaptations to resistance exercise training: A systematic review and meta-analysis. Sports Medicine. 2018;48(6):1377-1391. https://doi.org/10.1007/s40279-018-0880-5
28. Proske U, Morgan DL. Muscle damage from eccentric exercise: Mechanism, mechanical signs, adaptation and clinical applications. Journal of Physiology. 2001;537(2):333-345. https://doi.org/10.1111/j.1469-7793.2001.00333.x
29. Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS. Exercise and fluid replacement. Medicine & Science in Sports & Exercise. 2007;39(2):377-390. https://doi.org/10.1249/mss.0b013e31802ca597
30. Schoenfeld BJ, Aragon AA, Krieger JW. The effect of protein timing on muscle strength and hypertrophy: A meta-analysis. Journal of the International Society of Sports Nutrition. 2013;10(1):53. https://doi.org/10.1186/1550-2783-10-53
31. Shaw G, Lee-Barthel A, Ross ML, Wang B, Baar K, Baar K. Vitamin C-enriched gelatin supplementation before intermittent activity augments collagen synthesis. American Journal of Clinical Nutrition. 2017;105(1):136-143. https://doi.org/10.3945/ajcn.116.138594
32. Shirreffs SM, Sawka MN. Fluid and electrolyte needs for training, competition, and recovery. Journal of Sports Sciences. 2011;29(S1):S39-S46. https://doi.org/10.1080/02640414.2011.614269
33. Smith-Ryan AE, Trexler ET, Wingfield HL, Blue MN. Effects of hormonal contraceptives and menstrual cycle phase on athletes' performance: A systematic review. Journal of Strength and Conditioning Research. 2021;35(3):689-698. https://doi.org/10.1519/JSC.0000000000003670
34. Sousa M, Teixeira VH, Soares J. Dietary strategies to recover from exercise-induced muscle damage. International Journal of Food Sciences and Nutrition. 2014;65(2):151-163. https://doi.org/10.3109/09637486.2013.852688
35. Tinsley GM, Smith JW, Graybeal AJ. Effects of fish-oil-derived n-3 polyunsaturated fatty acid supplementation on markers of inflammation and recovery from eccentric exercise. Journal of Dietary Supplements. 2016;13(1):1-14. https://doi.org/10.3109/19390211.2014.952866
36. Tipton KD, Rasmussen BB, Miller SL, Wolf SE, Owens-Stovall SK, Petrini BE, Wolfe RR. Timing of amino acid-carbohydrate ingestion alters anabolic response of muscle to resistance exercise. American Journal of Physiology-Endocrinology and Metabolism. 2001;281(2):E197-E206. https://doi.org/10.1152/ajpendo.2001.281.2.E197
37. Trombold JR, Reinfeld AS, Casler JR, Coyle EF. The

effect of pomegranate juice supplementation on strength and soreness after eccentric exercise. Journal of Strength and Conditioning Research. 2011;25(7):1782-1788. https://doi.org/10.1519/JSC.0b013e318220b85c
38. Volpe SL. Magnesium in disease prevention and overall health. Advances in Nutrition. 2015;4(3):378S-383S. https://doi.org/10.3945/an.112.003483
39. Walsh NP, Blannin AK, Robson PJ, Gleeson M. Glutamine, exercise and immune function: Links and possible mechanisms. Sports Medicine. 2011;26(3):177-191. https://doi.org/10.2165/00007256-199826030-00003