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Resistance Training Supplements and their Potential Benefit

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Abstract

Resistance Exercise (RE) is a widely practiced activity both in leisure time and in training periods for competitive athletes. Recent advanced in molecular biology and muscle physiology has elucidated some of the mechanisms that regulate muscle growth. As a result of these biochemical advances, an increased number of supplements claiming to enhance adaptations to Resistance exercise have become available. Essentially, the aim of these supplements is to influence protein synthesis and therefore gradual protein accretion leading to increased muscle size and strength. The aim of this review is to discuss the most commonly consumed supplements associated with RE and make recommendations with regards to timing, volume and combinations of supplementations.

Keywords: Creatine; Protein; Carbohydrate; β-alanine; Weight training

Introduction

Resistance exercise (RE) is one of the most widely practiced forms of physical activity. This type of exercise is often used to enhance athletic performance, augment musculo-skeletal health, and alter body aesthetics. The health benefits of RE are primarily preventative or as a countermeasure to circumstances where muscle weakness compromises optimal function (injury or prolonged inactivity, sarcopenia or musculo-skeletal disorders) however, it can also have a positive effect on skeletal and general metabolic health as well as possible psychological benefits. This review will consider dietary factors that can influence the outcomes of RE, and will review current recommendations for favourable physiological & biochemical adaptation.

Nutrient intake before, during, and after training will support the adaptations that occur in response to the training stimulus [1]. The effect of nutrition on adaptations that arise from training may not be as important as the training itself, but the effect on the final outcome is important. In recent years, the effect of nutrition on training adaptations has received increasing attention, particularly with respect to maximising the benefits of RE. Consequently the nutritional supplements industry has expanded to become a multi-million dollar industry with an array of products for enhancement of both nutritional status and capacity for increased RE. This review will consider current opinion and practical advice on some of the key macronutrients of a standard diet, and the most commonly used supplements associated with RE.

Protein

Proteins are synthesised from 20 amino acid building blocks, and to ensure continuity of the synthesis of a given protein, the amino acids are collected in pools to ensure continuous availability for protein synthesis. The absence of any one amino acid from a pool results in immediate cessation of protein synthesis associated with that pool. To avoid a situation where amino acid shortage causes failure of essential protein synthesis, most proteins in the body are in a state of constant turnover (synthesis and degradation) to facilitate constant top up of amino acid pools. Typically a male body of 70 kg contains about 12 kg of protein, and 200 g of free amino acids. Roughly 120 g of free amino acids are located in skeletal muscle and around 5 g of free amino acids are found in circulation. Backup support is provided by a suite of transaminase enzymes that can both interchange amino acids, and produce amino acids from simple carbohydrates to make up any shortfall in amino acid pools (Figure 1). Of the 20 amino acids, 12 are designated non-essential in adults because they are readily synthesised as required, and 8 are designated essential and must be supplied in the diet (Table 1).

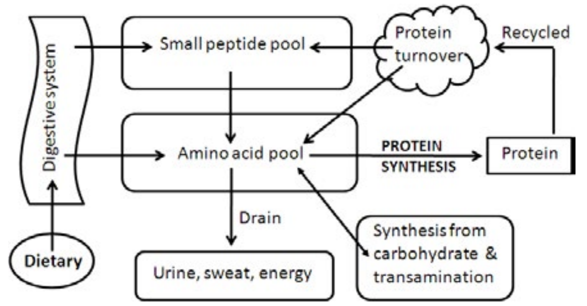

Figure 1: Amino acid pool showing sources of synthesis and degradation.

Non-essential	Essential
Alanine	Arginine *
Asparagine	Histidine
Aspartate	Isoleucine #
Cysteine#	Leucine
Glutamate	Lysine
Glutamine	Methionine
Glycine	Phenylalanine
Proline	Threonine
Serine	Tryptophan
Tyrosine	Valine #

(* only in growing young, not in adults)
(# BCAA branched chain amino acid)

Table 1: Non-essential and essential amino acids.

Protein has long been considered the most vital macronutrient to

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facilitate adaptations to RE especially if hypertrophy and strength gains are targeted. In recent times, individuals seeking increased aerobic power and stamina as well as weight loss have become increasingly concerned with the importance of protein in a diet [2,3]. Muscular hypertrophy is a developmental process founded on complex metabolism and signalling events in the body. In normal circumstances the body aims to maintain protein homeostasis by keeping protein anabolism and catabolism in balance. Increased mass of muscle is produced by increased anabolic activity to support synthesis of muscle myofibrillar proteins, and with suitable training regimes, protein homeostasis can be shifted toward adaptations that result in increased muscle mass. A positive change in the relative protein content of muscle requires a shift in major metabolic pathways (including energy) and hormone activity that support anabolic production of protein. A negative change in the relative protein content of muscle can occur when the balance shifts to catabolic activity as in periods of starvation when muscle is actively catabolised to provide amino acids as a source of energy. Exercise and nutrition have strong influences on the relative balance of anabolic and catabolic metabolism of muscle protein [4].

RE and Endurance Exercise (EE) both produce mixed muscle protein synthesis during the subsequent recovery phase and turnover of mixed muscle proteins is increased following RE [5]. Increased supply of amino acids during this time will ensure that amino acid pools are not depleted and will facilitate better muscle protein synthesis after RE [4,6]. This could be achieved with a product supply that creates a temporary hyperaminoacidaemia to increase amino acid delivery to the muscle, transport into the muscle cell, and intracellular amino acid pool top up [7]. Tipton and colleagues reported that increased provision of amino acids was responsible for the elevation of protein synthesis [8]. Kobayashi et al. [9] supported this observation by showing that lower levels of blood amino acids resulted in decreased muscle protein synthesis, and that protein synthesis was restored with restoration of increased blood amino acids. Clearly blood amino acid levels are essential for muscle protein synthesis.

Recent research has focused on the importance of individual amino acids to influence anabolism with leucine receiving most attention [1,10]. Leucine is one of the Branched-Chain Amino Acids (BCAA), and is an essential amino acid. Koopman et al. [10] investigated the effects of additional free leucine to a post exercise recovery drink (carbohydrate vs. carbohydrate and protein vs. carbohydrate, protein and leucine). The addition of leucine resulted in an increased plasma insulin response and increased net protein balance when compared with protein ingestion alone. However, Tipton suggests that additional leucine does not have a greater influence in an already anabolic situation following RE plus protein ingestion, and hypothesised that metabolism and hormone actions are already fully activated by RE and amino acids, including leucine, in whey proteins and therefore, no further activation by free leucine is possible [1,11]. As a result of these findings, it is unclear whether additional leucine supplementation provides any advantage. It is clear that post exercise recovery of muscle protein synthesis does require leucine, but it is likely that dietary or supplemented protein will provide sufficient amounts of leucine to facilitate synthesis.

Research into the optimum timing of protein and amino acid ingestion has also produced equivocal results [3,12]. Tipton et al. reported that protein ingestion pre and post RE both resulted in the change from negative net muscle protein balance to a positive balance [12]. However, the total response to an Essential Amino Acid-Carbohydrate (EAC) solution was greater when consumed immediately pre exercise compared to immediately post. Interestingly, muscle protein metabolism was also elevated for longer when the EAC solution was consumed pre-exercise compared to post. The length of the effect, plus higher blood flow during exercise in the PRE trial, resulted in significantly greater total uptake over the entire study period. A commonly discussed concept in RE and protein ingestion is that of the "metabolic window" (i.e. the 45 min-1 h immediately post RE). It has been suggested that this is the time when consumption of protein is most effective [13]. However, this phenomenon may not be as important as previously thought as Rasmussen et al. demonstrated that the response of muscle to an EAC solution was similar when ingested 1 and 3h following RE [14]. Interestingly, Cribb and Hayes reported greater increases in lean body mass, CSA of type II muscle fibres and 1-repetition maximum (1RM) when ingestion of an EAC was immediately pre and post compared to early morning and late evening suggesting that the timing of protein ingestion can enhance the desired adaptations from RE training [13].

While the importance of protein for muscular adaptation is clear and unquestioned, the amount of protein required is controversial. Protein synthesis is elevated post RE and the amount of protein intake should be sufficient to support the increased level of anabolism. Typically the protein requirement of an individual is based on nitrogen balance, which is generally elevated for athletes compared with sedentary individuals [14]. Many coaches and athletes advocate very high protein intake, up to 4.0 $gkg^{-1}day^{-1}$ [15]. Even the American Dietetic Association, Dieticians of Canada and the American College of Sports Medicine state that protein intake must be > 1.6 $gkg^{-1}day^{-1}$ for gains in muscle mass [16]. There is another school of thought that protein requirements for active individuals are not increased above that of sedentary controls [3,17]. This argument is supported by the fact that exercise increases the turnover and hence efficiency of amino acid utilisation possibly due to reutilisation of amino acids from muscle protein breakdown to re-supply amino acid pools [17,18]. RE trained individuals also exhibit a greater negative net muscle protein balance than untrained volunteers in a fasted state [4]. Tipton proposed that exercise decreases protein requirement. Ratamess and colleagues reported no increased response to a 10 week RE protocol when comparing low (< 1.2 $gkg^{-1}day^{-1}$), moderate (1.21 – 1.90 $gkg^{-1}day^{-1}$), and high (> 1.91 $gkg^{-1}day^{-1}$) protein intake in collegiate football players [1,18]. Ferrara et al. [19] reported similar findings when examining changes in body composition after a high (1.9 $gkg^{-1}day^{-1}$) and normal (1.3 $gkg^{-1}day^{-1}$) protein intake for six months. These findings suggest that high protein intake (> 1.9 $gkg^{-1}day^{-1}$) is unnecessary for gains in muscle mass and that moderate consumption (approximately 1.2 – 1.9 $gkg^{-1}day^{-1}$) appears sufficient. Conversely, Hoffman et al. [20] demonstrated a trend for increased lean body mass with protein supplementation of 2.0 $gkg^{-1}day^{-1}$ compared to 1.2 $gkg^{-1}day^{-1}$ in collegiate football players. The authors also demonstrated a significant increase in 1 RM squat performance after a 12 week RE program on the higher protein intake compared to moderate consumption. Interestingly, Hoffman et al. [20] did not observe any statistical difference in 1RM bench press, wingate performance, body mass, resting testosterone, insulin-like growth factor-1 (IGF1), or growth hormone (GH) between groups. The combination of these findings suggest that elevated protein intake > 2.0 $gkg^{-1}day^{-1}$ may augment strength development in RE trained individuals however the increase above moderate consumption is likely minimal. The purpose of protein ingestion is to top up amino acid pools that will then support protein synthesis, and it should be recognized that such pools are finite, such that when topped up to the maximum then further protein ingestion will not result in increased pool size. Excess amino acids are eliminated from the body and protein intake above moderate consumption may also be potentially harmful as removal of excess amino acids may add stress to the function of the kidneys (Figure 1).

The majority of studies investigating protein consumption on RE adaptations have not used competitive strength/power athletes directly, but instead seek to extrapolate from various populations what strength/power athletes need. This is a weakness in such studies and despite the high internal validity of these studies, their practical application to elite and competitive RE athletes is potentially limited.

It is known that not all proteins are equal as sources of amino acids that will support the synthesis of myofibrillar protein. The biological value of a protein is a measure of the efficiency with which a given protein is absorbed and assimilated into the protein of an organism. Milk and egg white are examples of proteins with high biological value, whereas plant sources have a relatively low value due to absence of some essential amino acids. Wilkinson and colleagues demonstrated that fat-free mass was increased to a greater extent in individuals consuming fluid milk (whey and casein) than when a soya protein beverage was consumed [21]. Numerous studies have reported diverse absorption characteristics of whey (rapidly absorbed) and casein (slowly absorbed) proteins [22]. Tang et al. [6] reported that muscle protein synthesis was elevated in a stepwise manner (whey > soy > casein) after exercise and at rest. These authors suggested that to increase muscle anabolism, a rapid increase in essential amino acids (possibly leucine specifically) is required. Yet, the benefit of one over the other is still unknown with regard to RE. Also important is the relationship between muscle and liver as a significant amount of ingested amino acids can be taken up by the liver and oxidized for fuel or used for other metabolic requirements.

From the evidence reviewed, moderate protein consumption (approximately 1.2-1.9 gkg^{-1}day^{-1}) is recommended for individuals partaking in RE for aesthetics or for general health as to date no study has shown favourable anthropometric changes for high consumption over moderate consumption [22]. For elite and competitive athletes higher levels of protein intake may result in weight gain and movement through weight categories, but may be important in supporting and maintaining a high level of protein turnover. Excessively high levels of protein intake will not result in increased protein synthesis due to limitations imposed by amino acid pools, and may be harmful as excess amino acids are removed from the body. With regards to timing of ingestion, immediately pre RE is likely to be more beneficial as this has shown to increase protein synthesis for a longer period than post-RE consumption.

Carbohydrate

Carbohydrate (CHO) supplementation is common in endurance athletes and provides an exogenous source of glucose [23]. Less importance has been placed on the consumption of CHO in RE trained individuals compared with protein. As discussed above, RE stimulates protein synthesis and supply of amino acids can elevate protein synthesis further. It has been suggested that an addition of CHO to a post exercise protein solution may increase muscle anabolism by taking advantage of the resultant insulin response to CHO. An increase in insulin, as a result of glucose ingestion, would counteract the adenosine monophosphate-activated protein kinase (AMPK) activity which promotes glucose and fatty acid oxidisation for energy and inhibits protein synthesis (Figure 2). AMPK promotes energy release and inhibits energy consumption, and protein synthesis is an energy-demanding process [24]. During exercise, metabolism rightly shifts to the catabolic mechanisms that provide energy for muscle activity. Anabolic activity is curtailed and although insulin is a key anabolic hormone in moving glucose into muscle cells via its regulation of GLUT4, the anabolic activity of insulin during exercise is inhibited.

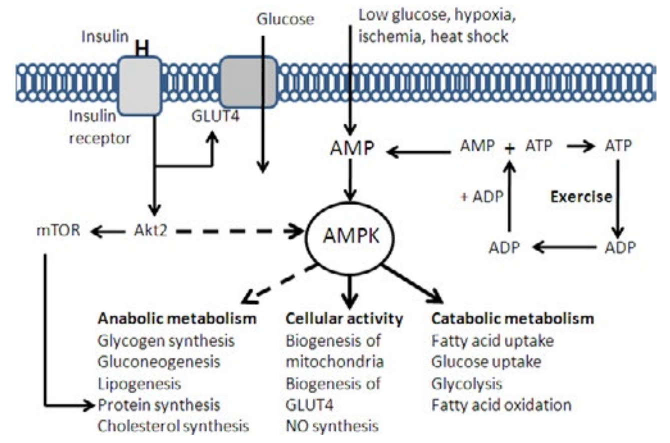

Figure 2: AMPK activity and subsequent metabolic effects.

It is the aim during RE to minimise the reduction in insulin as it has been shown to have significant effect on muscle protein synthesis when adequate amino acid concentrations are available, by reducing protein catabolism [22]. Exercise-induced mRNA transcription and synthesis of proteins is only fully activated when plasma insulin levels are elevated [24]. Elevations in insulin are expected to inhibit AMPK activity, therefore promoting protein synthesis (Figure 2). Insulin exerts its effect on translation through the protein kinase B (Akt2)-mammalian target of rapamycin (mTOR) pathway. This response is critical for increasing muscle protein synthesis and subsequent hypertrophy [25]. The mTOR signal serves to increase protein synthesis by increasing the number of messenger RNA translated per ribosome. Insulin concentrations parallel changes in blood glucose, and the response is enhanced when protein and carbohydrates are ingestion prior to, during, or after a workout [26].

It has previously been reported that insulin in the absence of amino acid availability does not stimulate protein synthesis [27]. Therefore, the ingestion of protein with CHO after exercise should allow insulin to exert its stimulatory effect on muscle, which, according to Ivy and colleagues would likely manifest itself as an interactive effect (i.e. the combined effects of hyperinsulinemia and the exogenous protein would be greater than the sum of their independent effects) [28]. This hypothesis has been both supported and opposed [10,29]. Ivy et al. [28] reported that supplementation with a CHO-protein drink after exercise increased phosphorylation of Akt, mTOR, ribosomal protein S6 and glycogen synthase kinase 3α/β when compared to a placebo. This in turn lead to increased release of amino acid into the blood and would theoretically stimulate muscle protein synthesis however this was not measured directly in the study. Interestingly, Ivy et al. [28] examined phosphorylation of these muscle proteins after repeated sprints on a cycle ergometer. It is therefore unclear if any hypertrophy did occur as this type of exercise may or may not result in muscular growth in already conditioned individuals.

Vollestad et al. [29] suggested that intermittent activities (such as RE) can stimulate significant glycogenolytic effects. MacDougall et al. [30] indeed reported that RE can significantly decrease muscle glycogen stores. Therefore, it is commonly accepted that muscle glycogen is an important fuel for RE and maintenance of these stores may enhance performance. Reductions in muscle glycogen have resulted in decreased isokinetic and isometric force production and accentuated exercise-induced muscle weakness [31]. A study by Haff et al. [32] demonstrated that RE-induced decreases in muscle glycogen can be attenuated by CHO feeding during RE. Haff et al. [32] however, did not report enhanced isokinetic leg extension performance with increased muscle glycogen as a result of CHO supplementation. This result may be a product of the performance test selected as Leveritt and Abernethy reported than decreased muscle glycogen resulted in impaired back squat performance but not isokinetic leg extension [33]. Lambert et al. [34] and Haff and colleagues have reported enhanced RE performance with CHO supplementation over isokinetic and free-weight testing protocols [35,36]. Conversely, Conley et al. [37] and Vincent et al. [38] reported no benefit of CHO supplementation on a RE protocol of high volume. It is important to note that these studies differed significantly in time; studies by Lambert et al. [34] and Haff et al. [35,36] lasted 56, 77, and 57 mins respectively whereas the investigations by Conley et al. [37] and Vincent et al. [38] were much shorter in duration. As exercise bouts lasting less than 41 min rely primarily on muscle glycogen as a fuel source, the increased duration and reliance of exogenous blood glucose may have promoted performance decrements in the three longer duration investigations. It appears from these findings that with increased duration of RE, the probability of decreased performance increases. Notably, these investigations asked participants to perform a RE session of high volumes of work similar to those performed using a hypertrophy protocol. Therefore the effect of CHO supplementation on a strength protocol (sets of 1-6RM) is unknown. The literature suggests that CHO supplementation may be vital to maximise performance of RE when using large-muscle mass free-weight exercise performed with high training volumes and moderate loads as the amount of glycogen used in these exercise appears to be related to the total amount of work and the duration of the RE protocol. More research is required to provide greater understanding of the effect of CHO supplementation on RE. To date no studies have concerned the effect of high/low glycemic CHO on RE, adaptations to chronic CHO supplementation without addition of protein, a dose-response relationship with CHO supplementation (dose), and RE performance (response) or the timing of CHO ingestion (before vs. after RE).

Creatine

Creatine supplementation has been surrounded by controversy since it gained popularity in the early 1990's [39]. Some anecdotal reports have claimed that creatine has a number of health risks, and is an unnecessary practice. However, many athletes and experts in the field have reported that use of creatine not only enhances exercise performance, but is also clinically safe [40]. In the initial stages of intense exercise when Adenosine Triphosphate (ATP) consumption is high, energy to re-phosphorylate adenosine diphosphate (ADP) to ATP (Figure 3) during and following intense exercise is provided by, and is therefore largely dependent on the amount of, phosphocreatine (PCr) stored in the muscle [41]. High-intensity exercise depletes PCr stores and the rate of energy availability diminishes as a result of reduced rate of ATP production. The capacity for maximal-intensity exercise declines and availability of PCr in muscle dictate energy generation until other mechanisms of ATP production take over. It has been hypothesised that increasing muscle creatine content by exogenous supplementation may allow greater training adaptations because of an enhanced quality and volume of work performed as a result of an improved rate of ATP resynthesis during high-intensity exercise.

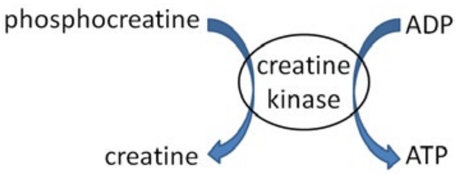

Figure 3: PCr actions.

Creatine is synthesised in liver and pancreas from amino acids arginine, methionine, and glycine with approximately 95% of the body's creatine stored in skeletal muscle [42]. Furthermore, small amounts of creatine can be found in the testes and brain. Approximately two thirds of creatine stored in muscle is stored as PCr and the rest as free creatine. Approximately 1-2% of the creatine pool is broken down per day into creatinine in the skeletal muscle and then excreted in urine [41]. Creatine stores can be replenished by dietary intake containing creatine (meat and fish) or through endogenous synthesis of creatine from arginine, methionine, and glycine. Relatively small amounts of creatine are found in meat and fish and therefore supplementation provides a cost effective and simple means of increasing creatine availability without excessive fat, protein or calorific intake. Tarnopolsky et al. compared 10 g creatine monohydrate and 50 g CHO against 10 g casein protein and 50 g CHO and reported that the creatine group reported a greater increase in fat free mass compared to the protein group [43]. The implications of this suggest that in sports where body weight is unimportant, creatine is a superior supplement than casein protein when combined with CHO to enhance hypertrophy.

Various supplementation protocols have been suggested as effective in increasing muscle stores of muscle creatine. The amount of increase in muscle storage is dependent on creatine levels in the muscle prior to supplementation. Individuals with lower muscle stores may experience storage increases of 20-40% whereas those with relatively high stores may only increase by 10-20% [41]. The extent of the increase in skeletal muscle creatine storage is important as studies have reported performance changes to be correlated to this increase [44]. The most commonly described protocol is known as the "loading" protocol; characterised by ingestion of approximately 5 g four times per day for 5-7 days and 3-5 $g \cdot d^{-1}$ thereafter [41]. This protocol has results in an increase of 10-40% in muscle creatine and PCr stores [45]. Further research has demonstrated that a shorter loading period is still beneficial, as is a reduced dosage, particularly if ingested with CHO or protein [45]. Other suggested protocols include those with no loading phase as well as "cycling". Cycling protocols typically consist of "loading doses" for 3-5 days every 3-4 weeks. These protocols have been shown to be effective in increasing strength and hypertrophy [46,47]. It would be interesting to compare these protocols within one research paper to establish optimum strategy and determine whether the strategy or the total creatine consumption is the key factor concerning RE adaptations.

Many forms of creatine currently exist in the marketplace within various formulations. However, few of these have shown any benefit over the traditional creatine monohydrate. Recently, Spillane et al. examined the effectiveness of creatine ethyl ester and reported no additional benefit in muscle strength or anthropometry when compared to creatine monohydrate [48]. Similar findings have been reported for creatine phosphate a creatine/β-hydroxy-β-methlybutyrate (HMB) combination and creatine plus glycerol [42,49,50]. However, the combination of CHO and creatine in a formula has been shown to increase muscle creatine retention with Pittas et al. suggesting only a small amount of CHO is required to optimise insulin-mediated creatine retention [45,51]. These authors also reported that a combination of protein, CHO and creatine was optimum for insulin response and creatine retention. Other recent studies have indicated a potential benefit to RE when combining creatine with protein [52]. From these findings, it appears that combining creatine with protein and/or CHO produces optimal results. Despite the trepidation surrounding creatine supplementation, it appears to be the most effective nutritional supplement in terms of improving lean body mass and anaerobic capacity. With regard to the medical safety of creatine supplementation, no peer-reviewed paper to date has reported any clinically significant side effect other than weight gain as a result of normal creatine intake (< 25 g d^{-1}).

β-Alanine

The dipeptide carnosine is synthesized in human skeletal muscle and has been shown to contribute increased capacity to buffer hydrogen ions (H^+) during intense exercise [53]. It is synthesized within skeletal muscle from histidine and β-alanine. While histidine, a non-essential amino acid (in adults), is found in high concentrations along with carnosine synthetase in skeletal muscle β-alanine, an amino acid derivative, is found in much lower concentrations [54]. Therefore, β-alanine is likely the rate-limiting step in carnosine synthesis [54]. Increased skeletal muscle carnosine levels through β-alanine supplementation have been shown to support the maintaintenance acid-base balance, delay fatigue, and improve exercise performance.

A number of investigations concerning the effect of β-alanine supplementation on EE events suggest that supplementation enhances performance [55]. Less research has been conducted on the efficacy of β-alanine on RE. Hoffman et al. compared supplementation of creatine with a combination of creatine and β-alanine in collegiate football players [56]. Addition of β-alanine appeared to provide a greater training stimulus than creatine alone. Significant improvements were observed for both squat and bench press exercise, lean tissue mass and fat loss in subjects supplementing with both β-alanine and creatine compared with creatine alone. Interestingly, no differences were noted in the magnitude of strength improvements between the groups. In fact, to date, no research suggests that β-alanine supplementation improves maximum strength. Hoffman et al. [56] showed no improvements in 1RM squat exercise after supplementation. Kendrick et al. [57] reported that β-alanine supplementation did not enhance performance of a box squat, bench press, dead lift or isokinetic leg extension at 180° s^{-1}. These results are not entirely surprising as β-alanine supports buffering capacity, and maximal strength is not limited by acidosis. Similarly, Portington et al. [58] also showed that other buffering agents such as sodium bicarbonate also failed to demonstrate any ergogenic effect on strength performance.

The major putative effects of greater buffer capacity are likely to be observed in activities eliciting a high intracellular acidosis. In particular, stronger buffer capacity has been especially ergogenic in multiple bouts of high-intensity short-term exercises interspersed by short recovery intervals [59]. Hoffman et al. [56] showed that β-alanine supplementation did not enhance maximal strength performance but resulted in a ~20% increase in total work volume during RE in well-trained resistance athletes. Conversely, when an exercise protocol elicits a less extreme muscular acidosis (i.e. exercise lasting < 60s or exercises using small muscle groups), no beneficial effects of β-alanine have been observed [59,60].

From the literature concerning β-alanine to date, it is possible to draw the following conclusions: 1) chronic supplementation of β-alanine can enhance performance of multiple bouts of high-intensity short-term exercise interspersed by short recovery; 2) acute supplementation of β-alanine appears not to enhance strength performance and; 3) total work during RE can be increased through β-alanine supplementation even in well-trained athletes.

Caffeine

Caffeine remains the most widely utilised ergogenic aid, and bears a strong evidence base for beneficial use in medium to long duration sports performance. However, the impact of caffeine upon short duration high intensity activity remains unclear; with some studies showing no effect or even a performance decrement with caffeine supplementation [61-63]. Duncan et al. however, reported that number of repetitions completed was higher when caffeine was ingested 60 min pre-RE [64]. This suggests that total work was higher in the caffeine condition. Therefore, if this phenomenon continued over time, RE adaptation would likely be augmented due to a greater stimulus. However, the study by Duncan et al. only concerned one RE bout and therefore, this is purely speculation. Astorino and Roberson suggest that trained athletes may respond more favourably than untrained participants to ergogenic effects of caffeine in resistance training [65]. Moreover, they suggest that RPE and Pain sensation remain unaffected by caffeine supplementation in short term activity. Like many proposed ergogenic supplements, the magnitude of response varies between individuals and this is arguably owing to different rates of metabolism [66]. The exact mechanism of caffeine, as an ergogenic substance, remains unclear although it is believed that the effector is located outside of the muscle cell thus, acute resistance exercise, where metabolism occurs within the cell, in understandably less affected by caffeine ingestion [65].

Nitrates

Dietary nitrates have recently attracted attention as a potential ergogenic aid to sports performance. Although there is some support for their use with endurance activity the efficacy of utilisation in short duration resistance exercise remains unsubstantiated [67-69]. This is perhaps unsurprising given their mechanism of impact via cardiorespiratory efficiency. However, as duration of exercise increases, where muscular endurance becomes an important performance factor, nitrate supplementation may yet prove beneficial. Evidence is beginning to support the use of nitrate supplementation, most often in the form of beetroot juice, for high intensity constant workloads; whilst the support for use in intermittent high intensity work remains equivocal [70]. Interestingly, Kelly and Colleagues observed that nitrate supplementation improved exercise tolerance during exercise at 60, 70, and 80% delta, but not 100% peak power, suggesting that nitrate can improve performance at submaximal intensity but not peak power output [71]. There is some debate as to the primary effector mechanism for the performance gains seen post nitrate supplementation; with suppressed muscular ATP turnover and alterations in mitochondrial efficiency both being posited [69]. Thus, whilst there is no argument for utilising nitrates during resistance training itself, there may be benefits to the athletes involved in resistance training as part of a broader programme for sports performance.

Conclusion

Availability of amino acids is important for protein synthesis associated with hypertrophy and inclusion of CHO may maximise the effect of insulin with creatine also increasing lean body mass. Therefore, a combination of CHO, protein and creatine could be beneficial to consume pre-, during-, and post-exercise to maximise hypertrophy and recovery. However, creatine is not recommended for athletes who compete in events that require acceleration of one's own body mass. Of course, acute program variables of the training protocol (volume, load, rest period length, exercise selection, and exercise order) have the largest impact upon adaptations to resistance exercise and these factors must be optimized to maximize resultant physiological modifications. A number of other factors affect adaptations to RE including age, genetics, gender, timing of training periods, posture as well as cultural and general habits.

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