REVIEW

CURRENT OPINION

Evidence-based nutritional approaches to enhance exercise adaptations

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Purpose of review
The purpose of this opinion paper is to provide current-day and evidence-based information regarding dietary supplements that support resistance training adaptations or acutely enhance strength-power or endurance performance.

Recent findings
Several independent lines of evidence support that higher protein diets, which can be readily achieved through animal-based protein supplements, optimize muscle mass during periods of resistance training, and this likely facilitates strength increases. Creatine monohydrate supplementation and peri-exercise caffeine consumption also enhance strength and power through distinct mechanisms. Supplements that favorably affect aspects of endurance performance include peri-exercise caffeine, nitrate-containing supplements (e.g., beet root juice), and sodium bicarbonate consumption. Further, beta-alanine supplementation can enhance high-intensity endurance exercise efforts.

Summary
Select dietary supplements can enhance strength and endurance outcomes, and take-home recommendations will be provided for athletes and practitioners aiming to adopt these strategies.

Keywords
endurance, nutrition, performance, strength-power

INTRODUCTION

The global sports nutrition market exceeded $40 billion USD in 2022 and is expected to expand at a ~7.4% compounded annual growth rate year-over-year [1]. Most athletes consume dietary supplements and, depending upon the sport, up to 100% of individuals polled indicate that they use one or more supplements to enhance performance [2]. Over the past 10 years several reviews and consensus statements have been written regarding the efficacy of various dietary supplements [3–7]. The purpose of this opinion paper is to discuss dietary supplements that have been well documented to enhance resistance training gains in muscle mass and strength, acutely enhance strength and/or power, and enhance aspects of endurance performance. In this regard, a plethora of evidence suggests that a daily protein intake ~2.5-fold higher than the recommended dietary allowance of 0.8 g/kg body mass/day, which can be readily achieved through animal-based and plant-based protein supplements, optimizes muscle mass and strength increases with resistance training. Creatine monohydrate supplementation and acute caffeine consumption enhance muscle strength and power. Several lines of evidence also suggest various aspects of endurance performance are positively affected with the acute consumption of caffeine, nitrate-containing supplements (e.g., beet root juice), and sodium bicarbonate. Finally, beta-alanine supplementation seemingly provides ergogenic benefits to certain types of endurance exercise endeavors. The following paragraphs will provide further insight into these topics.

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KEY POINTS

- Most competitive athletes consume dietary supplements, and this is reflected in a global sports nutrition market that exceeded $40 billion USD in sales in 2022.
- There are multiple lines of evidence to suggest that higher protein diets, creatine monohydrate supplementation, and peri-exercise caffeine consumption enhance resistance training adaptations, strength, and power through distinct mechanisms.
- Supplements that positively impact endurance exercise performance include peri-exercise caffeine consumption, nitrate-containing supplements (e.g., beet root juice), and sodium bicarbonate consumption. Additionally, beta-alanine supplementation enhances high-intensity exercise performance.
- Future directions to be pursued in sports nutrition research include the effects of nutritional supplements in female athletes and the combinatorial effects of the supplements covered in this review.

SUPPLEMENTS THAT AFFECT STRENGTH AND POWER OUTCOMES

Protein supplements

Protein supplements are popular amongst recreational and competitive athletes, and the intent of supplementation is to facilitate improved recovery from training through stimulating postexercise muscle protein synthesis rates beyond what is achieved with exercise alone [7]. Several protein supplements exist including milk-based protein powders (i.e., milk protein concentrate, whey, casein, or whey-casein-blends), beef and collagen protein powders, egg protein powders, soy protein powders, other plant-based protein powders (e.g., pea protein, peanut protein, potato protein, rice protein), and insect protein powders. Indeed, several of these protein supplements enhance postexercise muscle protein synthesis following a resistance exercise bout [8–12], and this lends credence to the potential ergogenicity of supplementation.

It is important to note that the amino acid profile and digestibility of these supplements are related to their ability to stimulate postexercise anabolism; specifically, the content of L-leucine and the other essential amino acids dictates the postprandial anabolic response [13]. In this regard, several lines of evidence support that whey protein, which contains a high content of L-leucine and essential amino acids, stimulates the highest increases in postexercise muscle protein synthesis. A seminal meta-analysis by Morton *et al.* [14] indicates that recreationally trained individuals obtain strength and muscle mass benefits from protein supplementation whereas novice trainees do not, and this is further supported by a prior meta-analysis by Pasiakos *et al.* [15]. These results may be associated with large and variable gains in fitness in novice trainees which may mask any small benefits of protein supplementation. Also noteworthy is evidence indicating that animal-based protein supplements provide enhanced resistance training adaptations versus plant-based protein supplements [16■], and protein supplements alone are just as effective for promoting resistance training adaptations versus multi-ingredient protein supplements containing added amino acids, creatine, vitamin D, polyunsaturated fatty acids, and β-hydroxy β-methylbutyrate (HMB) [17].

A 2013 meta-analysis by Schoenfeld *et al.* [18] indicates that the timing of protein supplementation is not as important as ensuring adequate daily intakes. Further, the current evidence indicates that protein intakes, which can be bolstered through protein supplementation, should be higher than what is generally recommended for nonactive adults (e.g., 0.80 g/kg body mass/day). In this regard, a 2019 review by Antonio that critically analyzed nine scientific studies indicated that strength-power athletes should consume at least 2.2 g/kg body mass/day to optimize muscle mass gains from resistance training [19]. This recommendation was subsequently validated by the Moore laboratory who used the indicator amino acid oxidation (IAAO) technique to show that resistance-trained men require >2.0 g/kg body mass/day of higher quality dietary protein to maximize whole-body anabolism after exercise [20]. In summary, protein supplementation, and more specifically animal-based protein supplementation in trained individuals, optimizes muscle mass and muscle strength increases during periods of resistance training. These effects are likely due to ensuring an optimized protein intake for athletes. Alternatively stated, athletes receiving >2.0 g/kg body mass/day of dietary protein are likely not going to attain appreciable benefits with additional protein supplementation.

Creatine monohydrate

Creatine monohydrate (α-methyl guandino-acetic acid) is one of the most popular dietary supplements [21■■]. Creatine is endogenously synthesized from arginine, glycine, and methionine primarily in the liver and kidneys, or can be ingested from food sources (e.g., red meat, seafood, poultry), or taken as a commercially available dietary supplement [22]. Following either a loading phase (20 g/day for 5–7 days) or a lower dose of creatine (3–5 g/day) for a longer period (4 weeks), intramuscular creatine stores can be elevated by ~20% (and up to 40% in vegans and vegetarians) [23]. Once creatine is taken up into the muscle, approximately two-thirds of the intramuscular pool is converted to phosphocreatine which is used to maintain intracellular adenosine triphosphate (ATP) stores to support muscular contractions [23]. In addition, creatine may have cellular signaling roles by favorably affecting the expression of numerous mRNAs implicated in muscle anabolism and enhancing satellite cell proliferation during periods of resistance training [24].

There are several systematic reviews and meta-analyses that consistently demonstrate that creatine supplementation enhances resistance training gains in muscle mass, strength, and power [25,26▪▪,27–29]. The largest systematic review and meta-analysis included 35 randomized controlled trials with a total of 1192 participants [26▪▪]. In sum, these data indicate that creatine supplementation together with resistance training enhance whole body gain in lean tissue that was 1.1 kg more than placebo supplementation. These results were similar across the lifespan but appeared to be greater in males versus females. Burke *et al.* [29] recently reported the effects of creatine supplementation on regional measures of muscle hypertrophy from 10 randomized controlled trials. There were modest but positive effects of creatine supplementation to enhance gains in muscle mass in both younger and older adults. Beyond increasing muscle mass, creatine supplementation enhances strength and power and this is critical from a performance perspective [30]. Overall, creatine is one of the most effective and safe dietary supplements to enhance resistance training adaptations across the lifespan.

Caffeine

Caffeine, or 1,3,7-trimethylxanthine, is readily absorbed from the gastrointestinal tract, mainly from the small intestine and stomach [31]. The bioavailability of caffeine is very high (i.e., ~100%), resulting in rapid plasma accumulation which peaks approximately 60 min postingestion, independent of ingestion modality. However, interindividual variability involving caffeine metabolism may influence its efficacy [32▪▪]. A recent review indicates that caffeine can mechanistically enhance contractile force during muscle contractions by potentiating calcium release from ryanodine receptors while also delaying fatigue through central adenosine receptors [33], and various meta-analyses have indicated that caffeine positively affects muscle strength and power [34–40]. Collectively, these series of meta-analyses indicate that the acute ingestion of 1–6 mg/kg body mass of caffeine ~60 min prior to exercise improves measures of muscle strength and power (namely in the upper body).

SUPPLEMENTS THAT AFFECT ENDURANCE PERFORMANCE

Caffeine

As discussed above, the acute ingestion of caffeine (1–6 mg/kg body mass) promotes ergogenic effects on muscle strength and power. These same doses can also enhance endurance performance through various mechanisms. In conjunction with the noted impacts on calcium release and reuptake, caffeine may increase sodium/potassium (Na^+/K^+) pump activity [41]. Additionally, caffeine blocks central A2A and A2B adenosine receptors [42], which can alter pain thresholds and decrease rating of perceived exertion during exercise.

It is well accepted that caffeine has ergogenic benefits for individuals participating in endurance exercise (i.e., running, cycling, and time trial performance) [43]. The first meta-analysis to examine the effects of caffeine on measures of muscle endurance was performed by Warren *et al.* [44], which estimated that caffeine elicited ~20% improvement in endurance during field tests. Since this publication, other meta-analyses have supported the efficacy of caffeine on measures of muscle endurance [43,45], and optimal ingestion has been posited to be 60 min before exercise. It is important to note that higher caffeine doses (i.e., 9–11 mg/kg) may be ergolytic for both strength and endurance events and can result in adverse effects such as feeling jittery, sleep disruptions, increased anxiety, and tachycardia [32▪▪]. In summary, caffeine ingestion (1–6 mg/kg body mass consumed ~60 min prior to exercise) is a viable option for augmenting muscular endurance performance.

Beetroot juice

Inorganic nitrate (NO_3^-) is a compound found naturally in beets and leafy green and root vegetables such as spinach and celery. Moreover, beetroot juice has been commonly used as a exogenous source of NO_3^-. Upon consumption, NO_3^- is reduced to nitrite (NO_2^-) by anaerobic bacteria in the oral cavity through the action of nitrate-reductase enzymes. Through digestive processes, nitrite is further reduced to nitric oxide (NO) which subsequently enters systemic circulation. Circulating NO becomes bioactive in tissues and blood primarily under conditions of hypoxia, and can influence blood vessel vasodilation, mitochondrial respiration, and muscle contractile function [46,47].

The purported physiological mechanisms explaining the ergogenic potential of beetroot juice are multifactorial. Nitrate alters oxygen kinetics and reduces the oxygen cost of performing aerobic exercise [48]. NO also promotes vasodilation and oxygen transfer via increased blood flow [49■■]. Most ergogenic investigations on beetroot juice have focused on aerobic-type events [50], and a recent meta-analysis in healthy adults ($n = 1061$) indicates that the peri-exercise ingestion of nitrate-containing supplements improves power output by ∼5 watts and time to exhaustion during higher intensity endurance events ∼25 s [51]. Peak nitrite concentration in the blood occurs within 2–3 h of ingesting nitrate-containing supplements, and ergogenic effects are typically observed <3 h postingestion. Hence, the collective evidence suggests that beetroot juice with 6–8 mmol (∼350–500 mg) of nitrate should be ingested less than three hours before exercise to produce aerobic-type exercise benefits.

Sodium bicarbonate

Sodium bicarbonate likely acts to enhance extracellular acid buffering capacity due to postingestion increases in plasma bicarbonate (HCO_3^-) concentrations. Grgic authored two meta-analyses examining the potential ergogenicity of sodium bicarbonate. In the first meta-analysis, the authors concluded that a dose of 0.3 g/kg body mass 1–3 h prior to exercise likely improves endurance performance during higher-intensity exercises lasting between 30 s and 12 min [52]. The second meta-analysis by Grgic *et al.* [53■■] was an umbrella review on several reviews and meta-analyses, and results indicated that the acute ingestion of sodium bicarbonate enhances peak anaerobic power, anaerobic capacity, performance in endurance events lasting ∼45 s to 8 min, 2000-m rowing performance, and high-intensity intermittent running performance. Given that bloating, nausea, vomiting, and abdominal pain can arise from single-dose preexercise protocols, multiple-day protocols could be utilized to reduce the risks of associated side-effects. Athletes susceptible to these adverse effects can either consume 0.1 g/kg body mass during three spaced meals prior to the day of competition or perform a multiday protocol whereby 0.5 g/kg body mass is consumed in smaller dose increments during the day 3–7 days prior to an event.

Beta-alanine

Beta-alanine is a nonproteogenic amino acid endogenously produced in the liver and consumable through foods such as poultry and meat [54]. The purported mechanism by which beta-alanine supplementation might enhance muscle performance is through its rate-limiting precursor carnosine. Carnosine (β-alanyl-L-histidine) is a naturally occurring cytoplasmic dipeptide present in high concentrations in skeletal muscle, formed by combining L-histidine and beta-alanine, with the assistance of the enzyme carnosine synthetase [55]. Due to its location in skeletal muscle and its structure, carnosine has been implicated in major functions related to intracellular pH buffering. Beta-alanine may also protect against neuromuscular fatigue via changes in Ca^{2+} sensitivity, resulting in more efficient muscle contraction [54]. From a practical perspective, beta-alanine seems to be a viable supplement for increasing performance in exercise bouts where anaerobic capacity is a limiting factor (i.e., ≥90 s), such as during exercise modalities such as, cycling, rowing, running, and paddling [55].

As outlined in the position stand paper by the International Society of Sports Nutrition [55], beta-alanine supplementation (at dosages of 4–6 g per day for ≥ 4 weeks) can significantly augment muscle carnosine concentrations. Some individuals may respond more favorably with multiple smaller doses throughout the day (e.g., 0.8–1.6 g every 3-4 h) due to the potential of paresthesia (i.e., tingling) or rapid changes in pH with larger doses. Furthermore, the efficacy of beta-alanine does not seem to depend on baseline muscle carnosine levels, muscle fiber type, dosage, or timing of ingestion. Finally, while beta-alanine may provide ergogenic benefits in exercise bouts lasting ∼1–4 min, most of the research to date suggests that supplementation does not improve other aspects of muscular performance (i.e., strength and power).

LIMITATIONS TO THE EVIDENCE PRESENTED HEREIN

Although the scientific publications discussed herein have been informative, the reader should be aware of various limitations. First, most sub-chronic supplementation studies range between 6 and 12 weeks, and longer-term studies are needed to determine if continued benefit can be gained (versus habituation) with continuous supplementation. In addition, almost all the studies or meta-analyses discussed herein examined noncompetitive athletes. This is noteworthy given that beetroot juice, for instance, has not been shown to affect performance or exercise economy in competitive race walkers [56], whereas whey protein supplementation has been shown to increase muscle mass and strength in collegiate female basketball players [57]. Thus, while challenges of accessing competitive

Table 1. Supplements providing ergogenic benefits to strength and endurance athletes

Supplement	Dose	Documented benefits
Strength-power athletes		
Animal-based protein powders (notably, whey protein)	One or multiple ~30 g doses per day to aid in achieving a total daily protein intake of >2.0 g/kg body mass/day	Enhanced muscle mass increases during periods of resistance training
Creatine monohydrate	Loading phase: 20 g/day for 5–7 days Maintenance dose: 5 g/day Relative dose: 0.1 g/kg/day	Enhanced muscle mass, strength, and power
Caffeine	1–6 mg/kg body mass taken 60 min prior to exercise	Enhanced strength (e.g., one-effort lifts) and power (e.g., jump performance)
Endurance athletes		
Beetroot juice (high NO_3^-)	Supplement shot (~70 ml) providing 6–8 mmol of NO_3^- ingested 1–2 h (but less than 3 h) before exercise	Improved TTE or enhanced power output during efforts lasting 30 s–12 min (or more) in duration
Caffeine	1–6 mg/kg body mass taken 60 min prior to exercise	
Sodium bicarbonate	0.3 g/kg body mass 1–3 h prior to exercise, or multidose protocol to reduce side effects as described in-text.	
Beta-alanine	4–6 g/d for 4 weeks	Improved TTE or enhanced power output during efforts lasting 1–4 min in duration

NO_3^-, nitrate; TTE, time-to-exhaustion.

athletes exist, more dietary supplement studies are needed in this population to determine if elite-level effects exist. Finally, although sex-specific differences likely do not exist with the dietary supplements discussed herein as posited by Murphy *et al.* [58], most of the data discussed are in male participants necessitating more studies in female participants. Specifically, future research is warranted to examine sex-based differences in hormonal, metabolic, and physiological responses to dietary supplements, which may also differ across the menstrual cycle.

CONCLUSIONS AND FUTURE DIRECTIONS

The table below provides a summary of the content discussed in this review in relation to dietary supplements that have been documented to provide ergogenic benefits to strength-power and endurance athletes ().

There are notable future directions to be pursued in this area of sports nutrition research. First, and as noted above, more data are needed in competitive athletes. In addition, the combinatorial effects of supplements discussed in this review need to be investigated. In this regard, a meta-analysis by Saunders *et al.* [59] indicates that co-supplementation with sodium bicarbonate and beta-alanine results in enhanced endurance exercise outcomes compared to beta-alanine supplementation alone. Moreover, although protein supplements alone have been reported to be just as effective for promoting resistance training adaptations versus multi-ingredient protein supplements [17], there is counterevidence suggesting whey protein + creatine supplementation promotes superior resistance training adaptations compared to whey protein supplementation alone [60]. Hence, again, this provides justification that investigating combinatorial supplement regimens is warranted.

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Conflicts of interest

From 2013 to 2023, M.D.R. has performed contract-based research for dozens of dietary supplement companies. The laboratory of M.D.R. has also received gifts from dietary supplement companies to support student-led projects. M.D.R. acts as a paid writing consultant for dietary supplement companies in accordance with guidance set forth by Auburn University. M.D.R. does not have patents or stock ownership in dietary supplement companies. D.G.C. has conducted industry sponsored research involving creatine supplementation and received creatine donations for scientific studies and travel support for presentations involving creatine supplementation at scientific conferences. In addition, D.G.C. serves on the Scientific Advisory Board for Alzchem (a company that manufactures creatine) and as an expert witness/consultant in legal cases involving creatine supplementation. S.C.F. has previously served as a scientific advisor *for a company that sold creatine and currently sells creatine educational videos. S.C.F. has received creatine donations for scientific studies.*

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
■ of special interest
■■ of outstanding interest

1. Nutritional Supplements Market Size, Share & Trends Analysis Report By Product, By Consumer Group, By Formulation, By Application, By Packaging, By Composition, By Gender, By Sales Channel, and Segment Forecasts, 2022–2030. Available at: www.grandviewresearch.com.
2. Daher J, Mallick M, El Khoury D. Prevalence of dietary supplement use among athletes worldwide: a scoping review. Nutrients 2022; 14:4109.
3. Kerksick CM, Wilborn CD, Roberts MD, *et al.* Exercise & sports nutrition review update: research & recommendations. J Int Soc Sports Nutr 2018; 15:38.
AQ4 4. Vitale K, Getzin A. Nutrition and supplement update for the endurance athlete: review and recommendations. Nutrients 2019; 11:.
5. Peeling P, Castell LM, Derave W, *et al.* Sports foods and dietary supplements for optimal function and performance enhancement in track-and-field athletes. Int J Sport Nutr Exerc Metab 2019; 29:198–209.
6. Maughan RJ, Burke LM, Dvorak J, *et al.* IOC consensus statement: dietary supplements and the high-performance athlete. Int J Sport Nutr Exerc Metab 2018; 28:104–125.
7. Phillips SM. The impact of protein quality on the promotion of resistance exercise-induced changes in muscle mass. Nutr Metab 2016; 13:1–9.
8. Khatri M, Naughton RJ, Clifford T, *et al.* The effects of collagen peptide supplementation on body composition, collagen synthesis, and recovery from joint injury and exercise: a systematic review. Amino Acids 2021; 53:1493–1506.
9. Hermans WJH, Senden JM, Churchward-Venne TA, *et al.* Insects are a viable protein source for human consumption: from insect protein digestion to postprandial muscle protein synthesis in vivo in humans: a double-blind randomized trial. Am J Clin Nutr 2021; 114:934–944.
10. Churchward-Venne TA, Pinckaers PJ, Smeets JS, *et al.* Myofibrillar and mitochondrial protein synthesis rates do not differ in young men following the ingestion of carbohydrate with whey, soy, or leucine-enriched soy protein after concurrent resistance-and endurance-type exercise. J Nutr 2019; 149:210–220.
AQ5 11. Oikawa SY, Bahniwal R, Holloway TM, *et al.* Potato protein isolate stimulates muscle protein synthesis at rest and with resistance exercise in young women. Nutrients 2020; 12:.
12. van Vliet S, Shy EL, Abou Sawan S, *et al.* Consumption of whole eggs promotes greater stimulation of postexercise muscle protein synthesis than consumption of isonitrogenous amounts of egg whites in young men. Am J Clin Nutr 2017; 106:1401–1412.
13. Zaromskyte G, Prokopidis K, Ioannidis T, *et al.* Evaluating the leucine trigger hypothesis to explain the postprandial regulation of muscle protein synthesis in young and older adults: a systematic review. Front Nutr 2021; 8:685165.
14. Morton RW, Murphy KT, McKellar SR, *et al.* A systematic review, meta-analysis and meta-regression of the effect of protein supplementation on resistance training-induced gains in muscle mass and strength in healthy adults. Br J Sports Med 2018; 52:376–384.
15. Pasiakos SM, McLellan TM, Lieberman HR. The effects of protein supplements on muscle mass, strength, and aerobic and anaerobic power in healthy adults: a systematic review. Sports Med 2015; 45:111–131.
AQ6 16. ■ Lim MT, Pan BJ, Toh DWK, *et al.* Animal protein versus plant protein in supporting lean mass and muscle strength: a systematic review and meta-analysis of randomized controlled trials. Nutrients 2021; 13:.
This meta-analysis indicates animal-based proteins more favorably affects muscle mass and strength gains with resistance training compared to plant-based proteins.
17. O'Bryan KR, Doering TM, Morton RW, *et al.* Do multiingredient protein supplements augment resistance training-induced gains in skeletal muscle mass and strength? A systematic review and meta-analysis of 35 trials. Br J Sports Med 2020; 54:573–581.
18. Schoenfeld BJ, Aragon AA, Krieger JW. The effect of protein timing on muscle strength and hypertrophy: a meta-analysis. J Int Soc Sports Nutr 2013; 10:53.
19. Antonio J. High-protein diets in trained individuals. Res Sports Med 2019; 27:195–203.
20. Mazzulla M, Abou Sawan S, Williamson E, *et al.* Protein intake to maximize whole-body anabolism during postexercise recovery in resistance-trained men with high habitual intakes is severalfold greater than the current recommended dietary allowance. J Nutr 2020; 150:505–511.
21. ■■ Antonio J, Candow DG, Forbes SC, *et al.* Common questions and misconceptions about creatine supplementation: what does the scientific evidence really show? J Int Soc Sports Nutr 2021; 18:13.
This review discusses that creatine supplementation is safe and is an effective way to enhance strength and power in athletes.
22. Kreider RB, Kalman DS, Antonio J, *et al.* International Society of Sports Nutrition position stand: safety and efficacy of creatine supplementation in exercise, sport, and medicine. J Int Soc Sports Nutr 2017; 14:18.
23. Kaviani M, Shaw K, Chilibeck PD. Benefits of creatine supplementation for vegetarians compared to omnivorous athletes: a systematic review. Int J Environ Res Public Health 2020; 17:. AQ7
24. Negro M, Avanzato I, D'Antona G. Creatine in skeletal muscle physiology. Nonvitamin and nonmineral nutritional supplements. Elsevier; 2019; 59–68.
25. Chilibeck PD, Kaviani M, Candow DG, Zello GA. Effect of creatine supplementation during resistance training on lean tissue mass and muscular strength in older adults: a meta-analysis. Open Access J Sports Med 2017; 8:213–226.
26. ■■ Delpino FM, Figueiredo LM, Forbes SC, *et al.* Influence of age, sex, and type of exercise on the efficacy of creatine supplementation on lean body mass: a systematic review and meta-analysis of randomized clinical trials. Nutrition 2022; 103–104:111791.
This meta-analysis included 35 studies with 1192 participants, and indicates that creatine supplementation increases muscle mass more effectively when combined with resistance training versus resistance training alone.
27. Dos Santos EEP, de Araujo RC, Candow DG, *et al.* Efficacy of creatine supplementation combined with resistance training on muscle strength and muscle mass in older females: a systematic review and meta-analysis. Nutrients 2021; 13:. AQ8
28. Forbes SC, Candow DG, Ostojic SM, *et al.* Meta-analysis examining the importance of creatine ingestion strategies on lean tissue mass and strength in older adults. Nutrients 2021; 13:. AQ9
29. Burke R, Piñero A, Coleman M, *et al.* The effects of creatine supplementation combined with resistance training on regional measures of muscle hypertrophy: a systematic review with meta-analysis. Nutrients 2023; 15:2116.
30. Fragala MS, Cadore EL, Dorgo S, *et al.* Resistance training for older adults: position statement from the national strength and conditioning association. J Strength Cond Res 2019; 33:2019–2052.
31. Chvasta TE, Cooke AR. Emptying and absorption of caffeine from the human stomach. Gastroenterology 1971; 61:838–843.
32. ■■ Guest NS, VanDusseldorp TA, Nelson MT, *et al.* International society of sports nutrition position stand: caffeine and exercise performance. J Int Soc Sports Nutr 2021; 18:1.
This position stand outlines the efficacy of caffeine ingestion on resistance training and endurance training outcomes.
33. Lima-Silva AE, Cristina-Souza G, Silva-Cavalcante MD, *et al.* Caffeine during high-intensity whole-body exercise: an integrative approach beyond the central nervous system. Nutrients 2021; 13:. AQ10
34. Barreto G, Loureiro LMR, Reis CEG, Saunders B. Effects of caffeine chewing gum supplementation on exercise performance: a systematic review and meta-analysis. Eur J Sport Sci 2023; 23:714–725.
35. Ferreira TT, da Silva JVF, Bueno NB. Effects of caffeine supplementation on muscle endurance, maximum strength, and perceived exertion in adults submitted to strength training: a systematic review and meta-analyses. Crit Rev Food Sci Nutr 2021; 61:2587–2600.
36. Grgic J. Exploring the minimum ergogenic dose of caffeine on resistance exercise performance: a meta-analytic approach. Nutrition 2022; 97:111604.
37. Grgic J, Del Coso J. Ergogenic effects of acute caffeine intake on muscular endurance and muscular strength in women: a meta-analysis. Int J Environ Res Public Health 2021; 18:. AQ11
38. Grgic J. Caffeine ingestion enhances Wingate performance: a meta-analysis. Eur J Sport Sci 2018; 18:219–225.
39. Grgic J, Pickering C. The effects of caffeine ingestion on isokinetic muscular strength: a meta-analysis. J Sci Med Sport 2019; 22:353–360.
40. Grgic J, Mikulic P, Schoenfeld BJ, *et al.* The influence of caffeine supplementation on resistance exercise: a review. Sports Med 2019; 49:17–30.
41. Lindinger MI, Graham TE, Spriet LL. Caffeine attenuates the exercise-induced increase in plasma $[K^+]$ in humans. J Appl Physiol 1993; 74:1149–1155.
42. Aguiar AS Jr, Speck AE, Canas PM, Cunha RA. Neuronal adenosine A(2A) receptors signal ergogenic effects of caffeine. Sci Rep 2020; 10:13414.
43. Wang Z, Qiu B, Gao J, Del Coso J. Effects of caffeine intake on endurance running performance and time to exhaustion: a systematic review and meta-analysis. Nutrients 2022; 15:148. AQ12
44. Warren GL, Park ND, Maresca RD, *et al.* Effect of caffeine ingestion on muscular strength and endurance: a meta-analysis. Med Sci Sports Exerc 2010; 42:1375–1387.
45. Grgic J, Del Coso J. Ergogenic effects of acute caffeine intake on muscular endurance and muscular strength in women: a meta-analysis. Int J Environ Res Public Health 2021; 18:5773.
46. Poderoso JJ, Helfenberger K, Poderoso C. The effect of nitric oxide on mitochondrial respiration. Nitric Oxide 2019; 88:61–72.
47. Benjamim CJR, Porto AA, Valenti VE, *et al.* Nitrate derived from beetroot juice lowers blood pressure in patients with arterial hypertension: a systematic review and meta-analysis. Front Nutr 2022; 9:823039.

AQ13 **48.** Dominguez R, Cuenca E, Mate-Munoz JL, *et al.* Effects of beetroot juice supplementation on cardiorespiratory endurance in athletes. A systematic review. Nutrients 2017; 9:.

49. Jones AM, Vanhatalo A, Seals DR, *et al.* Dietary nitrate and nitric oxide ▪▪ metabolism: mouth, circulation, skeletal muscle, and exercise performance. Med Sci Sports Exerc 2021; 53:280–294.

This review discusses the effects of dietary nitrates on exercise performance and delves into the mechanistic underpinnings of ergogenicity.

AQ14 **50.** Milton-Laskibar I, Martinez JA, Portillo MP. Current knowledge on beetroot bioactive compounds: role of nitrate and betalains in health and disease. Foods 2021; 10:.

51. Gao C, Gupta S, Adli T, *et al.* The effects of dietary nitrate supplementation on endurance exercise performance and cardiorespiratory measures in healthy adults: a systematic review and meta-analysis. J Int Soc Sports Nutr 2021; 18:55.

52. Grgic J, Pedisic Z, Saunders B, *et al.* International Society of Sports Nutrition position stand: sodium bicarbonate and exercise performance. J Int Soc Sports Nutr 2021; 18:61.

53. Grgic J, Grgic I, Del Coso J, *et al.* Effects of sodium bicarbonate supple- ▪▪ mentation on exercise performance: an umbrella review. J Int Soc Sports Nutr 2021; 18:71.

This meta-analysis demonstrates benefits of sodium bicarbonate supplementation and discusses strategies for athletes to adopt when using this supplement.

54. Varanoske AN, Stout JR, Hoffman JR. Effects of β-alanine supplementation and intramuscular carnosine content on exercise performance and health. Nutrition and enhanced sports performance. Elsevier; 2019; 327–344.

55. Trexler ET, Smith-Ryan AE, Stout JR, *et al.* International society of sports nutrition position stand: beta-alanine. J Int Soc Sports Nutr 2015; 12:30.

56. Burke LM, Hall R, Heikura IA, *et al.* Neither beetroot juice supplementation nor increased carbohydrate oxidation enhance economy of prolonged exercise in elite race walkers. Nutrients 2021; 13:. AQ15

57. Taylor LW, Wilborn C, Roberts MD, *et al.* Eight weeks of pre and postexercise whey protein supplementation increases lean body mass and improves performance in Division III collegiate female basketball players. Appl Physiol Nutr Metab 2016; 41:249–254.

58. Murphy MJ, Rushing BR, Sumner SJ, Hackney AC. Dietary supplements for athletic performance in women: beta-alanine, caffeine, and nitrate. Int J Sport Nutr Exerc Metab 2022; 32:311–323.

59. Saunders B, Elliott-Sale K, Artioli GG, *et al.* Beta-alanine supplementation to improve exercise capacity and performance: a systematic review and meta-analysis. Br J Sports Med 2017; 51:658–669.

60. Burke DG, Chilibeck PD, Davidson KS, *et al.* The effect of whey protein supplementation with and without creatine monohydrate combined with resistance training on lean tissue mass and muscle strength. Int J Sport Nutr Exerc Metab 2001; 11:349–364.

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