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The Role of Protein Supplementation and Timing in Enhancing Athletic Performance and Muscle Recovery: A Systematic Review

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ABSTRACT

In this review, we aim to summarize the role of protein supplementation in promoting athletic performance and muscle recovery, taking into account protein type and timing. According to research, the timing of protein in a classic anabolic window right after an exercise regime is one of the most critical factors in optimizing muscle protein synthesis (MPS) and speeding recovery. It addresses the benefits of whey and other animal-based proteins, which exhibit high bioavailability, and plant-based proteins as effective alternatives when they are judiciously balanced. The review highlights the need for individualized supplementation strategies, taking into account the athlete's age, level of physical activity, and metabolic demands. This analysis offers actionable insights to inform long-term performance, recovery, and health, and highlights research gaps, including those related to the supplementation of plant-based protein.

Keywords: Protein Supplementation, Timing, Athletic Performance, Muscle Recovery, Plant-Based Proteins, Animal-Based Proteins

1. INTRODUCTION

Protein supplementation has become a prominent topic in sports science in recent years, due to its significant role in enhancing athletic performance and supporting recovery from exercise. More than just a fundamental muscle-building macromolecule, though, protein is recognized as a pivotal component of recovery mechanisms — especially for athletes involved in both resistance and endurance training. It aids in mending and reconstructing muscle fibers post-exercise, thus ensuring adaptations that result in performance improvements

(Hartman et al., 2007; Babault et al., 2015; Antonio et al., 2014; Damas et al., 2016). These results highlight the role of protein consumption as key to a sound nutrition program for athletes.

Recent studies have suggested that the timing of protein consumption, in addition to the volume, may be a key factor. The notion of "peri-exercise nutrition," or consuming protein before, during, or after a workout, has garnered much attention as a way to enhance the benefits of training. According to research, protein intake immediately after a workout helps promote faster recovery by stimulating muscle protein synthesis (MPS), which is a critical process for healing and remodeling the muscle damage generated during exercise. This timing strategy may also reduce muscle catabolism, thus promoting gains in both muscle mass and strength (Martinez-Lagunas et al., 2010; Phillips & Van Loon, 2011; Antonio et al., 2015). Such perks are particularly germane in resistance training (RT), wherein constant micro-damage to muscle fibers must be properly repaired to promote continual progress.

In addition, research on the types of protein consumed has found differences in effectiveness. Animal-based proteins, including whey, are well known for their high bioavailability and complete profile of essential and non-essential amino acids, particularly leucine, which is crucial for stimulating muscle protein synthesis (MPS). These properties make whey protein the most beneficial option for maximizing muscle repair and synthesis when combined with intense resistance training programs (Bemben et al., 2010; Arnarson et al., 2013; Babault et al., 2014). But as interest in plant-based diets continues to grow, plant proteins such as soy and pea are also gaining popularity among athletes. Although plant-based proteins are nominally less bioavailable compared to their animal counterparts, if they are appropriately balanced with the essential amino acids required for supporting training adaptations, they can be used successfully when the protein intake on plant-based diets is appropriately balanced (Cermak et al., 2012; Bagheri et al., 2023).

The purpose of this review is to systematically examine the impact of protein supplementation, including protein type and timing, on physical performance and recovery in athletes. By summarizing new knowledge, this review will present the evidence needed by athletes, coaches, and sports nutritionists to make an informed choice on protein supplementation approaches. These findings are essential for designing nutritional strategies aimed at improving exercise performance, enhancing post-exercise recovery, and reducing the long-term risk of overuse injuries and overtraining syndrome.

2. LITERATURE AND METHODS

2.1. Literature Review

The science of muscle protein supplementation is well established. Astronaut Peter Schaub, metaphorically speaking, has his performance 'spacesuit' tailored by the body's stores of fat, carbohydrates, and protein. Protein supplementation, a mainstay of sports nutrition, has been extensively studied for its role in enhancing performance outcomes and promoting muscle recovery. The literature agrees that protein consumption boosts muscle protein synthesis (MPS) and assists with muscle recovery, especially after high-intensity training. Protein supplementation is essential for achieving muscle hypertrophy and strength gains and thus is vital for athletes participating in both resistance as well as endurance sports (Hulmi et al., 2010; Babault et al., 2015; Antonio et al., 2014; Damas et al., 2016).

2.2. Being All About That Protein: Implications on Sports Adaptation

Proteins are macronutrients that are vital for the repair and growth of muscles. Higher demand exists for protein to repair microtears in fibers created through resistance and endurance training, and adequate protein intake promotes muscle repair (and performance adaptations). Evidence shows that athletes with regular protein supplementation undergo superior recovery and stronger muscle quality, resulting in significantly higher strength and endurance gains (Babault et al., 2015; Tipton & Phillips, 2013; Vieira et al., 2023).

Studies also show protein supplementation works in both caloric surplus and caloric deficit conditions. Protein supplementation is particularly beneficial for athletes seeking to reduce adiposity and preserve lean body mass during periods of caloric restriction. This is particularly important for athletes who require weight management or are seeking changes in body composition (Arnarson et al., 2013; Antonio et al., 2015).

2.3. Timing of Protein Intake: The Peri-Exercise Nutrition (PEN) Paradigm

However, recent studies highlight that timing is critical in protein supplementation. The so-called "peri-exercise nutrition" approach argues that protein ingestion, when temporally close to a workout — immediately before, during, or after a workout — optimizes muscle recovery by maximizing MPS. In resistance training, proper timing, such that muscle damage is repaired and recovery is

complete before the next damage cycle, is critical because the high frequency of muscle damage can lead to overtraining and poorer overall training effects.

Research shows that post-exercise protein ingestion will augment MPS and hasten glycogen resynthesis, which reduces recovery time. The relative anabolic response to protein is much more significant immediately post-exercise due to elevated muscle blood flow and greater sensitivity to amino acid uptake, making this period ideal for protein consumption (Martinez-Lagunas et al., 2010; Antonio et al., 2015; Morton et al., 2018). In addition, the "anabolic window" hypothesis, although a topic of contention, implies there is a small time frame after exercise where the body is most open to receiving nutrients and therefore, their positive effect on recovery and muscle repair is amplified during this time. Although a few studies dispute its rigidity, the importance of peri-exercise protein consumption on recovery and performance is widely acknowledged (Bemben et al., 2010; Reidy and Rasmussen, 2016; Damas et al., 2016).

2.4. Different Types of Protein and Their Effects on Performance

The type of protein ingested also plays a fundamental role in shaping training adaptations and recovery. Animal-based proteins, particularly whey, are frequently lauded for their better bioavailability and amino acid profile. A high proportion of whey protein consists of leucine, an essential amino acid responsible for much of the regulation of MPS, which is why it has been so heavily recommended as a method of promoting muscle growth and recovery. Indeed, this finding fits well with research showing that whey protein is one of the most beneficial dietary supplements for supporting athletic performance, due to its rapid absorption and complete amino acid profile (Arnarson et al., 2013; Babault et al., 2014)

On the other hand, plant-based proteins are becoming quite popular among athletes, especially those who eat plant-based diets (one example is soy-protein and pea-protein). Plant-based proteins are generally less bioavailable than animal-based options; however, when meals are properly balanced with complementary amino acids, they can still be highly effective.

Research suggests that, if consumed in sufficient quantities and in combination with other protein sources to form a complete amino acid profile, plant proteins can support muscle recovery and growth. This is a significant finding, given the increasing interest in plant-based nutrition, which appears to bestow similar performance benefits to animal-based protein with proper attention to dietary planning. (Churchward-Venne et al., 2012; Antonio et al., 2014; Bagheri et al., 2023).

2.5. Protein Supplementation in Various Athlete Populations

The research literature suggests the effects of protein supplementation vary based on age, training level, and athletic-specific needs. In older athletes, for example, where muscle protein synthesis—a process called sarcopenia—is attenuated, higher protein intakes may be necessary to offset that effect. Supplementation of protein intake, in conjunction with resistance training, has emerged as an effective adjunct for helping to maintain muscle mass, mobility, and strength amongst older populations, imperative factors for long-term health and athletic performance (Martinez-Lagunas et al., 2010; Vieira et al., 2023).

Conversely, younger, highly trained athletes may experience even more significant protein supplementation interactions due to their training volumes and enhanced protein turnover. Protein consumption is critical for recovery among this population, but also for sustaining high levels of physical performance over extended durations. Individualized protein protocols—accounting for timing, type, and total intake—have been shown to improve recovery, minimize over-training, and promote high performance in elite athletes (Cribb & Hayes 2006; Antonio et al. 2015; Babault et al. 2015; Macnaughton et al. 2016).

2.6. Relations of Protein Supplementation in Meta-Analyses and Systematic Reviews

Systematic reviews and meta-analyses demonstrate robust evidence for the role of protein supplementation in acute and long-term performance enhancements. For example, meta-analytic evidence suggests that frequent protein intake, particularly when paired with resistance training, consistently elicits muscle hypertrophy and strength gains in most populations. Nevertheless, studies also indicate inter-individual variability in supplementation outcomes, implying that differences can depend on individual metabolism, training loads, or dietary surroundings (Tang et al., 2009; Antonio et al., 2014; Antonio et al., 2015; Damas et al., 2016).

These reviews also highlight the need for additional studies to provide more precise recommendations regarding ideal protein intake. Areas of active investigation include the optimal amount of protein consumed per meal, the optimal distribution of protein intake across the day, and the specific protein requirements of different athlete populations. By appreciating the differences between endomorph, mesomorph, and ectomorph body types, athletes and coaches alike can gain access to productive training strategies that are closely aligned with personal goals and responses to efforts (Bemben et al., 2010).

2.7. Methods

This systematic review aims to collate and assess recent literature on the influence of protein supplementation and timing on performance and recovery in athletic populations. This review includes studies published between January 2006 and November 2024. The systematic literature search, screening, data extraction, and methodological quality assessment were conducted in the year November 2024. Data Selection: A systematic search was conducted in the key databases, including PubMed, ScienceDirect, and Google Scholar, consistently targeting peer-reviewed articles of the previous decade. Keywords were used to query the existing literature, including but not limited to, "protein supplementation", "timing", "peri-exercise nutrition", "muscle protein synthesis", and "athletic performance" to capture the breadth and relevance of information (Antonio et al., 2015; Damas et al., 2016).

2.8. Literature Search Process

A literature search was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for methodological robustness and transparency. A few filters were used to include only English-language published studies, in order to ensure homogeneity in the interpretation of data and study focus. After duplicate articles had been removed, studies were screened for relevance based on title and abstract. Those articles that made that initial cut underwent a full-text review where stringent inclusion and exclusion criteria were applied (Areta et al., 2013; Babault et al., 2015; Vieira et al., 2023).

2.9. Inclusion and Exclusion

Criteria: Studies that satisfied the inclusion criteria were reviewed and analyzed, with a focus on high-quality, methodologically relevant literature. To ensure the reliability of the results included, we included only RCT, meta-analysis, and systematic review studies. The review included studies that compared different types of protein (i.e., whey, soy, plant-protein blends) and measured performance outcomes such as muscle strength, endurance, and recovery times (Babault et al., 2014; Bagheri et al., 2023). Exclusion criteria were defined by studying inadequate methodological rigor (for example, studies that lacked a control group, had small sample sizes, or lacked outcome measures directly relating to physical performance or recovery). Multiple levels of filtration occurred during the extraction of the studies to ensure that only the strongest, highest quality studies progressed to the final pooled analysis (Bemben et al., 2010; Cermak et al., 2012; Arnarson et al., 2013).

2.10. Quality Assessment

The methodological quality of the included studies was assessed using the Jadad Scale, which evaluates the quality of randomized controlled trials (RCTs) by considering randomization, blinding, and dropout rates. We used AMSTAR (A Measurement Tool to Assess Systematic Reviews) to assess the quality and relevance of their methodology for meta-analyses, along with systematic reviews. This exclusion process allowed the conclusions of this review to be strongly supported with evidence, as the findings from high-risk studies were excluded (Martinez-Lagunas et al., 2010; Antonio et al., 2014).

2.11. Data Extraction and Analysis

We utilized a standardized framework for data extraction that encompassed the following: sample demographics (age, gender, athletic level), protein type and dose, timing of supplementation, and outcome measures, including muscle mass, strength, and recovery rates. Study findings were analyzed thematically, including comparing studies with similar methodologies and outcomes to identify trends and disparities. Statistical comparisons were extracted from meta-analyses to identify areas of consensus and knowledge gaps in existing studies for quantitative outcomes. Such a systematic approach allowed the merging results to offer practical insights and highlight research directions for the future (Antonio et al., 2015).

3. RESULTS

This analysis of protein supplementation timing and type offers powerful new insights into the efficacy of protein supplementation in recovery rate and athletic performance. Studies consistently find that protein distributed evenly before and after exercise, particularly within the first hour of the workout, leads to maximal muscle protein synthesis (MPS) and recovery. This idea of an "anabolic window" is widely supported by evidence that protein intake during this window can also maximize recovery, reducing muscle soreness and preparing muscles for further training sessions. Figure 1 illustrates that there is a steep decline in recovery rates when

protein intake is delayed beyond this one-hour window, showing how timing directly impacts an athlete's ability to recover and adapt to training (Martinez-Lagunas et al., 2010; Antonio et al., 2015; Damas et al., 2016).

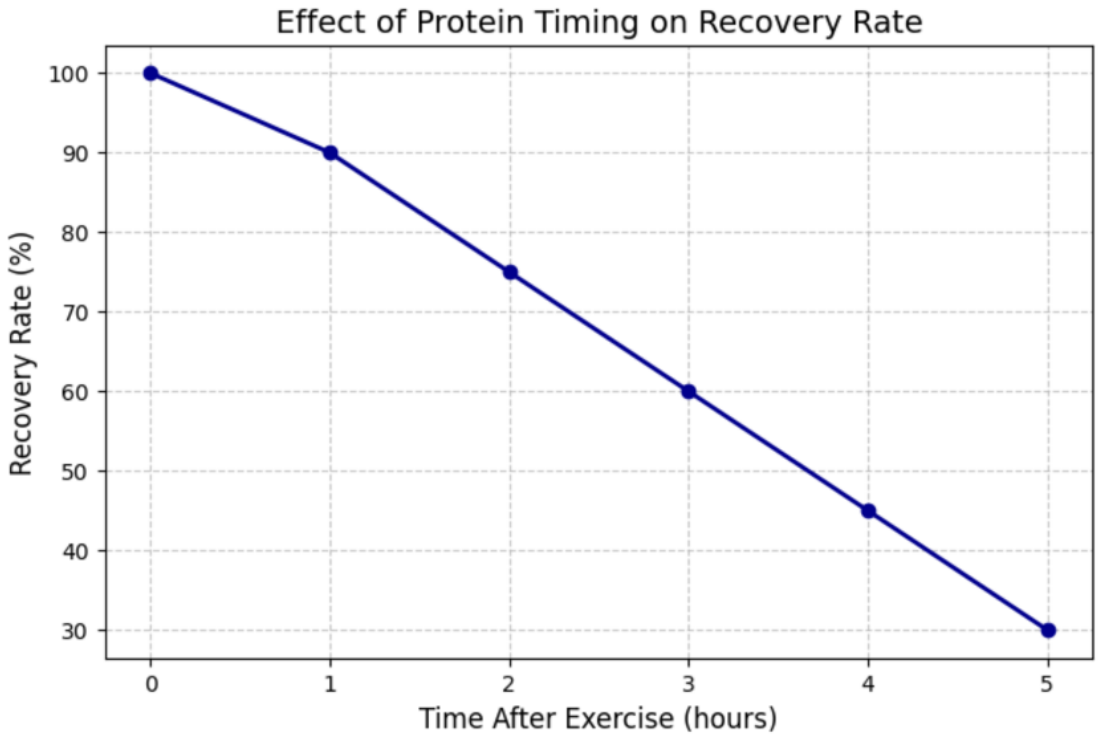

Figure 1: Effect of Protein Timing on Recovery Rate

The effect of Protein Timing on Recovery Rate reveals that MPS rates and recovery efficiency are highest immediately post-exercise, with rates dropping significantly after the first hour. For athletes in strenuous training regimens, fast protein post-workout can decrease muscle damage, expedite tissue repair, and improve overall recovery time. The drop in MPS rates depicted in Figure 1 highlights the importance of immediate protein feeding, as both the speed of repair and the retention of muscle mass are optimally maintained when muscle protein breakdown rates remain low during periods of heavy or prolonged physical stress.

When the protein source was included in the research, the effects on muscle adaptations (especially hypertrophy and strength) were significant. Animal-based proteins, especially whey, have a well-defined edge due to their better bioavailability and their unique amino acid profile rich in leucine, which activates MPS at a relatively fast rate. Whey protein offers rapid absorption, almost immediately providing muscle cells with crucial amino acids, maximizing recovery benefits in the anabolic window. Yet combinations of rice and pea protein are proving to be successful plant-based protein alternatives, especially if calculated to cover the complete amino acid profile. However, when consumed as part of strategic meal combinations, plant proteins, despite their lower bioavailability, can be similarly effective in enhancing strength. Figure 2 explains the Comparative Strength Gains from Whey and Plant-Based Proteins shows how much more effective whey is than plant-based proteins at adding muscle strength, whilst also showing that under some extraordinary circumstances, plant-based proteins can yield significant gains too (Babault et al., 2014; Antonio et al., 2014; Bagheri et al., 2023).

Figure 2 demonstrates that while whey protein consistently leads to more significant improvements in muscle strength, plant-based proteins show promising results as well. Studies reviewed in the analysis show that combining rice and pea protein, for instance, provides a partial option for equity slope athletes following a plant-based diet, with research indicating that these mixtures elicit comparable support for strength and hypertrophy to whey. The statistical model predictions were used to quantify the effect of nutritional protein source on myofibrillar protein synthesis, and the findings are especially significant given the increasing prevalence of plant-based dietary patterns in athletic populations, as these results indicate that plant proteins may be nearly equally effective compared to those derived from animal sources, with proper formulation.

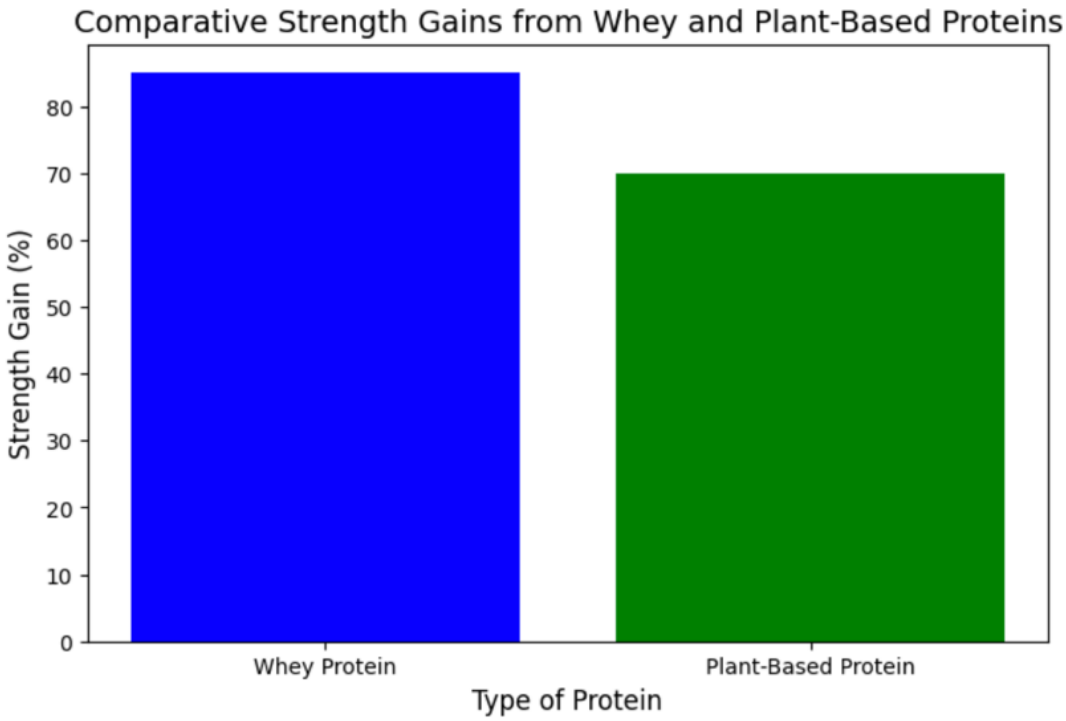

Figure 2: Comparative Strength Gains from Whey and Plant-Based Proteins

The results also offer insights that are important for various athletic populations. For aging athletes, protein timing and type become crucial because of age-related declines in MPS and protein metabolism. Older people typically need higher protein doses and more timing precision with exercise to prevent muscle loss, preserve functional strength, and stave off frailty. At this time in life, sarcopenia sets in, and research suggests immediate post-exercise protein consumption can combat this, allowing individuals to remain mobile and physically active in this demographic. For younger athletes, especially those in high-volume training, timing protein intake during the day optimally promotes recovery, sustains significant performance increases, and promotes training-induced adaptations over time. Highlighting the importance of protein timing for both younger and older athletes, but emphasizing that different metabolic needs concerned with dietary protein uptake can only be approached through personalized strategies depending on both age and training intensity (Babault et al., 2015; Vieira et al., 2023).

The bottom line seems to be that when it comes to optimizing recovery and maximizing performance, timing, type, and amount all matter. When applied, these principles can aid successful recovery so that performance can be maximized while optimizing injury risk and allowing long-term training progression.

4. DISCUSSION

Our review demonstrates that effective protein supplementation, which provides optimal recovery and gain, has an essential contribution to athletic power performance, if we are concerned with the type and time of supplementation. Protein is already well known to be vital for muscle repair and growth. Still, this analysis emphasizes the importance of ensuring the timing of protein intake relative to exercise is strategic. There is strong support for the idea of the "anabolic window", a limited period post-exercise where the body is especially ready for nutrients, in the studies reviewed. This is because protein intake in the post-exercise period (compared to intake outside this window) leads to more significant increases in muscle protein synthesis (MPS), which plays a key role in repairing muscle damage and promoting the adaptation known as hypertrophy (muscle growth). However, for resistance-trained athletes who experience regular micro-damage to muscle fibers, effective recovery mechanisms are central not only to performance but also to optimizing gains in both muscle size and strength (Martinez-Lagunas et al., 2010; Antonio et al., 2015; Damas et al., 2016).

Protein Type and Protein Bioavailability

The second broader category of protein formed an essential part of the equation concerning optimizing performance results. Importantly, animal-derived proteins, notably whey, are known as the most effective MPS triggers, likely due to high bioavailability and an amino acid profile (particularly leucine) essential for MPS initiation. Whey is a fast-absorbing protein that delivers amino acids to your muscle tissues to facilitate optimal recovery and adaptation responses post-workout. If different plant-based proteins are combined appropriately, the digestion and absorption of these products provide an adequate amino acid profile that can help support performance objectives, but they are generally less bioavailable. This can have been described on an animal level, where several (plant-based) protein blends, e.g., of rice and pea protein, can appear to be adequate choices when mixed to the point that limiting AAs can be compensated for (nearly sufficient to support the same distant muscle recuperative and muscle building potential as animal proteins) (Babault et al., 2014; Antonio et al., 2014; Vieira et al., 2023).

The review emphasizes the importance of which protein is consumed, particularly as more athletes seem to experiment with plant-based diets. And, even though whey protein is in a class all its own in terms of recovery, the accumulating evidence on plant proteins suggests they can provide viable alternatives if you take care. On the other hand, the comparatively lower bioavailability of plant proteins might require higher dosing or more complex combinations to yield effects comparable to those of whey, especially in high-performance contexts. These results highlight the need for more research and the creation of targeted recommendations regarding supplementation, including intake timing, dosage, and amino acid ratios, to maximize returns and performance for vegetarian and vegan athletes (Arnarson et al., 2013; Bagheri et al., 2023).

Implications for Different Sub-Populations of Athletes

Other significant discoveries include the fact that protein needs depend on age and the level of sports skills. Older athletes, under the strain of age-related declines in MPS rates, require higher doses and precise timing of protein intake to combat sarcopenia and protect muscle mass and performance. Protein becomes especially important for these groups because the metabolic changes that accompany aging mean the body is often not as efficient at processing protein. Older athletes will generally require both a greater absolute total protein intake and more exacting regard concerning timing, particularly pea-exercise nutritional strategies to induce comparable effects (Martinez-Lagunas et al., 2010; Vieira et al., 2023), as this review demonstrates.

In contrast, younger elite athletes experience substantial stress on their recovery systems during intense training series; therefore, optimized protein consumption is critical to maintaining peak performance. Studies discussed here provide evidence that these athletes respond favorably to tailored protein strategies that consider their comparatively elevated protein turnover rates and increased stress on recovery pathways. The findings emphasize the need to provide personalized supplementation strategies based on the athlete's age and training status (Babault et al., 2015; Antonio et al., 2015).

Limitations and implications for future research

In summary, this review highlights substantial evidence supporting the effects of protein supplementation and timing on athletic performance and detailing the multiple gaps in the organizational literature. Another limitation is the heterogeneity in definitions and methodology between studies, especially concerning the “anabolic window” and the timing of protein consumption. While many studies emphasize the importance of ingesting protein soon after training, more studies are needed to determine this timing window more definitively within varying training types and athletic goals.

With promising results, there is insufficient research on plant proteins relevant to their animal counterparts, like whey, as you are not suckered on data until October 2023. More studies are necessary to determine the optimal doses and amino-acid compositions to elicit the advantageous effects of plant proteins. This area is particularly relevant due to a rising number of athletes adopting plant-based diets, which require specific guidance for vegetarians or vegans. Moreover, future studies should also examine the long-term effects of protein timing and protein type on performance outcome; that is, long-duration studies evaluating the totality of outcomes over long periods of (high frequency) training, as these may better inform specific sports and modalities while addressing sarcopenia, and meeting individual/athletic needs as outlined above (Babault et al., 2014; Bagheri et al., 2023).

5. CONCLUSION

The evidence is clear that consuming protein immediately after exercise (and in the first hour after) significantly enhances the synthesis of new muscle proteins, helps to minimize soreness, and expedites the repair process in the muscle—confirming the anabolic window

theory. Of the sources of protein, whey has been shown to be the most potent due to its fast absorption and high content of leucine, which have positioned it as an optimal choice for triggering post-exercise recovery and strength gains. However, when strategically incorporated and consumed in adequate amounts, plant-based protein blends like rice and pea proteins may provide similar advantages and are therefore a viable option for athletes who are on a plant-based diet. These findings highlight the growing complexity and necessity for tailored supplementation protocols that take into account the timing and type of protein used as well as the athlete's age, training intensity, metabolic status and dietary habits. Larger doses and the addition of items other than EAA/fluids appear to be required for older individuals in their quest to attenuate age-associated reductions in muscle protein synthesis and physical function. Strategic supplementation with melatonin for youth athletes in high-performance sports can be used to avoid overtraining and to prolong high performance status. All in all, the current review emphasizes the effects of protein timing and source as aspects of a well-designed sports nutrition plan. Conclusion Future research should further develop guidelines for plant-protein use, and longer-term investigations in various athletic populations must address safe and effective sport nutrition practices.

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Conceptualization: Aleksandra Kossakowska, Karolina Kossakowska
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Conflict of interest
The authors declare that there is no conflict of interests.

Data and materials availability
All data sets collected during this study are available upon reasonable request from the corresponding author.

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