What Are the Dietary Protein Requirements of Physically Active Individuals? New Evidence on the Effects of Exercise on Protein Utilization During Post-Exercise Recovery

Roger A. Fielding, PhD ▪ Jascha Parkington, BS

Human Physiology Laboratory, Department of Health Sciences, Boston University

■ **ABSTRACT**

Exercise and physical activity increase energy expenditure up to 10-fold. This brief review will focus on the effect of exercise on protein requirements. Evidence has accumulated that amino acids are oxidized as substrates during prolonged submaximal exercise. In addition, studies have determined that both endurance and resistance training exercise increase skeletal muscle protein synthesis and breakdown in the post-exercise recovery period. Studies using nitrogen balance have further confirmed that protein requirements for individuals engaged in regular exercise are increased. The current recommended intakes of protein for strength and endurance athletes are 1.6 to 1.7 g/kg and 1.2 to 1.4 g/kg per day, respectively. Presently, most athletes consume an adequate amount of protein in their diet. The timing and nutritional content of the post-exercise meal, although often overlooked, are known to have synergistic effects on protein accretion after exercise. New evidence suggests that individuals engaging in strenuous activity consume a meal rich in amino acids and carbohydrate soon after the exercise bout or training session. *Nutr Clin Care.* 2002;5:191–196 ■

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Reprint requests to Roger A. Fielding, PhD, Human Physiology Laboratory, Department of Health Sciences, Boston University, Sargent College of Health and Rehabilitation Sciences, 635 Commonwealth Avenue, Boston, MA 02215. Email: fielding@bu.edu

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INTRODUCTION

Exercise and/or physical activity can cause up to a 10-fold increase in whole body energy expenditure. Adequate replenishment of these depleted energy stores along with overall nutritional status has dramatic effects on the nutritional requirements of the individual. This brief review will focus on nutrient utilization during exercise and the unique aspects of protein requirements of individuals engaged in regular physical exercise. Particular attention will be paid to the role of exercise on protein homeostasis in the post-exercise recovery period.

METABOLIC RESPONSE TO EXERCISE

The concept of the maximal oxygen uptake (Vo_{2max}) serving as an upper physiological limit for aerobic exercise was first described by Hill et al[1] and validated in classic studies by Taylor et al.[2] These studies demonstrated a direct relationship between whole body oxygen consumption and exercise intensity. As the intensity of exercise increases, oxygen consumption also increases in a linear fashion. Oxygen serves as the final electron acceptor during oxidative phosphorylation. Rates of adenosine triphosphate (ATP) turnover during energy production cannot be conveniently measured through direct means. Whole body oxygen consumption has traditionally been used as an indirect measure of energy expenditure during exercise and serves as the best correlate to the physical work of exercise.[3]

Physical exercise presents the most profound challenge to fuel homeostasis in normal humans. Whole body energy expenditure can increase 10-fold from rest to maximal exercise.[2] To maintain this increased rate of energy expenditure, the performance of physical activity is associated with a marked increase in the fuel and oxygen needs of working muscles. Since the available quantities of high-energy phosphate compounds, such as creatine phosphate (CP) and adenosine triphosphate (ATP), within muscle are relatively limited (26 mmol/kg wet weight CP, and 8 mmol/kg wet weight ATP), the availability of the necessary metabolic machinery and oxidizable substrate is a necessity for sustained muscular activity. Human skeletal muscle possesses the necessary enzymes to oxidize carbohydrate in the forms of glucose and glycogen, nonesterified fatty acids transported from adipocytes and derived from intramuscular triglycerides, and, to a small extent, specific amino acids for energy.[4] To meet these requirements and at the same time maintain the fuel and energy supply to other vital organs, major metabolic, hormonal, and cardiovascular adjustments are essential.

AMINO ACID OXIDATION

Oxidation of specific amino acids such as the branched-chain amino acids leucine, isoleucine, and valine can also be increased during exercise to a smaller extent than fat and carbohydrate, which account for the bulk of fuel utilization (10–15% amino acids of total oxidized substrate).[5] Women who exercise, however, have been shown to have lower rates of amino acid oxidation during prolonged exercise and reduced urea excretion following exercise compared to men.[6,7] Several studies have suggested that the increased amino acid oxidation during prolonged exercise results in an increased dietary requirement for protein in physically active individuals.[8,9]

EXERCISE AND PROTEIN REQUIREMENTS

The current recommended dietary allowance (RDA) for protein (0.8 g/kg/day) does not take into account differences in the level of daily physical activity.[10] Amino acid oxidation contributes little to resting energy expenditure,[11] suggesting that protein intake at the level of the RDA is sufficient for most sedentary individuals. However, as mentioned, the oxidation of specific amino acids has been shown to increase 85–500% depending on the intensity and duration of exercise.[5,12] This suggests a higher requirement for dietary protein in individuals undergoing regular exercise training. In light of these results, the American College of Sports Medicine has recommended that protein requirements be increased to 1.2 to 1.4 g/kg per day and 1.6 to 1.7 g/kg per day for endurance and strength athletes, respectively.[13] Endurance exercise and training may affect protein homeostasis by stimulating amino acid oxidation with the subsequent production of urea. In addition, protein synthesis is increased following submaximal aerobic exercise.[5,14] Urea nitrogen excretion increases with exercise intensity and also suggests a net protein catabolism during exercise.[15] In situations of energy deficiency, such as exercise coupled with diet-related muscle glycogen depletion, serum and urinary urea excretion are further increased.[16] This highlights the intricate balance between energy status and protein turnover in skeletal muscle. The ability to catabolize protein as an energy source reflects an adaptation to substrate deficiency. However, during prolonged energy deficiency such as starvation, the efficiency with which protein is oxidized for fuel increases.[17] This phenomenon is reflected in the fact that negative nitrogen balance is improved during starvation after an initial period of time.[17] The energy-deficient state of prolonged exercise has been likened to starvation[16,17] and similar improvements in protein utilization have been observed with chronic exposure to exercise training.[18,19] Evidence of exercise causing these alterations in protein homeostasis has led some,[7,8,15,20–22] but not all investigators,[18] to conclude that endurance training does in fact increase dietary protein requirements.

Among those who argue in favor of an increased protein requirement, some discrepancy exists regarding what the recommended intake should be. As such, protein recommendations based on nitrogen balance studies vary considerably (0.94–1.67 g/kg/day).[8,22] The wide range of results may reflect the many factors that regulate protein turnover in vivo, including the level of training, the amount of exercise performed, the total energy balance, age, and body composition of the individual. Though absolute protein requirements may increase, there is little evidence to suggest that the requirement as a function of total energy intake need change from the current recommendation of 10–15% of total calories, so long as energy intake adequately supports the greater energy expenditure incurred during exercise. For example, if energy balance is achieved at 5,000 kcal, even a small proportion of protein (10%) will provide more than the amount recommended for athletes (1.2–1.7 g/kg/day).[13]

Protein requirements are increased with heavy resistance training and are likely related to the structural remodeling associated with muscle hypertrophy. During the early stages of intense resistance exercise, requirements are reportedly 100% greater (~1.7 g/kg/day) than the RDA.[9,15] Interestingly, excessive protein intake has no further effect on synthesis and the additional amino acids are largely oxidized.[9] Conversely, Tarnopolsky et al[22] have shown that elite bodybuilders may require 80% less protein than novice bodybuilders and only slightly more (1.12g/kg/day) than the RDA. This may be attributed to the fact that resistance exercise reduces muscle protein turnover,[23] possibly due to decreased myofibrillar disruption following exercise in trained muscle.[24] As such, protein needs may be significantly increased during the early stages of resistance training but reduced thereafter due to training-induced adaptations. However, the limited amount of data on protein turnover in response to resistance exercise training suggests that further study is warranted.

Whether gender differences in protein requirements exist is unclear. Protein intake at the level of the RDA and RNI (0.86 g/kg) is reportedly inadequate for male and female endurance athletes.[7] However, evidence that amino acid oxidation and nitrogen excretion are less during exercise in women versus men suggests that there may be gender-related differences in protein need.[6,7]

DIETARY PROTEIN INTAKE OF ATHLETES

One of the nutritional problems associated with the dietary habits of athletes is the overnutrition of protein and suboptimal carbohydrate intake.[25] Elite and amateur athletes from a variety of sports habitually consume over 2.0 g/kg of protein per day.[25] When expressed as a function of total energy intake, protein intakes of U.S. athletes and the general population are similar, with the majority athletes consuming 12–18% of total energy intake in the form of protein.[26] While generally adequate, protein intake varies from as little as 0.44 g/kg to as much as 3.7 g/kg per day for some athletes.[26]

Athletes engaged in sports involving weight reduction typically consume a normal percentage of their daily intake of protein while overall energy intake is reduced. Evidence suggests that energy balance influences protein requirements[27] and, therefore, due to caloric restriction, these athletes may not meet protein requirements. As a result, muscle atrophy may follow and performance may be impaired. Athletes at risk may include wrestlers,[28] gymnasts, and figure skaters.[26] In contrast, men and women bodybuilders in many cases may consume excessive amounts of protein (40% of energy intake)[29] with no credible evidence to support an ergogenic benefit from such a large intake. Excess amino acids have not been shown to be beneficial to protein synthesis[9] and megadoses may have adverse effects on health, including increased risk for the development of chronic renal failure.[30]

PROTEIN HOMEOSTASIS DURING RECOVERY

Following resistance exercise, mixed muscle protein synthesis and breakdown rates are increased,[23,31–33] The acceleration in muscle protein synthesis occurs fairly rapidly, increasing by 50–100% or more within a few hours and returning to basal levels by 48 hours. Protein breakdown is also increased but to a lesser extent (<50%) such that there is a net increase in turnover. However, net protein balance remains negative (protein depletion) unless feeding occurs or amino acids are delivered intravenously soon after the exercise.[11,34] Because basal levels of protein turnover are not significantly affected by chronic resistance training,[23] the first 48 hours post-exercise is a critical time period for facilitating muscle hypertrophy and it may be assumed that most growth takes place within this window. However, resistance training reduces the acute turnover response of skeletal muscle,[23] suggesting that the eventual extent of growth may be limited. The chronic administration of protein-rich meals during recovery from exercise has not been fully evaluated and the long-term benefits are not known.

While resistance exercise has received much attention, fewer studies have directly investigated muscle protein turnover after endurance exercise in humans. Studies on exercising rats using labeled tyrosine and 3-methylhistidine as respective markers of total and myofibrillar protein breakdown have shown that total muscle protein breakdown is increased due to degradation of non-myofibrillar proteins.[35] In addition, protein synthesis is suppressed during exercise and recovery is prolonged in an intensity dependent fashion.[36] During the recovery period in humans, whole body protein synthesis is elevated[5,14] and muscle protein synthesis may be elevated,[37] although not all studies[38] are in agreement.

The availability of amino acids plays a significant role in promoting protein synthesis and inhibiting protein breakdown after exercise (Figure 1). Biolo et al[31] have shown that increases in protein synthesis after resistance exercise may be partly explained by an enhanced rate of amino-acid transport, mediated by increased blood flow. In another report by the same group, high physiological levels of infused amino acids and exercise were observed to have a combined effect on protein synthesis, possibly by optimizing transport.[34] The most likely effect of enhanced amino acid transport is to increase cellular amino acid concentrations, a rate-limiting factor of protein synthesis. Hyperaminoacidemia also reduces the normal protein breakdown response.[34] This finding is consistent with in vitro studies that have reported an inhibitory effect of amino acids on protein breakdown.[39] However, because protein synthesis reduces amino acid concentrations, the inhibition of breakdown is likely transient and may not necessarily indicate complete absence of proteolysis after exercise.[34]

The timing of amino acid ingestion is also known to effect protein metabolism after exercise. A mixed nutrient supplement ingested immediately after endurance exercise has recently been shown to increase both amino acid uptake and protein synthesis compared to later ingestion, resulting in net muscle accretion.[11] While protein breakdown was unchanged, consumption immediately after exercise stimulated a three-fold increase in synthesis. In contrast, ingestion at six hours resulted in net amino acid release from muscle and net loss of protein.[11]

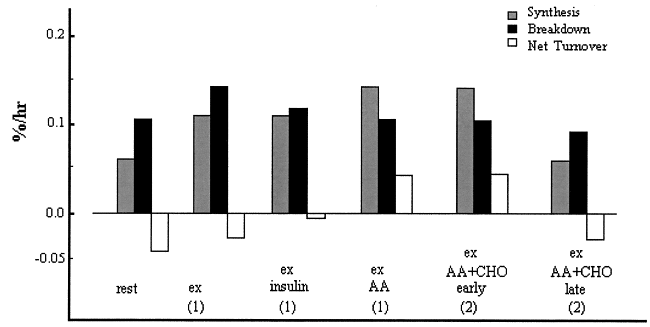

Figure 1. Plot of changes in protein synthesis, breakdown, and net turnover at rest, and following exercise (ex) under varying metabolic and nutritional conditions. Net protein turnover increases after ex but does not become positive until feeding occurs. Both amino acids (aa) and insulin inhibit protein breakdown during recovery. Provision of aa stimulates protein synthesis after resistance (1) and endurance exercise (2). In addition, provision of aa and carbohydrate (cho) immediately after exercise (early) results in net protein accretion but several hours (late) after exercise net turnover remains negative. Adapted from References 11, 31, 32, and 33.

Insulin may stimulate transport of some amino acids[32] but this is not believed to be the primary mechanism by which insulin regulates protein turnover. Recent evidence suggests that insulin does not stimulate muscle protein synthesis to a significant extent after heavy resistance exercise.[32] Insulin significantly reduces protein breakdon after exercise,[32,40,41] possibly due to its regulatory control

Table 1. Recommended Protein Intakes for Different Types and Volumes of Exercise

Exercise Type	Exercise Volume	Recommended Intake (g/kg/day)
Walking[21]	1 hr, 40% Vo_{2max}	unchanged
Moderate intensity jogging[21]	1 hr, 55–67% Vo_{2max}	1.0
Tour de France simulation[20]	~5 hr day, 70% Vo_{2max}	> 1.7
Habitual endurance (trained)[8,22]	≥10 hr/wk	0.94–1.67
Heavy resistance (novice)[15]	20–40 sets/day 70–85% 1RM	1.6–1.8
Habitual heavy resistance (trained)[22]	75 min/day	1.2

of systems (ubiquitin-dependent, lysosomal) responsible for protein degradation.

CONCLUSIONS AND RECOMMENDATIONS

In summary, exercise has profound effects of whole protein homeostasis. During exercise oxidation of amino acids is increased and following exercise both protein synthesis and degradation are elevated. Endurance and resistance exercise appear to have different impacts on protein metabolism. Therefore, protein requirements of people who engage in regular physical activity may be altered depending on the type of exercise performed and their level of conditioning (Table 1). The current recommended intakes of protein for strength and endurance athletes are 1.6–1.7 g/kg and 1.2–1.4 g/kg per day, respectively. Presently, most athletes consume adequate amount of protein in their diet. The timing and nutritional content of the post-exercise meal are known to have synergistic effects on protein accretion after exercise. It is recommended that individuals engaging in strenuous activity consume a meal rich in amino acids and carbohydrate soon after the exercise bout or training session.

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