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**ORIGINAL ARTICLE**

# Strategies to maintain skeletal muscle mass in the injured athlete: Nutritional considerations and exercise mimetics

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**Abstract**
The recovery from many injuries sustained in athletic training or competition often requires an extensive period of limb immobilisation (muscle disuse). Such periods induce skeletal muscle loss and consequent declines in metabolic health and functional capacity, particularly during the early stages (1–2 weeks) of muscle disuse. The extent of muscle loss during injury strongly influences the level and duration of rehabilitation required. Currently, however, efforts to intervene and attenuate muscle loss during the initial two weeks of injury are minimal. Mechanistically, muscle disuse atrophy is primarily attributed to a decline in basal muscle protein synthesis rate and the development of anabolic resistance to food intake. Dietary protein consumption is of critical importance for stimulating muscle protein synthesis rates throughout the day. Given that the injured athlete greatly reduces physical activity levels, maintaining muscle mass whilst simultaneously avoiding gains in fat mass can become challenging. Nevertheless, evidence suggests that maintaining or increasing daily protein intake by focusing upon the amount, type and timing of dietary protein ingestion throughout the day can restrict the loss of muscle mass and strength during recovery from injury. Moreover, neuromuscular electrical stimulation may be applied to evoke involuntary muscle contractions and support muscle mass maintenance in the injured athlete. Although more applied work is required to translate laboratory findings directly to the injured athlete, current recommendations for practitioners aiming to limit the loss of muscle mass and/or strength following injury in their athletes are outlined herein.

**Keywords:** *Skeletal muscle, injured athlete, immobilisation, muscle disuse atrophy, nutrition, neuromuscular electrical stimulation*

## Introduction

An inevitable part of sport and athletics is the risk of injury. Depending upon the age and competitive level of the injured athlete, the recovery period required to return to participation can lead to diverse negative physical, psychological and societal complications (Emery & Tyreman, 2009; Steffen & Engebretsen, 2010). Particularly at an elite level, the economic cost to a team or organisation of an athlete being unable to compete can be considerable (Griffin et al., 2000; Hickey, Shield, Williams, & Opar, 2013; Hupperets et al., 2010). Sport-related injuries occur in many forms, although knee injuries tend to be amongst the most frequent in many sports (Myklebust & Bahr, 2005), and often the most serious in terms of recovery time, the intensity of medical attention required during rehabilitation, the psychological stress imposed on the athlete and the overall financial burden (Griffin et al., 2000). Although contact sports are generally thought of as carrying more physical risk, only around a third of major knee injuries in sport occur due to direct contact with another person or object, while the remainder occur in non-contact situations/sports (Griffin et al., 2000). The initial phase (<6 weeks) of (knee) injury rehabilitation generally involves complete immobilisation of the joint, usually by plaster cast or metal brace (Grant, 2013). This prevents any weight bearing or muscle contraction of the affected muscle groups resulting in a period of muscle disuse. The consequent loss of muscle mass quickly leads to a decline in functional strength (White, Davies, & Brooksby, 1984), a reduction in (local) metabolic rate (Haruna, Suzuki, Kawakubo, Yanagibori, & Gunji, 1994), a decline in insulin sensitivity and increased local fat deposition (Richter, Kiens, Mizuno, & Strange, 1989). The actual amount of

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muscle tissue lost during injury is an important concern for the athlete when considering the level and duration of rehabilitation required before returning to full functional capacity (i.e. pre-injury performance levels; Grant, 2013; Myklebust & Bahr, 2005). Indeed, with recovery durations ranging from 12 weeks to more than a year depending on the severity of the injury, the varying tissues damaged and the magnitude of muscle loss, the importance of employing effective rehabilitation strategies to accelerate recovery is evident (Grant, 2013; Myklebust & Bahr, 2005). Due to obvious physical limitations immediately following injury and/or surgery, current recommendations suggest that the majority of ambulation/weight bearing and specific physical exercise therapy to support rehabilitation can only be undertaken two or more weeks post-injury/surgery (Grant, 2013). However, the initial two weeks of disuse actually induces the largest relative loss of muscle mass (Wall, Dirks, Snijders, et al., 2013; Wall, Dirks, & van Loon, 2013). Consequently, understanding the mechanisms responsible for (short-term) muscle disuse atrophy during injury and developing more effective countermeasures (not involving intense physical exercise) represent important goals in sports science research. The present review addresses the current understanding of the physiological basis for muscle disuse atrophy and discusses nutritional intervention strategies and other possible countermeasures to limit muscle tissue loss during recovery from injury (or, indeed, non-immobilisation induced disuse).

## Studying injury-induced muscle atrophy

Injuries, and consequent surgery, are associated with an acute hormonal and inflammatory stress response (Mendias et al., 2013), which likely contributes to the muscle atrophy process (Bonaldo & Sandri, 2013). However, by far the greatest challenge for preserving muscle mass during recovery from injury is the severe decline in the level of muscle contraction and weight bearing activity due to the limb becoming immobilised. With this in mind, the majority of relevant scientific data have been obtained in laboratory-based studies using limb immobilisation (either by leg/arm cast or knee brace and the use of crutches for ambulation) to induce local disuse in healthy young subjects. These studies show that healthy, inactive muscle tissue generally atrophies at approximately 0.5% per day (Phillips, Glover, & Rennie, 2009; Wall & van Loon, 2012). Numerous factors such as gender (Yasuda, Glover, Phillips, Isfort, & Tarnopolsky, 2005), training status (Miles, Heil, Larson, Conant, & Schneider, 2005), muscle group (LeBlanc et al., 1992) and age (Hvid et al., 2010) can affect the rate of muscle disuse atrophy. Of particular relevance is the time-course of muscle atrophy, with the first 1–2 weeks showing the greatest relative loss of muscle mass. During this period, 150–400 g of muscle tissue can be lost from a single, immobilised leg (Wall, Dirks, Snijders, et al., 2013). In line, the loss of muscle strength (Wall, Dirks, Snijders, et al., 2013) and decline in (local) insulin sensitivity (Richter et al., 1989) occur rapidly within the first 1–2 weeks after the onset of immobilisation. As such, performance and metabolic health detriments ensue quickly, providing an immediate need for effective countermeasures in order to minimise the subsequent rehabilitation efforts that are required. This is of considerable importance to the injured athlete since the initial two-week period following surgery is where, typically, little intervention (concerning physical exercise) is considered for the fear of aggravating the injury (Grant, 2013), and therefore alternative (non-exercise) strategies should be sought. Of additional concern to athletes is that muscle strength declines during disuse at approximately three times the rate that muscle tissue is lost (Farthing, Krentz, & Magnus, 2009; Wall, Dirks, Snijders, et al., 2013; Wall, Snijders, et al., 2013). For example, we recently reported that an 8% loss of quadriceps muscle mass during two weeks of immobilisation in healthy young men was accompanied by a 23% loss of muscle strength (Wall, Snijders, et al., 2013). This is generally attributed to alterations in motor unit recruitment occurring prior to muscle atrophy, which may also explain the greater relative loss of isometric compared with dynamic strength (Hortobágyi et al., 2000; Seki, Taniguchi, & Narusawa, 2001). Given that tendon tissue seems remarkably resistant to disuse atrophy (de Boer et al., 2007; Reeves, Maganaris, Ferretti, & Narici, 2005), and the loss of calcium from the skeleton during disuse occurs at a more modest rate (Rittweger et al., 2006), it is evident that muscle atrophy plays a key role in the loss of functionality experienced during disuse.

Unfortunately, few data are available that allow a more direct translation of laboratory-based findings on muscle disuse atrophy to the elite sporting setting. In a recent case study concerning an English Premier League soccer player recovering from anterior cruciate ligament surgery, we reported less than half the muscle atrophy (1.35 kg) from the immobilised leg than would be expected (~3 kg) based on controlled trials (Milsom, Barreria, Burgess, Iqbal, & Morton, 2014). This was despite the individual in question being highly trained with a greater initial leg muscle mass than an untrained person, characteristics that some studies suggest result in an accelerated rate of disuse atrophy (Miles, Heil, Larson, Conant, & Schneider, 2005). Accordingly, this case study suggests that nutritional and

other interventions (e.g. neuromuscular electrical stimulation [NMES]) that were implemented were effective in attenuating muscle atrophy, at least to a certain extent.

The present paper provides an overview of the current knowledge of the physiological basis of muscle loss during injury. Thereafter, the scientific rationale behind such currently adopted nutritional approaches and the use of NMES will be discussed. Finally, recent findings relating to nutritional and NMES interventions during disuse will be considered to provide contemporary, optimal recommendations for strategies to limit muscle loss in the injured athlete (an overview of which is provided in Figure 1).

## Skeletal muscle protein turnover during disuse

Mixed muscle protein is characterised by a relatively slow turnover rate (1–2% per day). On a daily basis 300–600 g of muscle tissue is being broken down and re-synthesised, theoretically resulting in an entire renewal of an individual's skeletal muscle within a 3- to 4-month period. In a healthy, weight stable individual, muscle mass remains constant due to the dynamic balance between muscle protein synthesis and breakdown. Over the course of a day, periods of net muscle protein loss (i.e. muscle protein breakdown > muscle protein synthesis) are compensated for by periods of net muscle protein accretion in a post-prandial state (i.e. muscle protein synthesis > muscle protein breakdown). Food intake, and protein consumption in particular, increases muscle protein synthesis rates and inhibits muscle protein breakdown (albeit the latter to a lesser extent) resulting in a positive net muscle protein balance (Rennie et al., 1982). Stimulation of muscle protein synthesis following food intake is mainly driven by the post-prandial increase in plasma essential amino acid availability (Tipton, Gurkin, Matin, & Wolfe, 1999), and the rise in leucine concentration in particular (Wall, Hamer, et al., 2013). Thus, the magnitude and frequency of post-prandial stimulation of muscle protein synthesis rates exert an important influence on muscle mass maintenance.

For a quantifiable loss of muscle mass there must be a persistent and chronic alteration in muscle

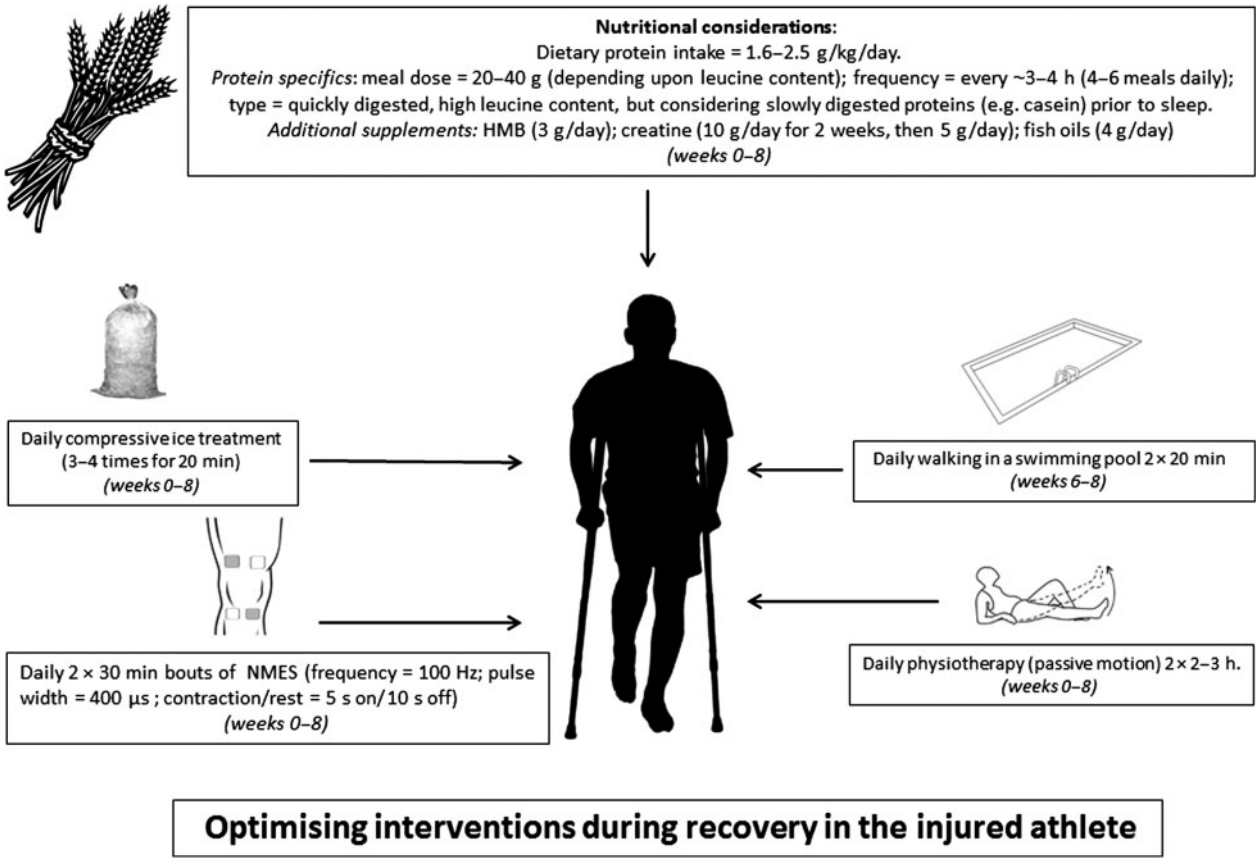


Figure 1. Schematic of potential approaches to limit muscle loss in an injured athlete based on current approaches (Milsom et al., 2014) and recent evidence progressing the understanding of how nutrition and NMES can be applied to attenuate muscle atrophy. Note that although protein recommendations are specified, carbohydrate and fat requirements are likely unique to each scenario depending on each individual's resting metabolic rate, daily activity levels and their desire to minimise any gains in fat mass.

protein turnover. That is to say, for a sustained period muscle protein synthesis decreases, muscle protein breakdown rates increase, or a combination of both occurs. Experiments employing ≥2 weeks of limb immobilisation in healthy or injured young men have consistently shown a considerable decline in fasting muscle protein synthesis rates (Gibson et al., 1987; Glover et al., 2008). More recently it was demonstrated that besides a decline in basal protein synthesis, limb immobilisation also reduces the muscle protein synthetic response to protein intake (termed "anabolic resistance"; Glover et al., 2008; Wall, Snijders, et al., 2013). Muscle protein breakdown rates have not been directly measured following limb immobilisation, and the assessment of changes in the expression or activity of key proteins regulating proteolysis do not provide detailed insight into the quantitative contribution of muscle protein breakdown to muscle disuse atrophy (Abadi et al., 2009; Jones et al., 2004; Wall, Snijders, et al., 2013). Consequently, impairments in muscle protein synthesis rates are now widely considered to represent the main cause for disuse atrophy observed during a period >2 weeks (Phillips et al., 2009; Wall & van Loon, 2012). This suggests that nutritional strategies aimed at compensating for anabolic resistance and/or surrogates for physical exercise capable of increasing muscle protein synthesis rates may be efficacious in attenuating muscle loss during injury. A caveat to this consensus may be in the very early stages (<1 week) of immobilisation, where multiple studies indicate that proteolysis may rise rapidly (Abadi et al., 2009; Tesch, von Walden, Gustafsson, Linnehan, & Trappe, 2008; Wall, Dirks, Snijders, et al., 2013; Wall, Dirks, & van Loon, 2013). We have previously argued that parallel changes in muscle protein synthesis and breakdown may account for the considerable loss of muscle mass during the first week of disuse (Wall, Dirks, & van Loon, 2013; Wall & van Loon, 2012). This highlights the importance of intervening as early as possible in the injured athlete, specifically targeting both muscle protein synthesis and proteolysis.

## Nutritional considerations to minimise muscle loss during injury

### *Macronutrient composition of the diet*

The fundamental concern for the practitioner working with an injured athlete is how best to manage the delicate balance between conserving muscle mass and preventing body fat accrual. In general, the first practical consideration would be how to prescribe overall energy intake and macronutrient composition of the diet. Naturally, with an injury comes a decrease in overall physical exercise and, therefore, a decline in energy requirements. This is of concern when attempting to minimise muscle loss. It has been established that inadequate energy intake accelerates muscle loss during disuse (Biolo et al., 2007), likely due to an additional challenge for preserving muscle protein synthesis rates (Pasiakos et al., 2010). Thus, maintaining energy balance is of key importance. However, providing excess energy does not further attenuate muscle loss, but rather results in increased fat deposition (Paddon-Jones et al., 2004). This is likely explained by the fact that, rather than reduced energy intake *per se*, it is actually the decline in dietary protein consumption that is of most relevance during injury. By way of example, even if an athlete consumed a relatively high habitual protein intake, possibly comprising 15–20% of a 15 MJ (daily) diet, this individual would ordinarily consume 140–185 g of protein daily. For an 85 kg athlete this would equate to 1.6–2.2 g protein per kilogram body mass (g $kg^{-1}$ bm). A significant overall decline in energy intake could easily bring this value down to 1.0–1.4 g $kg^{-1}$ bm, which fails to meet the recommended amount for muscle mass maintenance in athletes (~1.6 g $kg^{-1}$ bm; Phillips, 2012). In support, it has been demonstrated that energy balanced diets with moderate (1.0 g $kg^{-1}$ bm) compared with low (0.6 g $kg^{-1}$ bm) protein intakes attenuate whole-body nitrogen loss and prevent a decline in whole-body protein synthesis (Stuart, Shangraw, Peters, & Wolfe, 1990). As such, it is clear that efforts should be made to maintain adequate dietary protein intake during recovery from injury. However, it is also evident that maintaining or increasing habitual protein may alleviate, but does not prevent, muscle disuse atrophy. This is likely explained by the disuse-induced anabolic resistance to protein intake (i.e. a reduced responsiveness to a given amount of protein; Glover et al., 2008; Wall, Snijders, et al., 2013). As such, rather than solely addressing overall energy and macronutrient composition of the diet, successful dietary strategies should aim to compensate for anabolic resistance by optimising the anabolic response to each individual meal.

### *Overcoming anabolic resistance*

Recent research aimed at optimising the anabolic response to protein intake has focused on manipulating the amount (Moore, Robinson, et al., 2009; Pennings et al., 2012; Witard et al., 2014; Yang et al., 2012) and type (Boirie et al., 1997; Pennings et al., 2011; Tang, Moore, Kujbida, Tarnopolsky, & Phillips, 2009; Wall, Hamer, et al., 2013) of dietary protein, as well as the co-ingestion of other nutrients (Hamer et al., 2013; Staples et al., 2011). Most fundamentally, the anabolic response to the

ingestion of a bolus of protein increases in a dose-response manner (Moore, Robinson, et al., 2009; Pennings et al., 2012; Witard et al., 2014; Yang et al., 2012), with maximal protein synthesis rates being reached following the ingestion of ~20 g protein in healthy, young men. However, in healthy elderly individuals (>65 years), who have also been reported to display an anabolic resistance to dietary protein ingestion (Cuthbertson et al., 2005), a 35–40 g dose seems to be required to maximise post-prandial muscle protein synthesis rates (Pennings et al., 2011; Yang et al., 2012). It could be speculated that the injured athlete may also require a similar quantity of protein to overcome *disuse* related (as opposed to age-related) anabolic resistance. However, the reduced energy requirements of the injured athlete can make large and frequent, protein rich meals difficult to consume. With this in mind, much work has addressed the specific properties that dictate the anabolic potential of a dietary protein (Boirie et al., 1997; Pennings et al., 2011; Tang et al., 2009; Wall, Hamer, et al., 2013). The two characteristics of a dietary protein that primarily influence the post-prandial muscle protein synthetic response are its digestion and absorption kinetics and its amino acid composition. For instance, whey protein, which is rapidly digested and absorbed, has been shown to be more anabolic than "slower" proteins such as soy (Tang et al., 2009) or casein (Pennings et al., 2011; Tang et al., 2009). However, even when casein protein is hydrolysed before ingestion (i.e. artificially "pre-digested", facilitating digestion and absorption kinetics to a level that is similar to whey protein) it is still less effective with regard to its ability to stimulate muscle protein synthesis rates (Pennings et al., 2011). This may be attributed to the greater leucine content in whey as opposed to casein protein (Pennings et al., 2011; Wall, Hamer, et al., 2013). Indeed, it has been shown that fortifying sub-optimal amounts or types of dietary protein with only 2–3 g of crystalline leucine can amplify the anabolic response in elderly men (Katsanos, Kobayashi, Sheffield-Moore, Aarsland, & Wolfe, 2006; Wall, Hamer, et al., 2013). Moreover, the proposed anti-catabolic properties of leucine (Nair, Schwartz, & Welle, 1992) also support the concept that leucine-enriched meals may be applied throughout recovery in the injured athlete, particularly during the early stages of muscle disuse during which muscle protein breakdown rates are likely elevated. An additional property of leucine is its tendency for preferential transamination, both by muscle and liver tissue, to yield various derivatives, one of which is β-hydroxy-β-methylbutyrate (HMB). Recent data suggest that ingestion of this leucine metabolite accelerates muscle protein synthesis rates and inhibits muscle protein breakdown to a similar extent as leucine (Wilkinson et al., 2013). Moreover, initial studies suggest that prolonged HMB supplementation (1.5 g twice daily) may also offer protective effects on muscle mass during a period of bed-rest in older individuals (Deutz et al., 2013). Whether such beneficial effects would translate into the injured athlete (especially whether HMB administration would be of value alongside a high leucine diet) remains to be seen.

Although protein is the fundamentally anabolic macronutrient within the diet, research has addressed whether the co-ingestion of other nutrients can modulate the muscle protein synthetic response to the ingestion of a given quantity of dietary protein. For instance, increased post-prandial insulinaemia offers an attractive hypothesis in favour of carbohydrate co-ingestion to maximise post-prandial muscle protein synthesis rates. However, we (Gorissen et al., 2014; Hamer et al., 2013) and others (Staples et al., 2011) have shown no benefits of carbohydrate co-ingestion with protein in either young or older men. It should be noted, however, that the co-ingestion of carbohydrate (and the associated hyperinsulinaemia) and its impact on post-prandial muscle protein breakdown has not yet been comprehensively addressed. The importance of dietary fat to the anabolic response to meal ingestion is less clear, as few data are currently available. Thus, from a macronutrient perspective, dietary protein intake is of the greater relevance to the post-prandial anabolic response in the injured athlete.

Intriguingly, recent data suggest that fish oil derived omega-3 fatty acid supplementation may be of additional use to the injured athlete. Specifically, long-term supplementation with omega-3 fatty acids (4 g per day) has been shown to augment anabolic sensitivity to amino acids in healthy individuals of all ages (Smith et al., 2011a, 2011b). These beneficial effects were not attributable to any proposed anti-inflammatory properties of omega-3 fatty acids, but rather an apparent sensitising effect on the molecular signalling pathways regulating muscle protein synthesis (Smith et al., 2011a, 2011b). An additional nutritional supplement of relevance is creatine, the ingestion of which is a commonly adopted nutritional approach in athletes to enhance high-intensity exercise performance and/or training adaptations (Becque, Lochmann, & Melrose, 2000). It has also been shown that creatine supplementation (20 g per day – generally considered a "high" or initial "loading" dose) attenuated the loss of muscle mass and strength during seven days of upper arm immobilisation (Johnston, Burke, MacNeil, & Candow, 2009). The mechanism by which this beneficial effect occurred is unclear but may be related to increased intracellular osmolarity causing cell swelling and a consequent stimulation of anabolic signalling

pathways (Hespel et al., 2001). However, no information as to how such effects could modulate intracellular signalling pathways directly regulating muscle protein synthesis or breakdown is currently available. Although equivalent data investigating the efficacy of long-term omega-3 fatty acid and/or creatine supplementation for overcoming disuse induced anabolic resistance and/or attenuating muscle loss in the injured athlete are not available, both represent promising strategies and obvious areas for further research.

### *Nutrient timing and long-term considerations*

Aside from maximising the response to an individual meal, the timing and frequency of protein ingestion throughout the day are also of relevance when working with the injured athlete. Depending on each of the factors described above, each meal generally results in net muscle protein accretion for a period of 2–4 h (Moore, Tang, et al., 2009). Taking the 85 kg athlete used earlier as an example, ideally the 140–185 g of dietary protein consumed daily would be spread equally across four main meals (i.e. 35–45 g protein per meal). This would allow for maximal muscle protein anabolism for 6–12 h of the day. Indeed, such a feeding strategy (protein equally weighted across all main meals) has been demonstrated to result in favourable 24-h muscle protein synthesis rates compared with individuals fed equivalent amounts of daily protein, but with quantities unevenly spread across the three meals (Mamerow et al., 2014). Similar benefits of evenly spaced, adequate protein meals have also been obtained in healthy men during the post-exercise recovery period (Areta et al.). This underlines the importance of avoiding the typically low protein breakfast/high protein evening meal combination, in order to gain the maximum efficiency from daily dietary protein consumption. However, this strategy also allows scope for improvement. Since peak stimulation of post-prandial muscle protein synthesis rates occurs at ~2 h following meal ingestion (Moore, Tang, et al., 2009), there is also the opportunity to increase meal frequency to maximise the duration of the day (i.e. >12 h) spent under post-prandial net muscle protein accretion. Indeed, athletes wishing to maximise gains in muscle mass and strength during resistance-type exercise training programmes are generally advised to consume 4–6 smaller, high protein meals per day (Moore, Robinson, et al., 2009). Based on the same rationale, the injured athlete should consider the same advice. Recent data suggest that an ideal opportunity for additional meals to support higher rates of daily muscle protein synthesis may be prior to sleep. Indeed, the unusually low rates of muscle protein synthesis observed nocturnally (Groen et al., 2012) can be robustly stimulated by protein ingestion prior to sleep (Res et al., 2012) or intra-gastric protein administration during sleep (Groen et al., 2012) in young or elderly men. During this time period it also makes sense to utilise a more slowly digested protein (e.g. casein) to facilitate hyperaminoacidaemia throughout the night (Groen et al., 2012; Res et al., 2012).

It is of paramount importance that the basis of nutritional interventions designed to optimise muscle protein anabolism are translated into long-term studies aiming to attenuate muscle loss in the injured athlete. However, at present, such studies are lacking. Nevertheless, some of the principles highlighted above have been applied to nutritional intervention studies designed to attenuate muscle loss during conditions designed to simulate whole-body disuse during hospitalisation (i.e. bed-rest). For instance, the provision of large doses of essential amino acids (11–50 g per day; equivalent to 22–100 g dietary protein per day) during a period of 6–28 days of bed-rest has been shown to attenuate muscle atrophy, nitrogen losses and/or loss of function to varying degrees in young and older men (Ferrando et al., 2010; Fitts et al., 2007; Paddon-Jones et al., 2004; Stein et al., 2003; Stein, Schluter, Leskiw, & Boden, 1999). These studies offer support for the efficacy of manipulating the diet in an attempt to minimise muscle loss during injury. However, the injured athlete and the associated alterations in lifestyle, activity status, appetite and psychological well-being provide differing challenges when compared with the bed-rested or hospitalised patient. As such, it is vital that future studies translate the known acute effects of meal quantity, quality, frequency and timing upon long-term measures of muscle mass, function, rehabilitation time and the duration of time required to return to competition following injury.

## Neuromuscular electrical stimulation

Physical activity is by far the most potent strategy for maintaining muscle protein synthesis rates and therefore attenuating or preventing muscle disuse atrophy (Ferrando, Tipton, Bamman, & Wolfe, 1997). This holds true even when relatively low volumes of exercise are performed (Oates et al., 2010). However, the dynamic and intense nature of such exercise (usually resistance-type exercise training is recommended) provides concerns as to its safety, particularly in the early period of recovery from injury and/or surgery. As such, aside from nutritional considerations, alternative, non-exercise strategies are generally applied (see Figure 1; Milsom, et al., 2014). It is beyond the scope of the present review to consider all currently applied non-nutritional strategies, but the promising data

emerging concerning the application of NMES deserves further comment. In this regard, NMES offers an attractive surrogate for physical activity or exercise, capable of invoking involuntary, isometric contractions at a relatively low intensity, of specific muscle groups. We have previously shown that a single 60 min NMES session stimulates muscle protein synthesis rates for at least 4 h in elderly men (Wall et al., 2012). Moreover, self-administered daily NMES has been reported to maintain muscle protein synthesis rates and muscle mass during long-term recovery from tibia fracture (Gibson, Smith, & Rennie, 1988). Of interest to the injured athlete, we recently developed a strategy for applying NMES during the first few days of fully casted limb immobilisation (Dirks et al., 2013). Using a relatively high frequency (100 Hz) and pulse width (400 μs) we demonstrated that substantial muscle atrophy observed in the initial five days of immobilisation can be entirely prevented by merely 30 min of NMES performed twice daily in healthy, young men (Dirks et al., 2013). These beneficial effects were likely mediated through stimulation of muscle protein synthesis rates (Wall et al., 2012) in parallel with a possible blunting of muscle protein breakdown (Dirks et al., 2013). Moreover, maintenance of muscle mass was achieved without any safety concerns or negative side effects (substantial muscle pain, skin irritations, etc.) and the protocol specifics (electrode placement, specific muscle groups stimulated, etc.) are discussed in detail in the study by Dirks et al. (2013). It should be noted that the frequency and intensity of our protocol was slightly greater than that previously used in athletes (Milsom et al., 2014). As such, NMES (applied within these parameters) represents a feasible and practical strategy for maintaining a degree of physical activity even during the early stages of recovery from injury. The potential for structured and supervised NMES to maintain muscle protein synthesis rates, metabolic health and muscle mass and function during more prolonged rehabilitation requires future investigation. For instance, it is necessary to assess the viability and effectiveness of applying NMES to multiple muscle groups, either simultaneously or sequentially, in an attempt to maintain whole limb or even whole-body lean mass during differing types of injury. Attention should also be given to defining optimal NMES protocols in terms of duration, stimulation intensity and other specific parameters. Moreover, the potential synergy between the use of such exercise mimetics and nutritional support may offer the most fruitful avenue of further research and, ultimately, improved treatment strategies for the injured athlete.

## Summary and practical recommendations

- Limb immobilisation following injury leads to rapid muscle loss and declines in functional capacity.
- Muscle loss is most profound during the first 1–2 weeks of limb immobilisation, a time period where countermeasures are not conventionally considered a priority for the injured athlete.
- Muscle loss during disuse is primarily attributed to a decline in basal muscle protein synthesis rate and the development of anabolic resistance to dietary protein intake.
- Due to the reduced levels of energy expenditure during recovery from injury, it can be challenging to achieve optimal macronutrient intakes that serve to maintain skeletal muscle mass but prevent any gains in fat mass.
- Daily protein intake 1.6–2.5 g $kg^{-1}$ bm may be required to support muscle mass maintenance during disuse. This should be achieved by the regular (4–6 times daily) consumption of adequate amounts (20–35 g) of rapidly digested protein sources with a high leucine content (2.5–3 g) and spaced evenly across the day (every ~3–4 h). Dietary protein ingestion with breakfast and prior to sleep may be of specific relevance here.
- Specific nutritional compounds, such as omega-3 fatty acids, branched chain amino acids (including leucine), creatine, and HMB, may help support the maintenance of muscle protein synthesis rates during a period of injury.
- NMES offers an alternative means to invoke involuntary muscle contractions, thereby stimulating muscle protein synthesis rates and effectively attenuating muscle loss during recovery from injury.
- Attention should also be given to providing an exercise stimulus (especially resistance exercise) for the uninjured muscle groups (e.g. upper body) so as to prevent any unwanted reductions in regional lean mass that may subsequently affect whole-body muscle mass and metabolic function.

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