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Revisiting Protein Intake in Fitness Training: New Evidence on Dose, Timing, and Skeletal Muscle Adaptation

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Abstract
Protein intake is a fundamental nutritional determinant of skeletal muscle adaptation in response to resistance-based fitness training. Over the last two decades, advances in exercise physiology and nutritional science have substantially refined the understanding of how protein dose, distribution, and timing influence muscle protein synthesis, hypertrophy, and strength development. The purpose of this article is to revisit and critically synthesize contemporary evidence on protein intake in fitness training, with a specific focus on optimal dosing strategies, temporal distribution relative to exercise, and their interaction with resistance training–induced skeletal muscle adaptation.
This review integrates findings from recent systematic reviews, meta-analyses, and international position stands to examine the dose–response relationship between dietary protein intake and hypertrophic outcomes. Evidence indicates that daily protein intakes above traditional recommendations, typically in the range of ≥1.6–2.2 $g \cdot kg^{-1} \cdot day^{-1}$, are associated with greater increases in fat-free mass in resistance-trained individuals. Furthermore, emerging research challenges the traditional concept of a narrow post-exercise "anabolic window," suggesting that total daily protein intake and even distribution across meals may exert a more pronounced influence on long-term muscle adaptation than precise nutrient timing alone. Mechanistic insights related to amino acid availability, leucine threshold signaling, and regulation of muscle protein turnover are discussed to contextualize these findings.
In addition, individual moderators such as training status, age, energy balance, and training volume are examined for their role in shaping protein requirements and adaptive responses. By integrating physiological mechanisms with applied evidence, this article aims to clarify ongoing controversies and provide an updated, evidence-based framework for protein intake strategies in fitness training. The findings support a shift from rigid timing-focused models toward a holistic approach emphasizing adequate total protein intake, appropriate per-meal dosing, and alignment with resistance training demands to optimize skeletal muscle adaptation.

Keywords: protein intake, muscle hypertrophy, resistance training, nutrient timing, muscle protein synthesis, fitness training

1. Introduction

Skeletal muscle hypertrophy represents a primary adaptive outcome of resistance-based fitness training and is critically influenced by nutritional factors, particularly dietary protein intake. Resistance exercise provides the mechanical and metabolic stimulus necessary to initiate muscle remodeling, while protein ingestion supplies the essential amino acids required to support muscle protein synthesis (MPS) and net protein accretion. The interaction between training-induced stimuli and nutritional availability underpins the adaptive process leading to increases in muscle mass and strength.

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Historically, recommendations for protein intake in physically active individuals were derived from nitrogen balance studies and generalized dietary guidelines, often suggesting intakes only marginally higher than those for sedentary populations. However, accumulating evidence over the past two decades has demonstrated that such recommendations may underestimate the protein requirements necessary to optimize muscle hypertrophy, particularly in resistance-trained individuals and athletes. This growing body of research has prompted a reassessment of protein intake strategies in fitness training, with particular attention to daily dose, per-meal distribution, and nutrient timing.

One of the most influential concepts shaping protein intake practices has been the notion of the post-exercise "anabolic window," which posits that protein consumption immediately after resistance training is critical for maximizing hypertrophic adaptations. Early studies suggested that delaying protein intake following exercise could attenuate gains in muscle mass and strength. However, more recent systematic reviews and meta-analyses have questioned the rigidity of this window, proposing that total daily protein intake and habitual distribution across meals may play a more substantial role in long-term adaptation than acute timing alone. These findings have generated ongoing debate within both scientific and applied fitness communities.

In parallel, advances in molecular physiology have clarified key mechanisms through which dietary protein influences muscle adaptation. The availability of essential amino acids - particularly leucine - has been shown to activate intracellular signaling pathways such as the mechanistic target of rapamycin complex 1 (mTORC1), thereby stimulating MPS. Importantly, the responsiveness of skeletal muscle to protein intake appears to be modulated by factors including training status, age, energy balance, and exercise volume. These moderators suggest that optimal protein intake strategies may need to be individualized rather than universally prescribed.

From a practical perspective, fitness training encompasses a broad population, ranging from recreational exercisers to highly trained athletes, each with distinct nutritional needs and adaptive capacities. In this context, translating research findings into clear, evidence-based recommendations remains a challenge (Zhao et al., 2024). While numerous position stands and narrative reviews have addressed protein requirements, discrepancies persist regarding optimal dosing thresholds, meal frequency, and the relative importance of timing strategies (Petcu et al., 2025; Yasuda et al, 2022).

Therefore, the purpose of this article is to revisit protein intake in fitness training by synthesizing contemporary evidence on protein dose, timing, and skeletal muscle adaptation. By integrating findings from mechanistic studies, applied research, and large-scale meta-analyses, this review aims to clarify current controversies and provide an updated framework for understanding how dietary protein supports hypertrophic adaptation in resistance-trained individuals. Such clarification is essential for advancing both scientific knowledge and evidence-based practice in fitness training and sports nutrition.

2. Physiological Basis of Protein-Induced Skeletal Muscle Adaptation

Skeletal muscle hypertrophy is the result of a chronic positive balance between muscle protein synthesis (MPS) and muscle protein breakdown (MPB), achieved through the interaction of resistance exercise and dietary protein intake. Resistance training provides the primary mechanical stimulus that sensitizes skeletal muscle to amino acid availability, while protein ingestion supplies the substrates and signaling triggers necessary to support adaptive remodeling. Understanding the physiological mechanisms underlying this interaction is essential for

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contextualizing contemporary recommendations regarding protein dose and timing in fitness training.

2.1 Muscle Protein Synthesis and Resistance Exercise

Resistance exercise acutely stimulates MPS through mechanotransduction processes that activate intracellular signaling pathways involved in protein translation. Mechanical loading, muscle stretch, and metabolic stress converge to upregulate anabolic signaling cascades, most notably the mechanistic target of rapamycin complex 1 (mTORC1). Activation of mTORC1 increases translational efficiency and capacity, thereby enhancing the synthesis of myofibrillar proteins essential for muscle fiber hypertrophy.

However, resistance exercise alone is insufficient to sustain a net anabolic state. In the absence of adequate amino acid availability, exercise-induced increases in MPS are transient and may be accompanied by elevated MPB. Dietary protein intake plays a crucial role in shifting the net protein balance toward accretion by providing essential amino acids that both stimulate MPS and attenuate MPB. This synergistic effect explains why resistance training and protein ingestion are considered interdependent components of muscle hypertrophy.

2.2 Role of Essential Amino Acids and Leucine Signaling

Among dietary amino acids, essential amino acids (EAAs) are particularly critical for stimulating MPS, as they cannot be synthesized endogenously and must be obtained through diet. Leucine, one of the branched-chain amino acids, has emerged as a key regulator of anabolic signaling due to its capacity to directly activate mTORC1. This phenomenon, often described as the “leucine threshold,” suggests that a minimum leucine concentration is required to maximally stimulate MPS following protein ingestion.

Research indicates that protein sources with a high leucine content, such as whey protein, elicit a more robust MPS response compared to lower-quality or less digestible proteins. Importantly, once the leucine threshold is reached, additional protein intake within a single meal does not proportionally increase acute MPS, highlighting the concept of a saturable anabolic response. This finding has direct implications for per-meal protein dosing and supports the rationale for distributing protein intake evenly across the day rather than consuming large quantities in isolated meals.

2.3 Interaction Between Training Status and Protein Responsiveness

The anabolic response to protein intake is modulated by training status and prior exposure to resistance exercise. Untrained individuals typically exhibit a heightened sensitivity to both exercise and protein ingestion, resulting in pronounced increases in MPS even at relatively modest protein intakes. As training status advances, however, the muscle’s responsiveness becomes more attenuated, necessitating higher protein doses or more precise nutritional strategies to achieve comparable anabolic effects.

This phenomenon partly explains why resistance-trained individuals often require higher daily protein intakes to maximize hypertrophy. Additionally, repeated training bouts induce structural and metabolic adaptations that alter amino acid utilization and turnover, reinforcing the need for sustained protein availability to support ongoing remodeling processes.

2.4 Temporal Dynamics of Protein-Induced Anabolism

The temporal pattern of protein ingestion influences the magnitude and duration of MPS responses. Following resistance exercise, skeletal muscle exhibits a period of heightened anabolic sensitivity to amino acids that can persist for up to 24 hours. While early research emphasized immediate post-exercise protein intake as critical, more recent evidence suggests that this anabolic sensitivity is prolonged, allowing for greater flexibility in nutrient timing.

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From a physiological perspective, this extended window implies that the cumulative availability of amino acids across the post-exercise period is more relevant than the precise timing of a single feeding. Consequently, consistent protein intake across multiple meals may better sustain elevated MPS and support long-term hypertrophic adaptation.

2.5 Net Protein Balance and Long-Term Hypertrophy

While acute increases in MPS are necessary for muscle growth, long-term hypertrophy depends on the repeated accumulation of small, positive net protein balances over weeks and months of training. Protein dose, quality, and distribution collectively influence this cumulative process. Insufficient protein intake, irregular feeding patterns, or prolonged energy deficits can blunt the adaptive response to resistance training, even when training stimuli are optimal.

In this context, protein intake should be viewed not as an isolated nutritional variable, but as a dynamic modulator of training-induced adaptation. The physiological mechanisms outlined above provide a foundation for understanding why contemporary recommendations increasingly emphasize adequate total daily protein intake, appropriate per-meal dosing, and alignment with resistance training demands rather than rigid adherence to narrow timing strategies.

3. Protein Dose: Evidence from Systematic Reviews and Meta-Analyses

Establishing the optimal protein dose for maximizing resistance training–induced skeletal muscle hypertrophy has been a central focus of contemporary sports nutrition research. Over the last two decades, this topic has been increasingly addressed through systematic reviews, meta-analyses, and meta-regression models, which provide higher-level evidence than individual experimental studies. Collectively, these analyses have substantially refined traditional protein intake recommendations and clarified the dose–response relationship between dietary protein and hypertrophic adaptation.

3.1 Total Daily Protein Intake and Hypertrophic Outcomes

Current evidence consistently demonstrates that total daily protein intake is a primary nutritional determinant of muscle hypertrophy when combined with progressive resistance training. A landmark meta-analysis by Morton et al. (2018) examined the effects of protein supplementation on fat-free mass gains and identified a clear dose–response relationship, with maximal hypertrophic benefits occurring at approximately **1.6 $g \cdot kg^{-1} \cdot day^{-1}$**. Importantly, the upper 95% confidence interval of this estimate extended to **~2.2 $g \cdot kg^{-1} \cdot day^{-1}$**, indicating that some individuals may benefit from higher intakes depending on training status and contextual factors.

These findings align with position stands from the International Society of Sports Nutrition (ISSN), which recommend a daily protein intake range of **1.4–2.0 $g \cdot kg^{-1} \cdot day^{-1}$** for physically active individuals, with higher intakes justified during periods of intensified training, caloric restriction, or hypertrophy-focused phases (Campbell et al., 2007; Jäger et al., 2017). Notably, protein intakes beyond this range do not appear to confer additional hypertrophic benefits in healthy individuals when total energy intake and training stimuli are sufficient.

3.2 Dose–Response Relationship and the Anabolic Ceiling

The concept of an "anabolic ceiling" has emerged from meta-regression analyses examining the relationship between protein intake and lean mass accretion. This concept refers to a threshold beyond which additional protein consumption yields diminishing or negligible returns in muscle hypertrophy. Morton et al. (2018) demonstrated that increases in protein intake above ~1.6 $g \cdot kg^{-1} \cdot day^{-1}$ resulted in progressively smaller gains, suggesting a saturable physiological response.

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From a mechanistic standpoint, this plateau is consistent with the finite capacity of skeletal muscle to increase muscle protein synthesis (MPS). Once translational machinery and anabolic signaling pathways—particularly those mediated by mTORC1—are maximally stimulated, further increases in amino acid availability do not proportionally enhance protein accretion (Moore et al., 2019). Consequently, protein intake above the anabolic ceiling may contribute to oxidation or alternative metabolic pathways rather than additional muscle growth.

3.3 Influence of Training Status and Individual Variability

Training status is a critical moderator of the protein dose–hypertrophy relationship. Untrained or recreationally active individuals typically exhibit a heightened anabolic sensitivity to both resistance exercise and protein ingestion, allowing substantial hypertrophic adaptations at moderate protein intakes (approximately 1.4–1.6 $g \cdot kg^{-1} \cdot day^{-1}$). In contrast, resistance-trained individuals often display a relative attenuation in anabolic responsiveness, necessitating higher protein intakes to sustain incremental gains in muscle mass.

This phenomenon has been described as a form of “adaptive resistance,” whereby repeated exposure to mechanical loading reduces the magnitude of acute MPS responses over time. As a result, advanced trainees may benefit from protein intakes closer to the upper end of the recommended range (1.8–2.2 $g \cdot kg^{-1} \cdot day^{-1}$), particularly during high-volume training blocks or periods of intensified overload (Schoenfeld et al., 2016; Witard et al., 2016).

Inter-individual variability further complicates the establishment of universal protein recommendations. Genetic predisposition, habitual dietary patterns, training volume, and recovery capacity all influence protein requirements, underscoring the need for individualized nutritional strategies within fitness and athletic contexts.

3.4 Protein Quality, Digestibility, and Effective Dose

Beyond total quantity, protein quality plays a significant role in determining the anabolic efficacy of a given intake. Proteins with high digestibility and a complete essential amino acid (EAA) profile—particularly those rich in leucine—are more effective at stimulating MPS on a per-gram basis. Whey protein, for example, consistently elicits a robust anabolic response due to its rapid digestion kinetics and high leucine content.

However, evidence indicates that when total daily protein intake meets or exceeds recommended thresholds, differences between high-quality protein sources become less influential for long-term hypertrophy outcomes (Reidy & Rasmussen, 2016; Morton et al., 2015). Thus, achieving adequate total protein intake remains the dominant factor, with protein quality serving a secondary, albeit meaningful, modulatory role.

3.5 Practical Implications for Fitness Training

From an applied fitness perspective, the current body of evidence supports several key principles regarding protein dosing:

- Total daily protein intake is more influential than excessive intake at isolated meals.
- An intake range of **1.6–2.2 $g \cdot kg^{-1} \cdot day^{-1}$** appears sufficient for maximizing hypertrophy in most resistance-trained individuals.
- Protein intakes substantially exceeding this range provide minimal additional benefit for muscle growth.
- Protein requirements should be adjusted based on training experience, volume, energy availability, and individual responsiveness.

Taken together, these findings suggest that revisiting protein intake in fitness training does not necessitate advocating extreme consumption levels, but rather refining dosage recommendations to reflect contemporary evidence, individual variability, and the physiological limits of skeletal

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muscle adaptation.

4. Protein Timing: Evidence, Controversies, and Practical Relevance

Protein timing has long been a central topic in sports nutrition research, particularly in relation to resistance training–induced skeletal muscle hypertrophy. Early hypotheses proposed the existence of a narrow "anabolic window" immediately following exercise, during which protein ingestion was believed to maximize muscle protein synthesis (MPS) and promote superior hypertrophic adaptations. While this concept has shaped nutritional practice for decades, recent evidence suggests a more nuanced and context-dependent interpretation of protein timing.

4.1 The Post-Exercise Anabolic Window: Classical Perspective

Initial experimental studies demonstrated that protein ingestion shortly after resistance exercise enhances MPS compared to delayed intake, particularly in untrained or older individuals (Esmarck et al., 2001). These findings supported the idea that the post-exercise period represents a time of heightened anabolic sensitivity, during which amino acid availability is critical for supporting muscle remodeling.

Mechanistically, resistance exercise increases muscle blood flow, amino acid transport, and intracellular signaling through pathways such as mTORC1, thereby sensitizing muscle tissue to dietary protein. From this perspective, immediate post-exercise protein intake was viewed as essential for maximizing hypertrophic outcomes.

4.2 Reassessment of Protein Timing: Contemporary Evidence

More recent systematic reviews and meta-analyses have challenged the notion of a rigid anabolic window. Schoenfeld et al. (2013) reported that when total daily protein intake is adequate, the specific timing of protein ingestion relative to exercise has a limited independent effect on muscle hypertrophy and strength gains. These findings suggest that total protein dose and training stimulus may play a more dominant role than precise timing.

Similarly, Aragon and Schoenfeld (2013) argued that the post-exercise anabolic window is broader than initially proposed and that protein consumed in the hours before training may still contribute to post-exercise anabolism. This reinterpretation emphasizes the importance of overall protein distribution across the day rather than an exclusive focus on immediate post-workout feeding.

4.3 Protein Timing Across the Training Day

Emerging research supports the concept that evenly distributing protein intake across meals may optimize daily MPS, particularly when each feeding provides sufficient high-quality protein to surpass the leucine threshold required for maximal stimulation of muscle protein synthesis (Moore et al., 2012; Witard et al., 2016).

Studies indicate that consuming approximately 0.25–0.40 $g \cdot kg^{-1}$ of protein per meal, spaced every 3–5 hours, results in a more sustained anabolic environment compared to skewed intake patterns. In this context, post-exercise protein intake should be viewed as one component of a broader nutritional strategy rather than an isolated intervention.

4.4 Training Status, Age, and Protein Timing Sensitivity

The relevance of protein timing may vary depending on individual characteristics. Evidence suggests that older adults exhibit anabolic resistance, requiring higher relative protein doses and potentially greater emphasis on post-exercise protein intake to achieve comparable MPS responses to younger individuals (Witard et al., 2016; Dideriksen et al., 2013).

In trained individuals, adaptive efficiency and habitual protein intake appear to reduce sensitivity to precise timing, provided that total protein consumption is sufficient. Morton et al. (2015)

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demonstrated that protein supplementation enhances hypertrophy primarily in individuals with lower baseline protein intake, reinforcing the importance of nutritional context.

4.5 Practical Implications for Fitness Training

From an applied fitness perspective, current evidence supports flexible protein timing strategies tailored to individual preferences, training schedules, and total daily intake. Rather than rigid adherence to immediate post-exercise feeding, practitioners should prioritize:

- Adequate total daily protein intake,
- Even distribution of protein across meals,
- Inclusion of high-quality, leucine-rich protein sources,
- Alignment of protein intake with training frequency and volume.

Such an approach aligns with the International Society of Sports Nutrition (ISSN) position stands, which emphasize that protein timing should be considered secondary to total intake and protein quality (Campbell et al., 2007; Jäger et al., 2017).

4.6 Integration with Resistance Training Adaptation

Importantly, protein timing cannot be isolated from the mechanical and metabolic stimuli imposed by resistance training. Nutritional strategies serve to support, rather than replace, the primary adaptive drivers of hypertrophy, including mechanical tension, training volume, and progressive overload.

In digitally assisted or precisely controlled training environments - such as those employing variable resistance technologies - the interaction between training stimulus and protein availability may become increasingly relevant. Optimizing protein intake in relation to individualized training loads may further enhance the efficiency of skeletal muscle adaptation, representing a promising avenue for future research.

5. Practical Implications and Future Directions in Fitness Training

The evolving body of evidence on protein intake, timing, and skeletal muscle adaptation has important practical implications for fitness training, athletic performance, and applied sport nutrition. Contemporary research suggests that effective nutritional strategies should be grounded in physiological principles while remaining adaptable to individual needs, training demands, and real-world constraints.

5.1 Practical Recommendations for Protein Intake in Fitness Training

Based on current evidence, protein intake strategies for individuals engaged in resistance training should prioritize total daily protein consumption as the primary determinant of hypertrophic adaptation. For most physically active individuals and athletes, a daily protein intake ranging between **1.6 and 2.2 $g \cdot kg^{-1} \cdot day^{-1}$** appears sufficient to maximize gains in muscle mass and strength when combined with appropriate training stimuli (Morton et al., 2018; Jäger et al., 2017).

In addition to total intake, **protein distribution across the day** plays a meaningful role in sustaining muscle protein synthesis. Consuming moderate doses of high-quality protein (approximately **0.25–0.40 $g \cdot kg^{-1}$ per meal**) at regular intervals supports repeated stimulation of anabolic pathways, particularly when meals are spaced every 3–5 hours. This approach is especially relevant for individuals training multiple times per week or engaging in high-volume resistance training programs.

Post-exercise protein ingestion remains a practical strategy, particularly when training is performed in a fasted state or when long intervals separate training sessions. However, current

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evidence does not support rigid timing rules, emphasizing flexibility and consistency over precision.

5.2 Protein Quality and Amino Acid Composition

Protein quality remains a critical factor in supporting skeletal muscle adaptation. Proteins rich in essential amino acids - and leucine in particular - demonstrate superior anabolic potential due to their ability to activate mTORC1 signaling and stimulate muscle protein synthesis. Whey protein, dairy-based proteins, and high-quality animal proteins are consistently associated with robust anabolic responses, though appropriately formulated plant-based protein blends may also be effective when consumed in sufficient quantities.

From an applied perspective, emphasizing protein quality alongside quantity ensures that athletes and recreational trainees can meet anabolic thresholds without excessive caloric intake, supporting both body composition goals and metabolic health.

5.3 Integration of Nutrition and Training Variables

Protein intake should not be considered in isolation but rather integrated within a broader training framework that includes mechanical loading, volume progression, and recovery management. Resistance training remains the primary driver of hypertrophy, with nutrition serving a supportive role in facilitating adaptation and recovery.

Emerging training technologies, including digitally controlled resistance systems, offer new opportunities to align nutritional strategies with individualized training stimuli. Precise quantification of mechanical tension, training volume, and fatigue may allow practitioners to tailor protein intake more accurately to the physiological demands imposed on the athlete, enhancing training efficiency and personalization.

5.4 Implications for Coaches, Practitioners, and Educators

For coaches and fitness professionals, the shift away from rigid nutrient timing paradigms toward flexible, evidence-based strategies simplifies nutritional guidance and improves adherence. Educating athletes on the importance of consistency, adequate intake, and high-quality protein sources may yield greater long-term benefits than emphasizing narrowly defined feeding windows.

From an educational standpoint, incorporating current protein research into sports science curricula enhances students' ability to critically evaluate nutritional claims and apply scientific evidence in practical contexts. This approach supports the development of informed practitioners capable of integrating nutrition and training principles within diverse fitness and performance environments.

5.5 Future Research Directions

Despite substantial progress, several areas warrant further investigation. Longitudinal studies examining the interaction between protein intake, digitally monitored training variables, and individualized hypertrophic responses are needed to refine personalized nutrition strategies. Additionally, research exploring protein timing and dose-response relationships in specific populations—such as older adults, female athletes, and plant-based trainees—would contribute to more inclusive and precise recommendations.

Advancements in wearable technologies, training analytics, and nutritional tracking tools may further enhance our understanding of how dietary protein interacts with resistance training stimuli in real-world settings. Such developments hold promise for bridging the gap between laboratory research and applied fitness practice.

6. Conclusions

This article revisits contemporary evidence on protein intake in the context of fitness training, with a particular focus on dose, timing, and skeletal muscle adaptation. The synthesis of current literature indicates that total daily protein intake is the primary nutritional determinant of resistance training–induced hypertrophy, while protein timing plays a secondary, context-dependent role. Consuming adequate amounts of high-quality protein distributed evenly across the day reliably supports muscle protein synthesis and long-term gains in muscle mass and strength.

The evidence further demonstrates that rigid post-exercise “anabolic window” models are not universally supported, especially when total protein intake is sufficient. Instead, flexible timing strategies that align protein ingestion with habitual meals and training schedules are both effective and practical. Protein quality - particularly essential amino acid content and leucine availability - remains a key modulator of the anabolic response, reinforcing the value of high-quality protein sources or appropriately designed blends.

Importantly, protein intake should be conceptualized as a supportive factor within an integrated training system, where mechanical loading, training volume, recovery, and individual responsiveness collectively determine adaptation. Emerging digital training technologies and data-driven monitoring tools offer promising avenues to better synchronize nutritional strategies with individualized training demands, potentially enhancing the precision of protein recommendations in applied fitness settings.

From a practical standpoint, these findings support evidence-based, adaptable protein guidelines that prioritize consistency, adequacy, and quality over strict timing prescriptions. For practitioners and educators, integrating this nuanced understanding into coaching practice and sports science curricula can improve decision-making, adherence, and long-term training outcomes.

In conclusion, revisiting protein intake through the lens of recent evidence underscores the need to move beyond simplistic timing narratives toward holistic, individualized, and training-aligned nutritional strategies. Future research integrating precise training analytics, long-term interventions, and diverse populations will further refine best practices for optimizing skeletal muscle adaptation in fitness training.

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