Nutrition to Support Recovery from Endurance Exercise: Optimal Carbohydrate and Protein Replacement

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Abstract

Proper nutrition is vital to optimize recovery after endurance exercise. Dietary carbohydrate and protein provide the requisite substrates to enhance glycogen resynthesis and remodel skeletal muscle proteins, respectively, both of which would be important to rapidly restore muscle function and performance. With short recovery windows (<8 h), coingestion of these macronutrients immediately after exercise can synergistically enhance glycogen resynthesis and rapidly stimulate muscle protein synthesis (MPS), the latter of which is augmented by protein ingestion alone. Consuming frequent meals throughout the day containing adequate carbohydrate (according to training intensity) and protein (approximately 0.25 $g \cdot kg^{-1}$) will help fully restore muscle glycogen and sustain maximal daily rates of MPS over prolonged (8 to 24 h) recovery periods. Given the complementarity of these macronutrients, endurance athletes aiming to maximize postexercise recovery to maintain or enhance subsequent exercise performance should target a nutrition strategy that features optimal ingestion of both carbohydrate and protein.

Introduction

Endurance exercise is classically associated with relatively long-duration, constant-load exercise that is characterized by large increases in oxygen consumption, although repeated shorter-duration, higher-intensity exercise bouts also rely heavily on aerobic energy systems for optimal performance (6). These endurance-type exercises can be stressful events for the human body and can be accompanied by depletion of endogenous energy stores (*e.g.*, muscle and liver glycogen) and can serve as a stimulus for the remodeling and repair of a variety of different body proteins (*e.g.*, skeletal muscle, bone, cardiovascular system, etc.). For example, exercise performed at intensities greater than approximately 50% to 60% of peak aerobic fitness, such as constant-load running or cycling, or that which requires supramaximal intensities (especially when repeated), such as team sport exercises like soccer or ice hockey, rely primarily on carbohydrate as energy source (40,45). In addition, these exercise modalities represent potent stimuli for metabolic (*e.g.*, mitochondrial biogenesis, metabolic enzyme upregulation) (9) and structural (*e.g.*, contractile protein repair and synthesis) skeletal muscle adaptations (16) that, through the remodeling of muscle and body proteins, can ultimately translate into performance adaptations such as increased aerobic/anaerobic power production (9). In light of these acute stresses, the athlete who optimally recovers from an acute bout of exercise is better positioned to maintain or enhance their performance during a subsequent bout and/or to adapt, over time, to the repeated stress of multiple exercise bouts (*i.e.*, training).

Proper nutrition is vital to optimize postexercise recovery. Dietary carbohydrate and protein are important macronutrients for the endurance athlete, as they provide the requisite substrates to enhance glycogen resynthesis and muscle remodeling. While other aspects of recovery such as fluid restoration and/or maintenance of immune function are important considerations for the endurance athlete and have been reported to be influenced by these macronutrients as well, the focus of the present review will be on the role carbohydrate and protein have on the ability to enhance recovery primarily within skeletal muscle. Highly active endurance athletes may have recovery widows that range from relatively short (*e.g.*, two-a-day training, tournament play) to longer (*e.g.*, daily training bouts) intersession recovery periods depending on their training phase or competition schedule. Therefore, this review will summarize the current literature on the specific carbohydrate and protein ingestion strategies to support glycogen resynthesis and skeletal muscle remodeling over shorter

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(*i.e.*, <8 h) and longer (*i.e.*, 8 to 24 h) recovery periods. Moreover, focus will be placed on highlighting the synergies between optimal carbohydrate and protein replacement to provide practical nutrition guidelines for a comprehensive recovery strategy for the endurance athlete.

Carbohydrate

Endurance exercise that is sustained at a moderate to high intensity and repeated supramaximal efforts primarily rely on carbohydrate as a source of fuel (40,45). In the face of enhanced glucose uptake by working muscles, blood glucose levels are maintained to a large extent by the breakdown of liver glycogen stores. Despite this enhanced liver glycogenolysis, muscle glycogen is the most immediate energy supply during these higher-intensity endurance-type exercises due to the proximity of specific intramuscular pools to the mitochondria, sarcoplasmic reticulum, and/or or the contractile myofibrillar proteins, where instantaneous energy requirements are highest during muscle contraction (36). Bergström et al. (4) were the first to discover that fatigue during prolonged exercise was associated with muscle glycogen depletion. Subsequent research has expanded on this seminal study to elucidate the subcellular localization of intramuscular glycogen and the subsequent regional intracellular and/or fiber type-specific depletion of these energy stores with muscle fatigue (31,36). In light of the importance of this intramuscular energy store for exercise performance and the early work showing it can be influenced by diet (4,14), considerable attention has been placed on elucidating the optimal dietary strategies to restore, maintain, and/or enhance muscle glycogen for the goal of maximizing exercise performance.

It is well-known that athletes competing maximally during high-intensity endurance exercise must ensure that their carbohydrate stores are optimized before and during exercise to perform at their best (10). Managing precompetition carbohydrate intake and strategies to supercompensate glycogen stores (*i.e.*, glycogen loading) prior to competition are important considerations for endurance athletes. In addition, carbohydrate intake during exercise, either for a source of fuel for events >90 min and/or for "mental" energy (*e.g.*, carbohydrate mouth rinse), are useful dietary strategies to successfully enhance endurance exercise performance (22). While these aspects of carbohydrate ingestion would be important considerations for optimal endurance exercise performance, they are not within the remit of the present review focused on postexercise recovery, and therefore, interested readers are referred to additional reviews and/or consensus statements that cover these aspects of sports nutrition in more detail (*e.g.*, (10,22)).

Contemporary research suggests that training with low carbohydrate availability could represent a strategy to enhance training-induced adaptations (*e.g.*, mitochondrial biogenesis, enhanced fat oxidation) that may subsequently improve endurance exercise performance (for review, see (36)). These strategies may include fasted (*e.g.*, prebreakfast) or glycogen-depleted (*e.g.*, two-a-day training with low intersession carbohydrate intake) training and/or carbohydrate restriction during recovery (2). Progressive sports practitioners and athletes have begun experimenting with these different forms of low carbohydrate availability training to enhance aerobic adaptations during early base training stages (42). As such, these athletes may deliberately restrict carbohydrate intake during the postexercise recovery period to minimize glycogen resynthesis. While this emerging area of research is intriguing, the focus of the present review will be to summarize the nutritional requirements for athletes aiming to maximize glycogen resynthesis after exercise in order to maintain performance or training quality in subsequent bouts of exercise. Moreover, although some supplements (*e.g.*, caffeine, creatine) have been reported to enhance rates of glycogen resynthesis, the present review will limit the discussion to the impact carbohydrate and protein have in replenishing endogenous fuel stores.

Carbohydrate for Short-Term Recovery (<8 h)

Carbohydrate intake is crucial to enhance muscle and liver glycogen stores after high-intensity, carbohydrate-based exercise. The rate of muscle glycogen resynthesis is generally greatest during the initial ~1 h after exercise and is facilitated by the contraction-induced recruitment of GLUT-4 transporters to the muscle membrane and an enhanced activity of the rate-controlling enzyme glycogen synthase (21). For example, providing carbohydrate ingestion immediately after exercise resulted in an approximately 45% greater rate of glycogen resynthesis over the following 2 h as compared with delaying the ingestion by 2 h, which ultimately translated into a greater net glycogen synthesis over a 4-h postexercise recovery period (20). However, immediate postexercise carbohydrate ingestion does not confer any advantage toward net glycogen synthesis over longer periods of recovery as immediate and delayed (*i.e.*, 2 h) ingestion of carbohydrate result in equivalent muscle glycogen concentrations 8 h after recovery (32). Therefore, athletes who must maximize glycogen resynthesis for a subsequent exercise bout less than 8 h should target a nutritional strategy that initiates carbohydrate intake as quickly as possible after exercise.

The rate of carbohydrate ingestion is also an important determinant of how rapidly muscle glycogen is resynthesized. Although few studies have directly assessed the relative dose-response of carbohydrate ingestion on glycogen resynthesis, a comprehensive review by Jentjens and Jeukendrup (21) compared the rate of glycogen resynthesis relative to the carbohydrate intake across multiple studies. These authors (21) concluded that the maximal rate of glycogen resynthesis (approximately 0.3 $g \cdot min^{-1}$) during the early acute recovery period (*i.e.*, up to 8 h after exercise) appeared to occur with a relative carbohydrate intake of 1.0 to 1.2 $g \cdot kg^{-1} \cdot h^{-1}$ (Fig. 1). There was some evidence that protocols employing a feeding pattern of small carbohydrate boluses every 15 to 60 min elicited greater rates of glycogen synthesis than those with intervals at approximately 2 h (*e.g.*, (20,46)). However, it was concluded that the limited research directly comparing feeding patterns on maximal rates of glycogen resynthesis precluded the recommendation toward an optimal ingestion pattern, provided that target carbohydrate intake levels are reached (21).

Dietary protein has no appreciable role in gluconeogenesis (18) and therefore when ingested alone would not serve as a substrate for glycogen resynthesis during recovery from high-intensity endurance-type exercise. However, as summarized

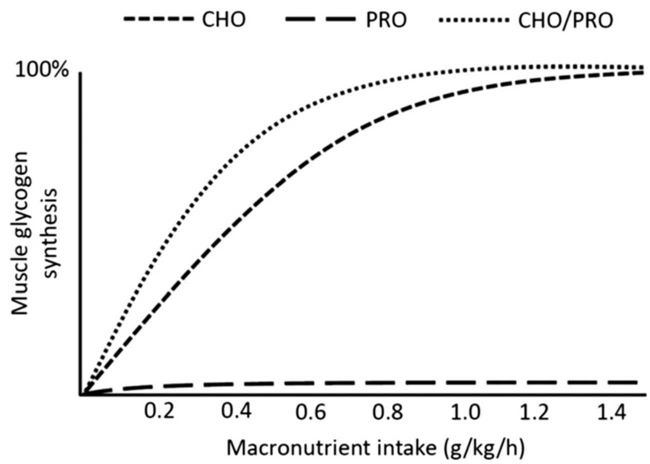

Figure 1: Schematic representation of the independent and combined effects of the rate of carbohydrate and/or protein ingestion on the relative rate of muscle glycogen resynthesis over short-term (*i.e.*, <8 h) recovery after endurance exercise. Carbohydrate is adapted from (5), with maximal glycogen resynthesis occurring at 1.0 to 1.2 $g \cdot kg^{-1} \cdot h^{-1}$. Carbohydrate/protein represents an estimated 3:1 ratio of each macronutrient and is estimated to enhance glycogen synthesis rates when suboptimal carbohydrate is ingested, as per (5). Protein is predicted to have no effect on glycogen resynthesis given that dietary protein is not a major source of gluconeogenic substrates (18). CHO, carbohydrate; PRO, protein.

by Betts and Williams (5), the addition of protein to a carbohydrate beverage can increase rates of glycogen resynthesis when carbohydrate intake is below optimal levels (*i.e.*, <1 $g \cdot kg^{-1} \cdot h^{-1}$) (Fig. 1). This enhanced glycogen resynthesis has generally been attributed to the insulinogenic effect of protein and certain amino acids (*e.g.*, leucine and phenylalanine), which helps drive glucose into the muscle when carbohydrate intake rates are submaximal (46). Although athletes can practically augment rates of muscle glycogen by consuming a protein/carbohydrate blend, the effect of this nutritional approach on subsequent exercise performance, especially with submaximal rates of glycogen resynthesis through suboptimal rates of carbohydrate delivery, is equivocal (27). Nevertheless, given the additional benefits of consuming protein immediately after exercise to support the repair and remodeling of skeletal muscle (see below), endurance athletes should consider including this macronutrient in their recovery nutrition.

Carbohydrate for Long-Term Recovery (8 to 24 h)

The nutritional strategies outlined previously (*e.g.*, carbohydrate timing and pattern) that are employed to maximize muscle glycogen resynthesis during short-term (*i.e.*, <8 h) recovery are generally not as important when longer periods of recovery are possible between successive exercise bouts. For example, the timing of carbohydrate intake relative to exercise (*i.e.*, immediate vs delayed by 2 h) has little bearing on the rate of glycogen resynthesis over 8 and 24 h of postexercise recovery (32). Moreover, consuming a carbohydrate-rich diet (*i.e.*, approximately 12 $g \cdot kg^{-1} \cdot d^{-1}$) as two large meals as compared with seven smaller meals results in similar net muscle glycogen synthesis over 24 h (14). Given that muscle glycogen gradually declines over 3 d of successive high-volume exercise (*i.e.*, approximately 16-km runs) despite consuming a moderately high-carbohydrate diet (estimated from average energy intake, percent carbohydrate, and average body weight at approximately 5 to 7 $g \cdot kg^{-1} \cdot d^{-1}$) (13), it is generally accepted that consuming adequate daily carbohydrate (independent of its pattern and/or timing) is the most important nutritional strategy to maximize muscle glycogen resynthesis with prolonged (*i.e.*, >8 h) postexercise recovery (10,21). Therefore, athletes aiming to maximize glycogen resynthesis and endogenous carbohydrate stores are recommended to consume carbohydrate relative to their body weight (and not as a percentage of total energy) and training load (10), which in the case of the previous study with suboptimal glycogen repletion over 3 d of high-volume training (13) may have been as high as 10 $g \cdot kg^{-1} \cdot d^{-1}$. Additional guidelines are briefly summarized in the Table but can be consulted in their entirety in the International Olympic Committee Consensus Conference on Nutrition for Sport review (10).

Protein

Amino acids represent a relatively minor energy substrate during normal exercise (approximately 2% to 5% of total adenosine triphosphate production), but their absolute oxidation can be increased several-fold with the increased energy demands of endurance-type exercise; this oxidation represents a net loss of amino acids from the free pool within muscle. In addition, endurance exercise is a major stimulus to remodel skeletal muscle, which results in the breaking down of old and/or damaged muscle proteins (muscle protein breakdown (MPB)) and the (re)building of new ones (muscle protein synthesis (MPS)) in their place. This enhanced protein "turnover" functions to remodel the major muscle protein fractions such as the energy-producing mitochondria and the force-generating myofibrillar proteins (16,48) and is primarily regulated by changes in MPS (8). Ultimately, this increased oxidation of amino acids and extensive remodeling of body and muscle proteins translate into a greater daily protein requirement (*i.e.*, 1.2 to 1.7 $g \cdot kg^{-1} \cdot d^{-1}$) for individuals engaged in chronic endurance exercise (*i.e.*, training) than the general population (44). Provided that energy intake meets the increased energy demands of this active population, endurance athletes generally meet their minimum protein requirements (44). However, contemporary research is revealing that it is not just "how much" protein an active individual consumes during the day but more importantly "when" and in "what pattern" they consume it in that is important to maximize MPS during recovery from exercise and, potentially, training-induced muscle remodeling (as discussed in the following section). While much of the research to date has centered on protein after resistance exercise, these nutritional tenets of maximizing MPS are arguably transferable to endurance-exercise modalities as well (28).

Short-Term Recovery (<8 h)

The most important nutritional factor for enhancing postexercise MPS is the ingestion of dietary protein (24) (Fig. 2), which provides the requisite amino acid building blocks for repairing, remodeling, and/or building new muscle. For example, carbohydrate ingestion alone has no effect on MPS (24) and does not augment the dietary amino

Table.

General carbohydrate and protein guidelines for glycogen resynthesis and muscle protein remodeling for endurance athletes.

	Glycogen Resynthesis		Muscle Protein Remodeling[a]	
Recovery Period	CHO[b]	Protein[c]	CHO	Protein
<8 h	Immediate postexercise ingestion	When CHO <1.2 $g \cdot kg^{-1} \cdot h^{-1}$	Approximately 30 g per meal (suppress MPB)	Immediate postexercise ingestion
	1.2 $g \cdot kg^{-1} \cdot h^{-1}$			20 g per meal (approximately 0.25 to 0.3 $g \cdot kg^{-1}$)
	High glycemic index			Meal every 3 to 4 h
	Multiple CHO sources			Leucine enriched
				Rapid digestion
8 to 24 h	Moderate training, 5 to 7 $g \cdot kg^{-1} \cdot d^{-1}$	N/A	N/A	20 g per meal (approximately 0.25 to 0.3 $g \cdot kg^{-1}$)
	High training, 6 to 10 $g \cdot kg^{-1} \cdot d^{-1}$			Meal every 3 to 4 h
	Very high training, 10 to 12 $g \cdot kg^{-1} \cdot d^{-1}$			Pre-bedtime ingestion
				1.2 to 1.7 $g \cdot kg^{-1} \cdot d^{-1}$

[a] Muscle protein remodeling: protein intake stimulates the prime-regulated variable of MPS, whereas carbohydrate has a mild suppressive effect on MPB.

[b] Carbohydrate intake over 8- to 24-h recovery adapted from Burke et al. (10) and represents daily targets: moderate training, approximately 1 $h \cdot d^{-1}$; high training, 1 to 3 $h \cdot d^{-1}$; very high training, 4 to 5 $h \cdot d^{-1}$. Carbohydrate guidelines are generally related to exercises that rely primarily on carbohydrate as a fuel, such as repeated high-intensity interval exercise and/or constant workload at ≥65% maximal aerobic capacity.

[c] Protein coingestion may be as low as approximately 20 g (10).

CHO, carbohydrate; N/A, not a major consideration.

acid-induced stimulation of MPS after exercise (23,41). While carbohydrate (and primarily the associated insulin response) can suppress MPB after exercise, this effect is observed with as little as a 30-g bolus of the macronutrient and has a relatively minor role (as compared with amino acid-induced stimulation of MPS) in determining the net muscle protein balance (*i.e.*, the algebraic difference between MPS and MPB) during recovery from exercise (19). Therefore, endurance athletes who prioritize carbohydrate intake for enhanced rates of glycogen resynthesis will undoubtedly elicit an insulin response that is sufficient to maximally attenuated MPB.

Previous studies have demonstrated that a single 20-g bolus of high quality protein (*i.e.*, egg or whey) is sufficient to maximize MPS after resistance exercise with greater protein amounts, resulting in increased amino acid oxidation (*i.e.*, the utilization of dietary amino acids as a source of fuel) (30,49). While no similar dose-response studies exist after endurance exercise, it has been shown that 16 g of milk protein (25) and 20 g of whey protein (7) augment postexercise rates of MPS after aerobic-based exercise. Therefore, it is likely that a similar ingested dose should be targeted for endurance athletes aiming to enhance MPS after exercise. From a more personalized approach, the absolute 20-g dose utilized in previous studies (30,49) would be equivalent to approximately 0.25 $g \cdot kg^{-1}$ (based on average study body weights) of high-quality protein (see the following section for additional discussion and Fig. 2), which is a similar relative protein dose that has recently been reported to maximize MPS at rest in young adults (29).

The timing of the protein ingestion also may be an important factor to initiate the recovery process after a bout of endurance exercise. Consuming a source of protein immediately after endurance exercise is critical to enhance MPS, as delaying this ingestion by as little as 3 h has been shown to markedly attenuate the anabolic effects of the dietary amino

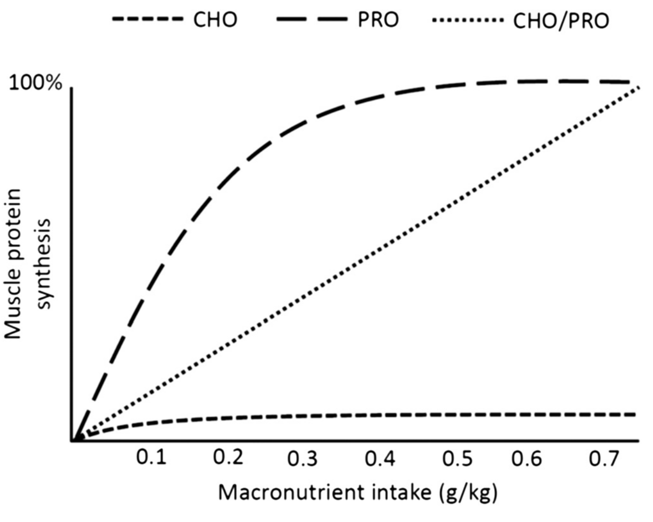

Figure 2: Schematic representation of the independent and combined effects of a single meal ingestion of carbohydrate and/or protein on MPS after endurance exercise. Carbohydrate would be predicted to generally have no effect on MPS after exercise (23,41). Protein would induce a dose-dependent stimulation of MPS up to a plateau of 20 g or 0.25 to 0.3 $g \cdot kg^{-1}$ (29,30). Carbohydrate/protein represents a 3:1 ratio of each macronutrient and would be estimated to induce a linear dose-response up to 0.7 $g \cdot kg^{-1}$ (or the equivalent of approximately 0.23 g $protein \cdot kg^{-1}$). CHO, carbohydrate; PRO, protein.

acids (24). This enhanced MPS would be consistent with a greater remodeling and/or repair of skeletal muscle and subsequently maximizing this process as quickly as possible after a bout of exercise would intuitively facilitate a more rapid recovery for the endurance athlete. A recent systematic review suggests that postexercise protein intake has little effect on exercise performance in a subsequent single bout up to 24 h after the first (27), which may suggest that the acute enhancement of MPS does not directly enhance acute recovery. However, additional research is required to elucidate the potential benefits of postexercise protein ingestion on adaptations to endurance-training (*i.e.*, recovery from multiple exercise bouts), as a subsequent systematic review from the same group suggested that protein supplementation, which would presumably stimulate MPS during recovery, may enhance aerobic/anaerobic power adaptations in athletes (34). Nevertheless, in the absence of any ostensible ergolytic effects, the postexercise ingestion of dietary protein to augment rates of MPS (7,24,25), should be viewed as an important nutritional strategy for the endurance athlete to support muscle remodeling and recovery.

Dietary proteins are not all created equal and can differ in both their amino acid composition and digestion rate (*i.e.*, how quickly their constituent amino acids appear within the circulation). For example, despite all being similarly high-quality proteins according to the protein digestibility corrected amino acid score (1.0), whey protein generally elicits a more robust stimulation of MPS than both soy and micellar casein at rest and after resistance exercise (43). The greater anabolic effect of whey protein is generally attributed to its naturally high leucine content (an essential amino acid that is an important initiator of MPS (17) and its rapid digestion (47), which has led to the suggestion that a postexercise protein source should carry these attributes to maximize MPS (35). However, vegetable-based proteins (43), protein blends (37), and whole foods (12) also can be sufficiently high-quality protein sources that induce a postexercise amino acid profile that would likely support enhanced rates of MPS after exercise. It may be worth noting that a potentially slightly greater protein intake may be required to achieve a similar postexercise MPS response given the relatively lower leucine content of these protein sources (37). Therefore, in light of the previously determined ingested protein dose-response with high-quality egg or whey protein, athletes who prefer alternative protein sources may wish to consider a slightly greater (*e.g.*, approximately 25%) intake to enhance their anabolic effects.

Long-Term Recovery (8 to 24 h)

A single bout of high-intensity endurance exercise has been reported to increase the remodeling of skeletal muscle for up to 24 h, as evidenced by the stimulation of force-generating myofibrillar and mitochondrial protein synthesis during this prolonged recovery period (16). As such, maximizing MPS during this period with proper nutrition could be viewed as a key strategy to support optimal recovery and skeletal muscle remodeling for the endurance athlete. It has recently been demonstrated that the daytime pattern, and not just the absolute amount, of protein intake can influence the elevation of MPS after an acute bout of resistance exercise. For example, the repeated ingestion of 20 g of protein every 3 h (*i.e.*, 80 g in total) was shown to support greater rates of myofibrillar protein synthesis over 12 h after resistance exercise as an identical amount ingested as either eight feedings of 10 g every 1.5 h or two feedings of 40 g every 6 h (1). Therefore, given that dietary protein acutely augments postexercise rates of MPS after a bout of endurance exercise (7,24), athletes aiming to optimize their recovery with this training modality would likely also benefit from the ingestion of 20 g (or approximately 0.25 $g{\cdot}kg^{-1}$, see previous section) protein every 3 to 4 h to sustain maximal rates of MPS. This meal feeding frequency (*i.e.*, four to six meals per day) would be consistent with current practice in elite athletes (11) and also could represent a strategy to help achieve their relatively high target daily carbohydrate intake levels (see previous section and Table).

Aside from optimal feeding strategies during daytime waking hours, it has been demonstrated that the postexercise increase in MPS with dietary protein ingestion does not extend into the overnight recovery period (3). This is likely due to a lack of circulating plasma amino acids, which generally return to fasted levels within approximately 3 to 4 h after protein-containing meal consumption (12), to support maximal rates of MPS. However, it has recently been demonstrated that pre-bedtime protein ingestion represents a practical means to sustain circulating amino acids and support MPS during an 8-h sleep period after a bout of resistance exercise (38) and to enhance training-induced increases in muscle mass and strength (39). Therefore, as proper sleep is vital to support overall health and optimal recovery in athletes, pre-bedtime protein ingestion represents an additional feeding opportunity during the recovery from endurance exercise to support enhanced rates of skeletal muscle remodeling.

Practical Recommendations

As outlined previously, endurance athletes have unique nutritional requirements for both carbohydrate and protein during recovery to facilitate the restoration of endogenous fuel stores (*i.e.*, glycogen) and to support the repair and remodeling of skeletal muscle, respectively. Generally, distinct recommendations are made for either glycogen resynthesis (*e.g.*, (10)) or muscle remodeling independently (*e.g.*, (35)). However there are arguably complementary features of carbohydrate and protein replacement strategies that can be leveraged toward a more holistic nutritional strategy for effective postexercise recovery (Fig. 1). The purpose of the following section will be to provide a brief guide for some practical strategies to enhance overall muscle recovery after endurance exercise.

Athletes who have limited time between exercise bouts (*e.g.*, <8 h) and who are aiming to perform at their highest level in each bout of exercise should consume protein and CHO immediately after the first bout of exercise to initiate the recovery process (20,24). The restoration of muscle glycogen would be the relatively more important variable to maintain exercise performance or training quality in the subsequent exercise bout, although supporting skeletal muscle remodeling (*i.e.*, MPS) during this early recovery window should be an important aspect of a multifaceted nutritional recovery strategy, especially in the context of a longer-term training program (33,34). As such, athletes should target approximately 0.25 $g{\cdot}kg^{-1}$ of high-quality protein (*e.g.*, leucine-enriched, rapidly digested sources such as whey) to stimulate MPS combined with at least 0.75 $g \cdot kg^{-1}$ of carbohydrate, the latter of which will enhance glycogen resynthesis and would far exceed the minimum dose that is sufficient to suppress MPB (19). Athletes who can consume greater carbohydrate will ensure glycogen synthetic rates are maximized; however, if this high intake is not practical or feasible, then protein coingestion will augment glycogen synthesis below maximal carbohydrate ingestion rates of 1.0 to 1.2 $g \cdot kg^{-1} \cdot h^{-1}$. It may be most practical to consume sports nutrition products (*e.g.*, recovery drinks, bars, gels, etc.) during this first postexercise meal, as they are generally convenient sources of multiple simple carbohydrates (*e.g.*, glucose, fructose, sucrose), which would provide ready substrates to replenish both liver (*e.g.*, fructose) (15) and muscle (*e.g.*, glucose) (21) glycogen. Additionally, nutrition in beverage form would not only help with postexercise fluid replacement but also enhance the rate of amino acid appearance (12), which would help facilitate greater rates of MPS (47). Outside this immediate postexercise recovery window, athletes should aim to consume carbohydrate-rich foods at a similar rate as above at least every 2 h (as practically possible) with the coingestion of approximately 0.25 $g \cdot kg^{-1}$ of dietary protein; this target protein intake may need to be increased slightly to maximize MPS if lower quality proteins (*e.g.*, plant based and/or blends thereof) are ingested (37,43). While currently lacking direct empirical evidence to support its efficacy over short-term recovery, adhering to these guidelines to maximize glycogen resynthesis and support MPS (in addition to other aspects of recovery such as rehydration) would ultimately position an athlete in the best possible condition to maintain and/or enhance their exercise capacity and performance within an abbreviated recovery window.

Athletes who have the luxury of a longer intersession recovery window (*i.e.*, 8 to 24 h) may not need to be as aggressive with their muscle glycogen recovery strategy, as timing and pattern of carbohydrate intake have little impact on the restoration of this endogenous energy store beyond the early (*i.e.*, 8 h) recovery period (14,32). Nevertheless, consuming a source of carbohydrate immediately after exercise could be considered a universal tenet regardless of the available window of recovery, as this would help initiate muscle glycogen resynthesis early in recovery. Moreover, this early recovery nutrition, which as discussed could be practically supported by convenient sports nutrition products (although this is not a requirement with a longer recovery window), should contain approximately 0.25 $g \cdot kg^{-1}$ of protein to support skeletal muscle repair and/or remodeling through enhanced rates of MPS. After this initial feeding, athletes should consume adequate carbohydrate intake through natural, carbohydrate-rich food sources to support their habitual training loads (Table). Frequent meal feedings (*i.e.*, 5 to 6 meals over a 12- to 15-h wake period) would be similar to that of many elite athletes (11) and represent a practical, convenient means to meet their high daily carbohydrate and elicit an insulin response that would sufficiently attenuate any exercise-induced increase in MPB (19). More importantly, each of these meals should contain adequate protein (approximately 0.25 $g \cdot kg^{-1}$ depending on protein quality, see previous section) including a pre-bedtime snack to sustain maximal rates of daily MPS (1,38) and to obtain their increased daily protein requirements (*i.e.*, 1.2 to 1.7 $g \cdot kg^{-1} \cdot d^{-1}$). Additionally, it could be argued that this meal frequency and protein intake pattern that is aimed at maximizing MPS (and presumably muscle repair) may be most critical after particularly intense training bouts (*e.g.*, supramaximal training, long duration, and/or with large muscle-lengthening component, such as downhill running), as muscle damage reduces endurance exercise performance (26) and has been reported to interfere with the ability to replenish glycogen stores during long-duration recovery (50). Therefore, athletes who practice these nutritional strategies over a more prolonged recovery period would ultimately maximize their chances of maintaining exercise performance in subsequent exercise bouts. In the context of a high-intensity training program that stimulates significant aerobic adaptations (9) that are ultimately underpinned by changes in MPS (28), nutrition to support optimal recovery to sustain a high work output during repeated exercise bouts may ultimately enhance training-induced adaptations. This optimized training nutrition represents a potentially fruitful area of future study for the endurance athlete.

Conclusions

The resynthesis of muscle glycogen and the repair and/or remodeling of muscle protein are highly influenced by the nutritional environment and are of paramount importance for optimal postexercise recovery after endurance exercise. As such, a multidimensional nutritional strategy targeting the combined ingestion of dietary carbohydrates and protein (rather than either one alone) will be most effective in achieving these recovery goals. Ultimately, the athlete who optimizes postexercise nutrition after an acute bout of exercise will be best positioned to maintain or enhance performance during a subsequent bout and/or to adapt, over time, to the repeated stress of multiple exercise bouts (*i.e.*, training).

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