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Review

Effects of Dietary Nitrate Supplementation on Weightlifting Exercise Performance in Healthy Adults: A Systematic Review

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Abstract: Dietary nitrate (NO_3^-) supplementation has been evidenced to induce an ergogenic effect in endurance and sprint-type exercise, which may be underpinned by enhanced muscle contractility and perfusion, particularly in type II muscle fibers. However, limited data are available to evaluate the ergogenic potential of NO_3^- supplementation during other exercise modalities that mandate type II fiber recruitment, such as weightlifting exercise (i.e., resistance exercise). In this systematic review, we examine the existing evidence basis for NO_3^- supplementation to improve muscular power, velocity of contraction, and muscular endurance during weightlifting exercise in healthy adults. We also discuss the potential mechanistic bases for any positive effects of NO_3^- supplementation on resistance exercise performance. Dialnet, Directory of Open Access Journals, Medline, Pubmed, Scielo, Scopus and SPORT Discus databases were searched for articles using the keywords: nitrate or beetroot and supplement or nut*r or diet and strength or "resistance exercise" or "resistance training" or "muscular power". Four articles fulfilling the inclusion criteria were identified. Two of the four studies indicated that NO_3^- supplementation could increase aspects of upper body weightlifting exercise (i.e., bench press) performance (increases in mean power/velocity of contraction/number of repetitions to failure), whereas another study observed an increase in the number of repetitions to failure during lower limb weightlifting exercise (i.e., back squat). Although these preliminary observations are encouraging, further research is required for the ergogenic potential of NO_3^- supplementation on weightlifting exercise performance to be determined.

Keywords: beetroot; ergogenic aid; exercise; nutrition; muscle

1. Introduction

Weightlifting exercise is well established as an exercise modality of resistance exercise to improve skeletal muscle mass [1,2], strength [3–5], endurance [6,7] and power [8,9]. These positive adaptations in skeletal muscle function translate into athletic performance [10–14] and health-related [15–19] benefits in a range of populations [20–22]. To achieve specific muscular adaptations, resistance exercise training

programs can manipulate variables such as muscle action, loading and volume, exercise selection and order, free weights vs. resistance machines, rest periods, number of repetitions and sets, velocity of muscle action and frequency [23]. It is well documented that a propensity for high muscular power production, velocity of contraction and endurance are required for optimal performance in various sports [13,24] and that resistance exercise training can improve these performance determinants [8].

There are different methods to assess muscle strength and power [25]. Static methods include isometric muscle strength assessments to evaluate maximal voluntary isometric contraction (MVIC) force and/or the rate of force development (RFD) at a fixed muscle joint angle. Single limb isokinetic methods allow for the assessment of muscle torque, work and power along a joint's full range of motion (ROM) (i.e., single knee extension and/or flexion movement). A dynamic method can assess one repetition maximum (1RM) strength and maximum power developed against either a constant (i.e., free weights and exercise machine) or variable (i.e., exercise machine) resistance along a single joint's full ROM (i.e., bicep curl: elbow joint) or exercises involving multiple-joints (i.e., back squat: ankle, knee and hip joints). Most actions performed in daily physical activities (i.e., walking up and down stairs, handling, press and push) and sports actions (i.e., run, jump, throw) include dynamic muscle contractions, which involve repetitive concentric and eccentric muscle contractions and an associated stretch-shortening cycle (SSC) [26]. However, since isometric methods only assess muscle strength at a fixed joint angle, isokinetic methods measure strength only within a single limb in a specific joint range of motion, and neither of these assessment approaches involve an SSC [27], the application of the findings from such assessments into sporting actions is limited [28–32].

There is also interest in the application of dietary interventions in conjunction with resistance exercise training in an attempt to augment resistance training adaptations and, by extension, sport-specific exercise performance [11,33]. Dietary supplements, such as creatine, caffeine and sodium bicarbonate, have a strong historical evidence basis to support ergogenic effects in certain exercise settings [34]. More recently, inorganic nitrate (NO_3^-) ingestion, often administered as concentrated NO_3^--rich beetroot juice (BR), has been reported to confer ergogenic effects in various exercise modalities [35], including running [36–47], rowing [48,49], kayaking [50], knee extensions [37,51] and cycling [52–64]. Although an ergogenic effect of NO_3^- supplementation appears less likely in endurance-trained individuals, i.e., [65–74], recent systematic reviews support its efficacy as an ergogenic aid during continuous endurance-type exercise [75–77] and high-intensity intermittent-type exercise [78].

Dietary NO_3^- supplementation has been observed to elevate nitric oxide (NO) bioavailability via the reduction of exogenous NO_3^- to nitrite (NO_2^-) by commensal anaerobic bacteria in the oral cavity [79], followed by the one-electron reduction of NO_2^- to NO (and other nitrogen intermediates) catalyzed by various NO_2^- reductases [80–84] in the tissue and blood. The reduction of NO_2^- to NO is potentiated under conditions of hypoxia [85] and acidosis [86], as are known to occur intramuscularly during exercise [87]. Elevations in [NO_3^-] and [NO_2^-] following NO_3^- supplementation have been observed in skeletal muscle [88–91] and plasma [53,64,92], and are associated with positive physiological effects [41,64,74,93] that facilitate a greater capacity for muscular work [51,53,59] and/or improved muscle contractile efficiency (i.e., a lower high-energy phosphate cost of force production) [51,94]. The elevation of plasma [NO_2^-] is dependent on methodological considerations, such as the supplementation regimen (i.e., dosage of NO_3^-, timing and duration) [64], and there is evidence to suggest that performance enhancement may be more likely after chronic, compared to acute, NO_3^- supplementation [56,63,67].

Although the effects of NO_3^- supplementation on performance during continuous endurance and high-intensity intermittent exercise have been investigated in numerous studies [35], its effects on the contractile properties of isolated muscle groups completing weightlifting exercise has received comparatively limited empirical investigation. There is some evidence that NO_3^- supplementation can enhance force production during voluntary and evoked isometric assessments [73,95,96] and isokinetic voluntary knee extensor power and velocity [97]. Data from animal studies support these observations and have indicated that 7 days of NO_3^- supplementation increased evoked force production in rodents

at low-stimulation frequencies and the rate of force development at high-contraction frequencies compared to age-matched controls [98]. These improvements in skeletal muscle contractile function were accompanied by increased protein expression of calcium (Ca^{2+})-handling proteins in the extensor digitorum longus, which is predominantly comprised of type II muscle fibers, but not the soleus, which is predominantly comprised of type I muscle fibers [98]. However, in contrast to the rodent studies, there was an increase in evoked contractile force after NO_3^- supplementation without an effect on muscle Ca^{2+}-handling proteins in human skeletal muscle [96]. Collectively, these findings suggest that dietary NO_3^- supplementation has the potential to increase contractile force production, skeletal muscle power and velocity of contraction, particularly in type II muscle fibers, which are heavily recruited during weightlifting exercise [99]. However, findings regarding involuntary contractions evoked by neuromuscular electrostimulation (NMES) may not readily translate to voluntary contractions, since there are some important differences between NMES and voluntary actions [100]. Specifically. motor unit recruitment during NMES is spatially fixed, temporally synchronous and nonselective (i.e., randomized), such that it may not conform to the orderly recruitment of motor units during voluntary contractions [101].

In addition to enhancing force production during single muscle contractions, NO_3^- supplementation has the potential to enhance performance during repeated sub-maximal knee-extensor contractions continued to failure [51]. This increased time to task failure following NO_3^- supplementation was accompanied by lower rates of ATP and PCr turnover, and ADP and Pi accumulation, factors that would be expected to lower skeletal muscle fatigue [102]. In addition, it has been reported that NO_3^- supplementation can lower the PCr cost of muscle force production at the end of a protocol comprising 50 MVIs of the knee extensors [94] and is more effective at improving skeletal muscle contractile function after the muscle has become fatigued [103]. Since resistance exercise training sessions typically comprise a series of sets to task failure using the same exercise modality with a relatively short recovery period, overall performance in a resistance exercise training session will also be influenced by the ability to recover between sets. The recovery of muscle force during repeated bouts of high-intensity exercise is linked to muscle PCr resynthesis [104–106], which is largely an O_2-dependent process [107,108]. Since NO_3^- supplementation has been reported to increase skeletal muscle blood flow, with a preferential shunting of blood flow to type II muscle fibers [109], this has the potential to aid recovery between sets during a resistance exercise training session, which might translate into more repetitions completed in the training session.

Despite the evidence outlined above, which suggests that NO_3^- supplementation has the potential to enhance resistance exercise performance during voluntary isometric and/or isokinetic assessments, and muscle isometric contractions evoked by NMES, a limited number of studies have assessed the potential for ergogenic effects of NO_3^- supplementation on a more transferable form of resistance exercise, such as weightlifting performance. The aim of this review was to provide an up-to-date summary of data from experimental studies that have examined the efficacy of dietary NO_3^- supplementation to improve weightlifting performance (i.e., muscle force production, velocity of contraction, muscular endurance) in healthy adults and to discuss potential physiological mechanisms that may underpin these effects.

2. Methodology

A systematic search using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines [110] was conducted for studies that investigated NO_3^- supplementation on weightlifting exercise performance using Dialnet, Directory of Open Access Journals, Medline, Pubmed, Scielo, Scopus and SPORTDiscus databases until April 2020, using the following terms: (concept 1) (nitrate OR beet *) AND (concept 2) (supplement * OR nutr * OR diet *) AND (concept 3) (strength OR "resistance exercise" OR "resistance training" OR "muscular power"). The original search yielded a total of 619 studies. After the elimination of duplicate articles and screening for inclusion criteria, a total of 291 articles were independently read and reviewed by three authors (RD, JJM and ASF).

A quality assessment procedure was performed by three authors (ALR, RD and JJM) using the PEDro scale [111]. A total of four articles met the eligibility criteria for the present systematic review (Figure 1).

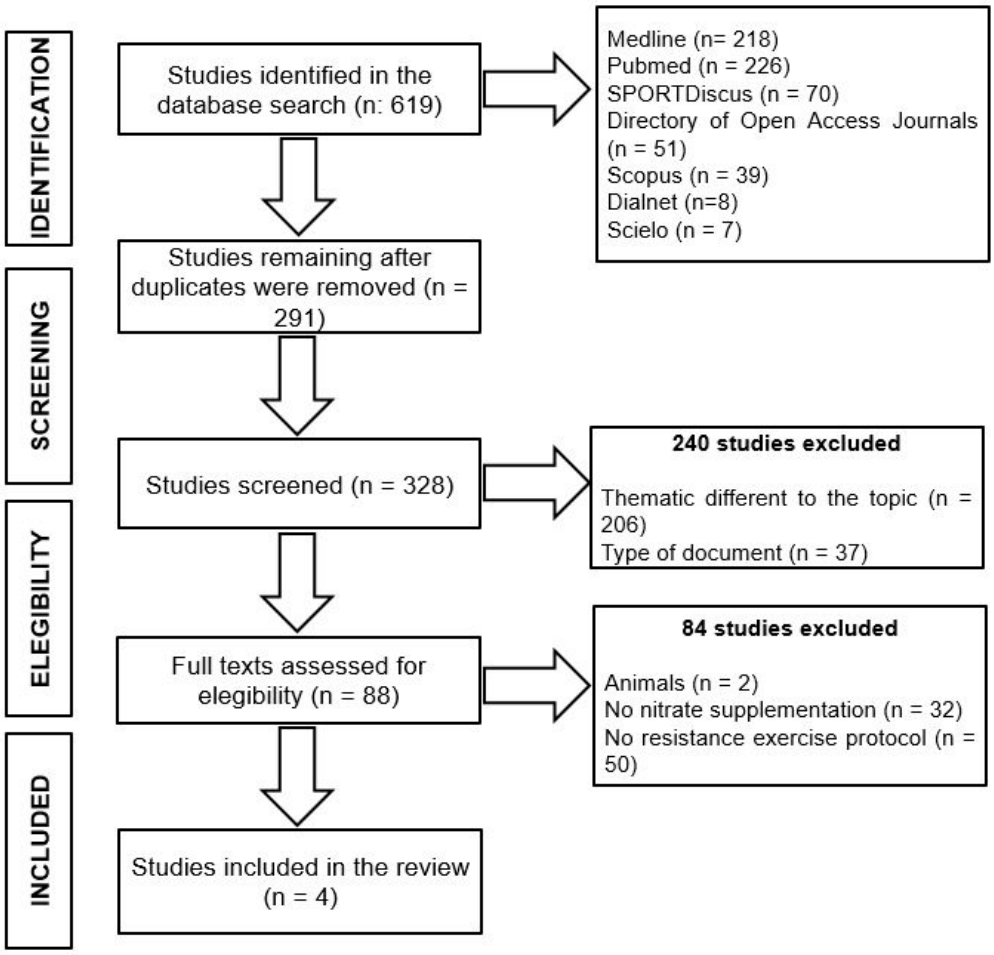

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flowchart.

To ensure that the selection of studies assessed the effects of NO_3^- supplementation on weightlifting exercise performance, the authors applied a set of inclusion criteria [112]:

1. Studies that were published as a full article (i.e., not a conference abstract) and performed in healthy humans (aged 18 to 65 years).
2. Studies that included a NO_3^- and a placebo intervention.
3. Studies which assessed voluntary dynamic resistance strength (i.e., not isometric or isokinetic strength and not involuntary muscle contractions evoked by NMES).
4. Studies that included any of the following variables: i) one repetition maximum (1RM); ii) power or velocity movement; iii) number of repetitions to failure with submaximal loads.

The four studies selected for our systematic review included a total of 49 men, all of whom were resistance trained (i.e., performed resistance exercise a minimum of twice per week).

In two of the selected studies [113,114], the influence of acute BR ingestion was assessed by adminstering 1 × 70 mL of BR (~6.4 mmol of NO_3^- per 70 mL) ~2 h prior to the commencement of exercise. In the remaining two studies [115,116], longer-term (≥ 3 days) dosing strategies of NO_3^- supplementation were employed. Mosher et al. [116] administered 1 × 70 mL of BR per day (~6.4 mmol of NO_3^- per 70 mL) for 6 consecutive days, although the authors did not report the timing of ingestion, which has important implications for the elevation of plasma NO_3^- and NO_2^- [64]. Flanagan et al. [115]

administered 2 × NO_3^--rich performance bars (32.5 mg of NO_3^- per two bars) for 3 consecutive days with the final two NO_3^--rich performance bars ingested ~60 min prior to the commencement of exercise.

3. Results and Discussion

The exercise modalities used to assess weightlifting exercise performance were bench press using free weights [113], bench press using a Smith machine [114,116] and box squats using a Smith machine [114,115]. The details of the performance tests employed are summarized in Table 1.

Table 1. Studies assessing the effects of dietary NO_3^- supplementation on resistance exercise performance in humans.

Reference	Subjects	Supplementation	Exercise Protocol	Findings
Flanagan et al. (2016) [115]	Fourteen resistance-trained men	Three days and 60 min prior to exercise ingestion of 2 × NO_3^--rich bars (32.5 mg NO_3^-·d^{-1})	Smith machine box squats: three sets x 3-s isometric squats interspersed with 120-s rest, then dynamic box squats @ 60%1RM with 10% increases up to 90%1RM, then 10% decreases to 60%1RM, then RTF on last 60%1RM set	↔ RTF: −1.5% (599 ± 5 vs. 608 ± 5 reps) ↑ EMG amplitude: +5% (83 ± 3 vs. 79 ± 4%)
Mosher et al. (2016) [116]	Twelve resistance-trained men	Six days of 1 × 70 mL NO_3^- rich BR supplementation (~6.4 mmol NO_3^-·d^{-1})	Smith machine bench press: three sets of RTF @ 60%1RM interspersed with 2 min of recovery between sets	↑ RTF: +19.4% ↑ total weight lifted: +18.9% (2583 ± 864 vs. 2172 ± 721 kg)
Williams et al. (2020) [113]	Eleven resistance-trained men	Two hours prior to exercise ingestion of 1 × 70 mL NO_3^- rich BR (~6.4 mmol NO_3^-)	Free-weight bench press: two sets x 2 explosive reps, 5 min rest, then three sets x RTF @ 70%1RM interspersed with 2 min of recovery between sets	↑ RTF: +10.7% (31 ± 6 vs. 28 ± 6 reps) ↑ P_{mean}: +19.5% (607 ± 112 vs. 508 ± 118 W) ↑ V_{mean}: +6.5% (0.66 ± 0.08 vs. 0.62 ± 0.08 m·s^{-1})
Ranchal-Sanchez et al. (2020) [114]	Twelve resistance-trained men	Two hours prior to exercise ingestion of 1 × 70 mL NO_3^- rich BR (~6.4 mmol NO_3^-)	Smith machine bench press and back squat: three sets x RTF @ 60−70−80%1RM with 2 min of recovery between sets. After the eccentric phase of each rep, participants rested for 1.0−1.5 s	↑ RTF back squat: +23.4% (60 ± 20 vs. 46 ± 16 reps) ↑ RTF total (sum bench press and back squat): +17.7% (89 ± 25 vs. 75 ± 21 reps)

↑ = significant increase; ↔ = no change; 1RM = one-repetition maximum; BR = beetroot juice; EMG = surface electromyography; m·s^{-1} = meters per second; min = minutes; NO_3^- = nitrate; P_{mean} = mean power of bench press; reps = repetitions; RTF = repetitions to failure; s = seconds; V_{mean} = mean velocity of bench press; W = Watts.

This is the first systematic review to have focused on the ergogenic effect of dietary NO_3^- supplementation on weightlifting exercise performance. The main findings were that dietary NO_3^- supplementation can increase muscular power and velocity, and the number of repetitions to failure during bench press exercise, but not box squat exercise, in resistance-trained males.

3.1. The Effects of Dietary Nitrate Supplementation on Weightlifting Exercise Performance

Williams et al. [113] examined the effect of acute dietary NO_3^- supplementation (BR ingested 2 h prior to exercise) on muscle power, velocity and number of repetitions to failure during free-weight bench press exercise at 70%1RM in resistance-trained men. The authors observed a 19.5% increase in mean power, a 6.5% increase in mean velocity, and a 10.7% increase in the number of repetitions to failure [113]. In another study, Ranchal-Sánchez et al. [114] observed an enhancement in the number of repetitions to failure (+17.7%) in the sum of sets for bench press and back squat with loads of 60%, 70% and 80% 1RM after NO_3^- supplementation (BR ingested 2 h prior to exercise), although authors failed to find an effect on muscular velocity and power. These conflicting findings may be attributed to inter-study differences in the protocols used to assess muscular power and

velocity. Indeed, whereas Williams et al. [113] assessed muscle power and velocity during two single explosive repetitions with full recovery (5 min rest between sets), Ranchal-Sánchez et al. [114] assessed power and velocity during sets of repetitions until failure. Muscle velocity and muscle power assessment require optimal neuromuscular conditions and, as such, studies analyzing the effect of different supplements on muscular velocity and power selected a maximum of two repetitions with a submaximal load, with recovery periods of 2–5 min [117–122]. Thus, the procedure used by Ranchal-Sánchez et al. [114] to assess muscle power and velocity may not be suitable to detect a potential effect of NO_3^- supplementation. Longer-term NO_3^- supplementation was also observed to be effective, as 6 days of BR supplementation increased the number of repetitions to failure (+19.4%) and increased the total amount of weight lifted (+18.9%) during Smith machine bench press exercise at 60%1RM in resistance-trained men [116]. Therefore, the existing evidence suggests that acute and short-term NO_3^- supplementation can improve bench press performance in resistance-trained males. In contrast, Flanagan et al. [115] did not observe any change in the number of repetitions to failure during box squat exercise at 60%1RM in resistance-trained men following the administration of NO_3^--rich performance bars over 3 days. A limitation in Flanagan et al. [115] was the low NO_3^- dose administered. Specifically, Flanagan et al. [115] administered 32.5 mg (~0.5 mmol) of NO_3^- daily, which is markedly lower than Williams et al. [113] (6.4 mmol NO_3^- acutely) and Mosher et al. [116] (6 days of 6.4 mmol NO_3^- daily), both of whom observed improved resistance exercise performance. Since plasma [NO_2^-] increases dose-dependently after NO_3^- supplementation and is correlated with enhanced exercise capacity [64], the low NO_3^- dose administered in the study of Flanagan et al. [115] is likely to have underpinned the lack of effect of NO_3^- supplementation in that study. This interpretation is reinforced by Coggan et al. [123] who reported that the relative magnitude of the increase in knee-extensor peak power output following NO_3^- ingestion was positively correlated with the increase in plasma [NO_2^-]. However, a limitation of all existing studies assessing the effect of NO_3^- supplementation on resistance exercise performance is the lack of plasma [NO_2^-] determination.

In addition to inter-study differences in the dosing strategies, the exercise modality (upper body vs. lower body) employed might also have contributed to the disparate findings across studies assessing the ergogenic potential of NO_3^- supplementation on resistance exercise performance to date. Indeed, two studies reported improved resistance exercise performance after NO_3^- supplementation during bench press exercise [113,116], whereas squat performance was not improved after NO_3^- supplementation in the study by Flanagan et al. [115], but the total number of repetitions during three sets of back squats was enhanced in the study by Ranchal-Sánchez et al. [114]. Given that there is evidence to suggest that NO_3^- supplementation may be more effective at enhancing physiological responses in type II muscle fibers [124] and since the proportion of type II muscle fibers may be greater in the upper body musculature, i.e., [125], this might account for the improved bench press and the inconsistent effects observed on squat performance after NO_3^- supplementation. However, there is evidence that weightlifting training increases both the hypertrophy and proportion of type II muscle fibers, such that the proportion of type II muscle is greater in resistance-trained individuals [126,127]. Accordingly, this could partly account for the improvements observed in Mosher et al. [116], Williams et al. [113] and Ranchal-Sánchez et al. [114], who recruited resistance-trained men.

Taken together, the existing, albeit limited, evidence suggests that acute and short-term dietary NO_3^- supplementation can enhance weightlifting exercise performance by increasing muscle power production, velocity of contraction and muscular endurance in healthy resistance-trained adults. However, the results are incongruous with inconsistencies likely linked to differences in supplementation strategies and exercise modality. Therefore, further research is required to assess the weightlifting exercise settings and populations in which NO_3^- supplementation is more or less likely to be ergogenic. Moreover, while encouraging preliminary evidence suggests that dietary NO_3^- supplementation may enhance weightlifting training quality, further research is also required to assess whether this translates into greater adaptations to chronic resistance exercise training.

3.2. Physiological Mechanisms

Consistent with the potential for improved weightlifting exercise performance after NO_3^- supplementation, enhanced skeletal muscle contractile function has been observed during electrically stimulated contractions [95,96,103], and enhanced peak power output has been observed during isokinetic dynamometry [97,123,128] and cycling [45,57,60,129–133] exercise. Although the exact physiological mechanisms responsible for enhanced exercise performance following dietary NO_3^- supplementation are unclear, a number of putative mechanisms have been identified which could contribute to improved weightlifting exercise performance.

Using a mouse model, Hernández et al. [98] demonstrated that 7 days of NO_3^- supplementation increased the rate of force development at 100 Hz by 35% and force production at 50 Hz during evoked skeletal muscle contractions at a supraphysiological PO_2. The increase in evoked force production was accompanied by the increased expression of Ca^{2+}-handling proteins, dihydropyridine receptors (DHPRs) and calsequestrin (CASQ) in type II but not type I skeletal muscle [98]. There is also previous evidence indicating that $NaNO_2$ administration can increase cytosolic [Ca^{2+}] without altering force production at a supraphysiological PO_2 [134], or lower cytosolic [Ca^{2+}] concomitant with lower submaximal, but not maximal, force at a physiological PO_2 [118], during single evoked isometric contractions in isolated mouse muscle fibers. However, during a repeated, fatigue-inducing contraction protocol, $NaNO_2$ administration increased time to task failure by offsetting the reductions in Ca^{2+} pumping rate and Ca^{2+} sensitivity [135]. While these data suggest that increasing the exposure of mouse skeletal muscle to NO_3^- and/or NO_2^- can modulate skeletal muscle contractility via changes in skeletal muscle Ca^{2+} handling, the findings from Whitfield et al. [96] challenge the notion that improved skeletal muscle contractile function after NO_3^- supplementation in human skeletal muscle is linked to increased content of Ca^{2+}-handling proteins. Specifically, these authors observed an increased force production and rate of force production during evoked isometric twitches in healthy humans without changes in skeletal muscle CASQ, DHPR or SERCA protein content following 7 days of BR supplementation.

Another mechanism that could improve skeletal muscle contractile function after NO_3^- supplementation is the post-translational modification of the skeletal muscle contractile or Ca^{2+}-handling proteins [136]. Indeed, NO can react with protein thiols (i.e., moieties containing sulfhydryl groups, RSH or RS^-) to form RSNO groups in a reversible process termed S-nitrosylation [137]. S-nitrosylation and denitrosylation alter the structural conformation and thus function of proteins [138]. For example, NO has been reported to S-nitrosylate myosin heavy chains in skeletal muscle, leading to increased contractile force [139]. The potential influence of S-nitrosylation on excitation–contraction coupling is complex given that various contractile-related proteins can undergo reversible post-translation modifications at cysteine residues on thiols, such as myosin [140], troponin [141], SERCA [142] and ryanodine receptors (RyRs) [143,144], and that these post-translation protein modifications are likely dependent on interactions between NO, reactive oxygen species and glutathione bioavailability [145]. In addition, RyR proteins contain a markedly greater number of sulfhydryl groups compared to other contractile proteins [146], which supports the proposed hypothesis that NO-mediated RyR modulation and Ca^{2+} release could contribute to enhanced muscle contractility following NO_3^- supplementation [123]. Importantly, these effects could occur independent of changes in the content of Ca^{2+}-handling proteins. An interesting observation by Flanagan et al. [115] was that EMG amplitude increased during weightlifting exercise after NO_3^- supplementation despite no change in weightlifting exercise performance. However, other studies have not observed changes in EMG after NO_3^- supplementation [95,103] and, as such, it is unclear whether NO_3^- supplementation alters neural drive. Further research is required to evaluate how NO_3^- supplementation can modulate excitation–contraction coupling in human skeletal muscle.

In addition to potential changes to excitation–contraction coupling proteins, NO_3^- supplementation has been reported to alter high-energy phosphate turnover and phosphorus metabolites in human skeletal muscle [51,94]. Specifically, NO_3^- supplementation has been reported

to lower the high-energy phosphate cost of skeletal muscle contractile force production [51,94] and the intramuscular accumulation of ADP and Pi [51], factors which would be expected to abate the development of skeletal muscle fatigue [102]. Dietary NO_3^- supplementation has also been shown to increase muscle blood flow [109], which might aid muscle PCr resynthesis between sets to failure [107,108] and the recovery of force and performance [104–106].

Taken together, the existing evidence suggests that NO_3^- supplementation can improve skeletal muscle contractile function and might enhance weightlifting exercise performance in humans. Therefore, NO_3^- supplementation holds promise as an effective nutritional ergogenic aid for weightlifting exercise. The potential candidate mechanisms for improved weightlifting exercise performance after NO_3^- supplementation include enhanced excitation–contraction coupling, via modulation of Ca^{2+}-handling and contractile proteins [98,134,135,139]; improved skeletal muscle metabolic control, via lowering the high-energy phosphate cost of contraction and fatigue-related metabolite accumulation [51,94]; and improved skeletal muscle perfusion [109]. However, further research is required to resolve the mechanisms for improved weightlifting exercise performance after NO_3^- supplementation. Furthermore, while NO_3^- supplementation appears to potentially enhance resistance training quality, it is unclear if this will translate into improved weightlifting training adaptations. Notably, although NO_3^- supplementation has been reported to enhance the adaptations to sprint interval training [62,147], the molecular bases for skeletal muscle oxidative metabolism and hypertrophy training adaptations are different and can be potentially antagonistic [148,149]. For example, NO_2^- has been reported to activate AMPK [150], which is a key regulator of skeletal muscle oxidative metabolism adaptations, but interferes with mTORC1 signaling, which is a master regulator of skeletal muscle hypertrophy [148,149]. Therefore, further research is required to assess how NO_3^- supplementation impacts chronic adaptations to weightlifting exercise training.

4. Limitations

Although there are numerous studies analyzing the effect of NO_3^- on various aspects of exercise performance, the number of high-quality studies (i.e., randomized controlled trials) focused on weightlifting exercise is limited, which restricted the sample analyzed in the present systematic review. In addition, existing between-study differences in the supplementation dosage (from 32.5 mg NO_3^- to 6.4 mmol NO_3^-) and the period of supplementation (from acute to chronic over 6 days), along with differences regarding the type of exercise selected, prevented a firm conclusion on the ergogenic potential of NO_3^- supplementation on weightlifting exercise performance at this stage. Nevertheless, this systematic review is an important contribution to the literature as it highlights both the potential promise of NO_3^- supplementation as an ergogenc aid for weightlifting exercise performance and the necessity to conduct further studies to improve understanding on this topic.

5. Conclusions

In conclusion, the limited exisiting literature suggests that acute and short-term dietary NO_3^- supplementation holds promise as a nutritional intervention to enhance weightlifting performance in resistance-trained males. Indeed, NO_3^- supplementation can improve muscular power production, velocity of contraction, and the number of repetitions to failure during weightlifting exercise. Given the important athletic and clinical implications of improved weightlifting exercise performance, NO_3^- supplementation might offer potential as an ergogenic and therapeutic nutritional aid. The mechanistic bases responsible for the potential ergogenic effect of NO_3^- supplementation on weightlifting exercise performance may be linked to improvements in skeletal muscle excitation–contraction coupling, high-energy phosphate metabalism and perfusion. However, further research is required to resolve the putative underlying mechanisms for, and the conditions in which, NO_3^- supplementation might enhance weightlifting exercise performance, as well as its effects on chronic adaptations to weightlifting exercise training.

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