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Human Kinetics
SCHOLARLY REVIEW

Effect of Beta-Alanine Supplementation on Maximal Intensity Exercise in Trained Young Male Individuals: A Systematic Review and Meta-Analysis

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Beta-alanine is a nonessential amino acid that is commonly used to improve exercise performance. It could influence the buffering of hydrogen ions produced during intense exercise and delay fatigue, providing a substrate for increased synthesis of intramuscular carnosine. This systematic review evaluates the effects of beta-alanine supplementation on maximal intensity exercise in trained, young, male individuals. Six databases were searched on August 10, 2023, to identify randomized, double-blinded, placebo-controlled trials investigating the effect of chronic beta-alanine supplementation in trained male individuals with an age range of 18–40 years. Studies evaluating exercise performance through maximal or supramaximal intensity efforts falling within the 0.5–10 min duration were included. A total of 18 individual studies were analyzed, employing 18 exercise test protocols and 15 outcome measures in 331 participants. A significant ($p = .01$) result was observed with an overall effect size of 0.39 (95% confidence interval [CI] [0.09, 0.69]), in favor of beta-alanine supplementation versus placebo. Results indicate significant effects at 4 weeks of supplementation, effect size 0.34 (95% CI [0.02, 0.67], $p = .04$); 4–10 min of maximal effort, effect size 0.55 (95% CI [0.07, 1.04], $p = .03$); and a high beta-alanine dosage of 5.6–6.4 g per day, effect size 0.35 (95% CI [0.09, 0.62], $p = .009$). The results provide insights into which exercise modality will benefit the most, and which dosage protocols and durations stand to provide the greatest ergogenic effects. This may be used to inform further research, and professional or recreational training design, and optimization of supplementation strategies.

Keywords: exercise performance, maximal intensity performance, trained males, athletic performance, amino acid

Physical and sports performance can benefit from various supplemental and nutritional intervention strategies. There is increasing interest in the ergogenic benefit of beta-alanine, which is the precursor to the histidine-containing dipeptide carnosine (β-alanyl-L-histidine), itself shown to have a key role in acid–base regulation during exercise, with other important health-linked roles (such as antioxidant and anti-glycation properties) also posited (Sale et al., 2013). Carnosine is one member of the histidine-containing dipeptides found in humans, with most animals also hosting one or both of its methylated variants, anserine (also expressed in human skeletal and cardiac muscle) or ophidine (Dolan, Saunders, et al., 2019; Toviwek et al., 2022). Already established as having a pH-buffering effect, the synthesis of carnosine in muscle tissue, where it is predominantly found, is rate-limited by the availability of beta-alanine (Perim et al., 2019; Stellingwerff et al., 2012).

Beta-alanine is a nonproteinogenic, nonessential amino acid which is synthesized in relatively small amounts in the liver (Trexler et al., 2015) and can be acquired in the diet from animal, but not plant sources. Supplementation strategies have been shown to significantly increase the amounts of beta-alanine found in blood plasma and subsequently elevate muscle carnosine content; specifically, dosages of beta-alanine ranging from 3.2 to 6.4 g per day given for 4 weeks have been shown to increase muscle carnosine levels by 42%–66% (Harris et al., 2006).

Meta-analyses by Hobson et al. (2012) and Saunders et al. (2017) demonstrated that the greatest ergogenic effects of beta-alanine were attained in exercise lasting 0.5–10 min, where the dominant contributor to energy production is the anaerobic-glycolytic pathway (Artioli et al., 2010). While the tests conducted in these meta-analyses differentiate between performance and capacity tests, they do not focus exclusively on maximal/supramaximal efforts as they also include tests which may contain significant bouts of submaximal output, particularly concerning performance tests. It was also recently shown that beta-alanine supplementation improved output during the second level of the Yo-Yo intermittent performance test (Grgic, 2021) and aerobic–anaerobic transition zones during performance testing (Ojeda et al., 2020). However, it was unclear whether beta-alanine was more effective at improving exercise capacity (i.e., work done and power) or performance (i.e., time to completion/exhaustion), likely due to a lack of studies focusing on performance at the time of their publication. Furthermore, the exercise testing protocols in some of the included studies may have biased the results; for example, studies measuring maximal oxygen capacity ($\dot{V}O_2max$) via a cardiopulmonary exercise test measure the total time taken for the test, which also includes the early, low-intensity stages of the test that do not stress the most relevant energy production system. Thus, it

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remains unclear for which types of exercise, and at which exercise intensities, beta-alanine supplementation is most effective.

The aim of this study was to perform a systematic review and meta-analysis on the effects of beta-alanine supplementation on maximal intensity exercise output; specifically, strength and power as capacity measures, and performance time in young, male, trained individuals. Ergogenic supplements in general (muscle building and endurance enhancing) have a larger proportion of sales arising from men, as opposed to women, who generally gravitate more to weight loss supplements (Austin et al., 2017); taking this discrepancy into account, and in an effort to maintain a more homogeneous group to minimize bias, studies focusing on men were selected over those focusing on women or mixed groups, to be included in this study. Maximal intensity exercise is defined herein as efforts which reach muscular failure during strength and power tests at which no further, technically proficient, repetition can be executed, or efforts in which voluntary output of required (maximal/supramaximal) intensity must be sustained for a given duration. Thus, this study did not examine the effects of beta-alanine supplementation on submaximal exercise. The secondary aims of this study were to add resolution and nuance to the data sets, by applying subanalyses on supplementation duration and dosage, as well as the duration of the tests being performed.

Methods

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines (Page et al., 2021), with the question determined according to PICO (Population, Intervention, Comparator, and Outcomes). The protocol of this systematic review was registered at the Open Science Framework (https://doi.org/10.17605/OSF.IO/AYZ5K).

Literature Search

Relevant articles were identified via electronic search using six databases (PubMed, Google Scholar, Cochrane Library of Science, Scopus, Web of Science, and ScienceDirect). Key search terms "beta-alanine" and "β-alanine" were concatenated with "trained male individuals," "maximal intensity exercise," and "athletic performance," as well as ("trained males" OR "sports performance" OR "athletic performance" OR "maximal intensity") AND ("beta-alanine" OR "β-alanine"). The terms were combined with the databases' filter for controlled trials of interventions on humans. Screening was initiated with a title and abstract search against key search terms. Duplicates and nonpublished articles were removed after importing to Microsoft Excel. All remaining studies (titles and abstract) were screened against inclusion/exclusion criteria, with unclear studies remaining at this stage. The remaining articles were then retrieved and thoroughly assessed against criteria. All reviewers participated in this process and discussed any studies which needed further scrutiny before finalizing the studies being included.

Study Selection

The inclusion criteria of this systematic review were as follows: (a) human study; (b) placebo (PL)-controlled, double-blinded, randomized study; (c) male participants; (d) participants supplemented with beta-alanine; (e) participants who were physically active or recreationally active with consistent training more than three times per week for at least 6 months, and professional/semiprofessional/recreational athletes; (f) participants 18–40 years of age; (g) studies that investigated exercise involving maximal or supramaximal intensity efforts of 0.5–10 min duration, exercise tests involving a single bout of sustained effort, or shorter intervals of high-intensity effort interrupted by brief recovery periods; and (h) peer-reviewed studies published in English. The exclusion criteria were: (a) nonrandomized clinical studies; (b) untrained, inactive, or unhealthy participants; (c) participants under the age of 18 years or above the age of 40 years; (d) participants supplementing other dietary or ergogenic supplements with beta-alanine; (e) unspecified supplementation duration; (f) studies that investigated outcomes not relevant to exercise output; (g) Ph.D. theses, comments, editorials, or reviews; and (h) crossover designed studies that failed to report an appropriate washout period; studies have shown a decrease in supplemented levels of muscle carnosine at a rate of approximately 2% per week following cessation of supplementation protocol, with durations of up to 16 weeks being shown necessary for complete return to baseline levels (Baguet et al., 2009). Thus, 16 weeks was set as an appropriate washout period. Females were excluded due to the possibility of bias arising from the inherently lower levels of carnosine present in these participants (Derave et al., 2010), which can result in females experiencing a greater increase in intramuscular carnosine (Glenn et al., 2015).

Data Extraction

Three reviewers (K. Antoniou, Georgiou, and S. Antoniou) extracted the data from the eligible articles. The information extracted was as follows: study design, participant characteristics (number, sports, or physical activity), group characteristics (number of participants and age), beta-alanine group (dosage), PL/comparison group (form and dosage), study duration, outcome measures, testing protocol, load, and results.

Statistical Analysis

For the meta-analysis, descriptive and statistical analysis was performed using Review Manager (version 5.4.1; Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, 2014). The meta-analysis compared differences between beta-alanine and PL supplementation, and all quantitative data were processed as continuous measurements. The information analyzed for each study included the number of participants, standardized mean difference (SMD) and standard error of SMD of the intervention (beta-alanine) and control (PL) groups. Where available, means and other data were extracted directly from the studies. In cases where data were omitted and authors did not respond to requests for additional data sets, the *SD* of the difference between means (SD_{change}) for each group of each study was calculated using *Formula 1*;

$$SD_{\text{change}} = \sqrt{|(SD_{\text{pre}})^2 + (SD_{\text{post}})^2 - (2 \times r \times SD_{\text{pre}} \times SD_{\text{post}})|},$$

where SD_{pre} and SD_{post} represent the *SD* of the pre- and post-supplementation means, and *r* represents the correlation coefficient of the data, set at .75 to facilitate a conservative estimate (Rosenthal, 1991). A second meta-analysis using identical data, but assuming *r* to be .50, was also performed for comparison. The DerSimonian and Laird inverse-variance model was used to estimate variance, *p*-values, and confidence intervals (CIs).

The overlap of CIs (95% CI) of outcome measurements from the included studies was used to determine statistical heterogeneity, represented by Cochran's Q (chi-square test) and I^2. The percentage of observed total variation between studies was indicated by the I^2 statistic showing real heterogeneity as opposed to sampling error. I^2 value is separated into three categories: low heterogeneity (25%–50%), moderate (50%–75%), and high (>75%; Grant & Hunter, 2006).

Quality and Risk of Bias Assessment

Quality assessment and the risk of bias were performed by all reviewers, in accordance with the Revised Cochrane Collaboration's tool for assessing risk of bias in randomized trials (RoB2; Higgins et al., 2011). The tool comprises six domains: bias arising from the randomization process, bias arising from period and carryover effects, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. For each domain, a possible risk of bias judgment was low risk, some concerns and high risk, as well as not applicable. A sensitivity test of the studies with highest bias is included (see Figure S4 in Supplementary Materials [available online]).

Results

Study Selection

After searching the six databases, 1,478 articles were identified, of which 328 were not randomized controlled trials. The remaining were filtered by title, and irrelevant ($n = 594$) and duplicated ($n = 427$) articles were excluded. All reviewers (Georgiou, K. Antoniou, S. Antoniou, and Michelekaki) took part in the screening process. The remaining 129 articles were retrieved, of which 70 were excluded because they failed to meet inclusion criteria. One report was not retrieved as it was written in Spanish. A total of 58 were then assessed for eligibility, of which 32 were excluded. Finally, a total of 26 articles were eligible for inclusion in the qualitative synthesis of this systematic review. Eight articles were not eligible for inclusion in the meta-analysis because the authors did not mention means and/or *SDs* of their data. The article selection process is shown in Figure 1. The characteristics of the included articles are summarized in Table 1.

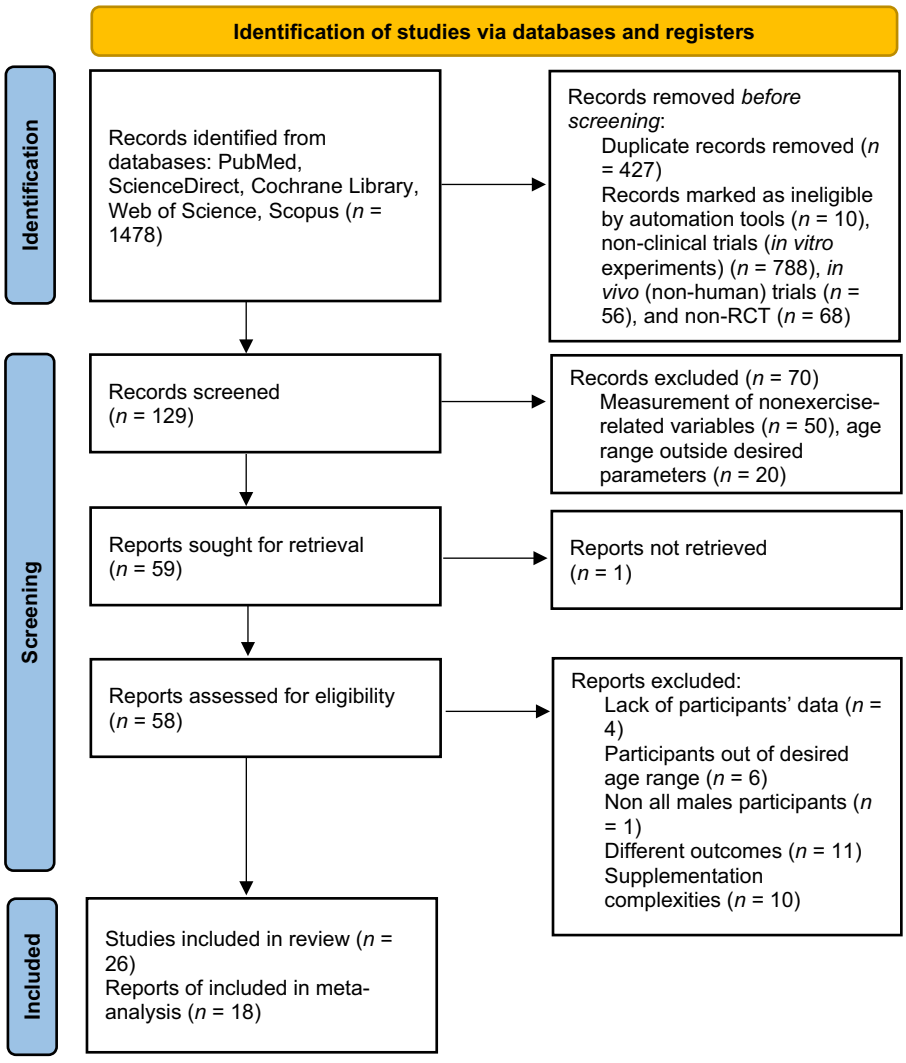

Figure 1 — Preferred Reporting Items for Systematic Reviews and Meta-Analysis flow diagram.

Table 1 Summary of Randomized Controlled Trials Considering Supplementation of BA

Study	Design	Participants	Groups and mean age (±*SD*)	Supplementation group	Placebo/ comparison group	Duration	Outcomes measured	Testing protocol	Training load	Results
Derave et al. (2007)	Randomized, double-blind controlled trial	15 track-and-field athletes	BA: $n = 8$, 23.8 (±4.2) years PL: $n = 7$, 18.4 (±1.5) years	2.4 g/day (Days 1–4), 3.6 g/day (Days 5–9), and 4.8 g/day (Day 10–4 weeks)	Maltodextrin equivalent	4 weeks	Performance time, isometric endurance, knee extension torque	Isokinetic and isometric muscle fatigue protocol, 400 m sprinting	N/A	Dynamic knee extension torque during the fourth and fifth bouts significantly improved with BA by 6.1% and 3.8%, respectively, with no effect on performance time
Brisola et al. (2018)	Randomized, double-blind controlled trial	22 water polo players	BA: $n = 11$, 19 (±5) years PL: $n = 11$, 18 (±3) years	4.8 g/day × 10 days and 6.4 g/day × 18 days	Dextrose equivalent	4 weeks	Performance time	Repeated sprint ability swimming test	N/A	None of the results were significantly different between the BA and PL groups Likely beneficial effect for mean time (81%), worst time (78%), and total time (81%) Possible beneficial effect for total time (52%)
Milioni et al. (2019)	Randomized, double-blind controlled trial	18 physically active males	BA: $n = 9$ PL: $n = 9$ Age: 25 (±5) years	6.4 g/day	Dextrose 6.4 g/day	4 weeks	VO_2max, maximal aerobic velocity, performance time	Supramaximal running test at 115% of vVO_2max, repeated sprint ability test	4-week HIIT program	Improved performance time by −3.0% ± 2.0%
Bellinger and Minahan (2016b)	Randomized, double-blind controlled trial	14 male trained cyclists	BA: $n = 7$ Placebo: $n = 7$ Age: 24.8 (±6.7) years	6.4 g/day	Dextrose monohydrate equivalent	4 weeks	Performance time and power output	1-, 4- and 10-km cycling TTs, supramaximal cycling TTE	Subjects' normal training regimen	Improvement in performance time by 17.6 ± 11.5 s, no statistically significant changes in power output
de Salles Painelli et al. (2014)	Randomized controlled trial	40 trained and nontrained cyclists	TBA: $n = 10$ 32 (±8) years TPL: $n = 9$ 33 (±12) years NTBA: $n = 10$ 25 (±4) years NTPL: $n = 10$ 26 (±4) years	6.4 g/day	Dextrose, 6.4 g/day	4 weeks	Total work done and mean power output	Lower-body 30-s cycling Wingate test —four bouts	N/A	Significantly improved total work done and mean power output in both trained and nontrained participants in the BA group
Bellinger and Minahan (2016a)	Randomized controlled trial	17 trained cyclists	BA: $n = 9$ PL: $n = 8$ Age: 24.5 (±6.2) years	6.4 g/day	Dextrose monohydrate 6.4 g/day	4 weeks	Time to exhaustion, performance time	Supramaximal cycling test 120% VO_2max, 4,000-m cycling TT	N/A	Significant improvement in time to exhaustion (17.6 ± 11.5 s) in BA group No statistical difference in performance time

(continued)

Table 1 *(continued)*

Study	Design	Participants	Groups and mean age (±*SD*)	Supplementation group	Placebo/ comparison group	Duration	Outcomes measured	Testing protocol	Training load	Results
Saunders et al. (2012)	Randomized controlled trial	16 elite hockey players and 20 nonelite players	BAE: $n = 8$ 20 (±1) years PLE: $n = 8$ 19 (±2) years BANE: $n = 10$ 22 (±2) years PLNE: $n = 10$ 22 (±3) years	6.4 g/day	Maltodextrin equivalent	4 weeks	Sprint performance	Loughborough Intermittent Shuttle Test	N/A	No effect of supplementation in sprint performance neither in the elite group nor the nonelite group
Ducker et al. (2013b)	Randomized controlled trial	18 recreational runners	BA: $n = 9$ 22 (±6) years PL: $n = 9$ 22 (±5) years	6.4 g/day	Glucose equivalent	4 weeks	Time performance	800-m run	N/A	Significant improvement in time performance with a very likely benefit (99%) in the BA group
Tobias et al. (2013)	Randomized double-blind, parallel group controlled trial	37 Judo and Jiu Jitsu athletes	PL + PL: $n = 09$ 26 (±5) years BA + PL: $n = 10$ 26 (±4) years PL + SB: $n = 9$ 23 (±4) years BA + SB: $n = 9$ 26 (±5) years	6.4 g/day	Dextrose equivalent or calcium carbonate or sodium bicarbonate	4 weeks	Mean and peak power, total work done	Four 30-s upper body Wingate tests	N/A	BA improved total work done by +7%, however, nonsignificant
Hobson et al. (2013)	Randomized double-blind crossover controlled trial	20 well-trained rowers	BA: $n = 10$ 24 (±3) years PL: $n = 10$ 23 (±4) years	6.4 g/day	Maltodextrin equivalent ×28 days maltodextrin eq. and sodium bicarbonate ×2 days	4 weeks	Time performance	2,000-m rowing TT	Normal training regimen	Very likely beneficial effect (6.4 ± 8.1 s) of BA supplementation, however, not statistically significant
Freitas et al. (2019)	Randomized double-blind controlled trial	23 recreationally trained males	BA: $n = 12$ PL: $n = 11$ Age: 23.7 (±3.9) years	6.4 g/day	Maltodextrin equivalent	4 weeks	Maximal strength maximal aerobic velocity	45 leg press incremental treadmill running test	Resistance training protocol	No effect of BA supplementation
Ducker et al. (2013c)	Randomized double-blind controlled trial	24 football hockey and soccer athletes	BA: $n = 6$ 23 (±5) years SB: $n = 6$ 21 (±3) years BA + SB: $n = 6$ 23 (±4) years PL: $n = 6$ 19 (±3) years	~6 g/day	Glucose 10 g/day	4 weeks	Time performance	Repeated sprint test	N/A	No effect of BA supplementation
Ducker et al. (2013a)	Randomized controlled trial	16 competitive male rowers	BA: $n = 7$, 26 (±9) years PL: $n = 9$, 26 (±9) years	6–7 g/day	Sucrose, 10 g/day	4 weeks	Total time, average power output	2,000-m rowing ergometer test	N/A	Significant improvement in performance time at 750 m and at 1,000 m by 87% and power output at 750 m by 3.6% and at 1,000 m by 2.9% for BA group

(continued)

Table 1 *(continued)*

Study	Design	Participants	Groups and mean age (±*SD*)	Supplementation group	Placebo/ comparison group	Duration	Outcomes measured	Testing protocol	Training load	Results
Howe et al. (2013)	Randomized, double-blind controlled trial	16 highly trained cyclists	BA: $n = 8$, 26 (±8) years PL: $n = 8$, 22 (±5) years	65 mg^{-1} kg^{-1} day	Dextrose monohydrate equivalent	4 weeks	Average power, average power/ repetition, total work done	Maximal cycling test, isokinetic knee contraction (180°/s)	N/A	Isokinetic average power/repetition significantly increased with 85% likely benefit for BA group Total work done and average power were not statistically significant
Gross et al. (2014)	Randomized controlled trial	nine professional alpine skiers	BA: $n = 5$ PL: $n = 4$ Age: 19.5 (±1.1) years	4.2 g/day	Maltodextrin equivalent	5 weeks	Maximal power, average power	Countermovement jumps 90-s cycling 110% VO_2max maximal 90-s box jump test	Strength and conditioning training	Significantly improved maximal (+7.0% ± 2.5%) and average power (+7.0% ± 2.4%) in BA group in countermovement jumps Tendency for improved overall performance (+2.6% ± 2.4%) in BA group
Jagim et al. (2013)	Randomized controlled trial	21 rugby players, wrestlers, and strength-trained athletes	BA: $n = 10$ 20.5 (±2.32) years PL: $n = 11$ 20 (±2.45) years	4 g/day × 1 week, and 6 g/ day × 4 weeks	Rice flour equivalent	5 weeks	Time to exhaustion	Running incremental tests at 115% and 140% of VO_2max	Regular exercise habits	No effect of BA supplementation
Mate-Munoz et al. (2018)	Randomized controlled trial	30 young, healthy resistance-trained men	BA: $n = 15$ PL: $n = 15$ Age: 21.85 (±1.6) years	6.4 g/day	Sucrose equivalent	5 weeks	Average and peak power	Back squat incremental load test, 1RM	Strength training	Significantly greater average power at 1RM by 42.65% and at maximum power output by 20.17% for BA group
Smith et al. (2019)	Randomized, double-blind controlled trial	15 collegiate male rugby players	BA: $n = 8$ PL: $n = 7$ Age: 21.0 (±1.8) years	6.4 g/day	6.4 g/day of maltodextrin	6 weeks	Upper- and lower-body maximal strength and muscular endurance, intermittent sprint performance	Bench press and back squat 1RM, five sets of bench press and back squat repetitions (70% of 1RM), Intermittent Running test	Six weeks of weight training and sport-specific training	No positive outcomes observed
Kern and Robinson (2011)	Randomized double-blind controlled trial	37 collegiate wrestlers and football players	BAWR: $n = 10$, 20.1 (±2.06) years PLWR: $n = 12$, 19.8 (±1.83) years BAFB: $n = 7$, 18.4 (±0.59) years PLFB: $n = 8$, 18.9 (±2.1) years	4 g/day	Dextrose equivalent	8 weeks	Anaerobic power performance	300-yard shuttle test, 90° flexed arm hang	Regular sport-specific resistance training and practice sessions	Both BA groups achieved better results than the PL groups, however, with no statistically significant difference

(continued)

Table 1 *(continued)*

Study	Design	Participants	Groups and mean age (±*SD*)	Supplementation group	Placebo/ comparison group	Duration	Outcomes measured	Testing protocol	Training load	Results
Askari and Rahmaninia (2018)	Randomized controlled trial	20 healthy young men	BA: $n = 10$, 17.7(±1) years PL: $n = 10$ 17.1(±0.6) years	4.8 g/day	4.8 g/day polydextrose	8 weeks	Maximum strength, anaerobic power	1RM bench press and leg press, RAST test, vertical jump test	8-week resistance training	Significant differences in power performance and strength gains for the BA group
Turcu et al. (2022)	Randomized controlled trial	20 basketball players	BA: $n = 10$ PL: $n = 10$ Age: 23 (±0.6) years	6.4 g/day	Maltodextrin 6.4 g/day	8 weeks	Lower-body power, anaerobic power, VO_2max	Countermovement jump, anaerobic sprint test running incremental test	Regular basketball training	Increased anaerobic power, no significant differences in VO_2max
de Camargo et al. (2023)	Randomized, double-blind, controlled trial	19 resistance-trained men	BA: $n = 9$, 26.1 (±5.5) years PL: $n = 10$ 28.5 (±5.5) years	6.4 g/day	Maltodextrin equivalent	8 weeks	Maximal strength	1RM bench press and 1RM back squat	Resistance training protocol	BA supplementation did not maximize RT-induced adaptations
Hill et al. (2007)	Randomized, double-blind controlled trial	25 physically active young males	BA: $n = 13$ 25.4 (±2.1) years PL: $n = 12$ 29.2 (±6.9) years	4 g/day (Week 1) 4.8 g/day (Week 2) 5.6 g/day (Week 3) 6.4 g/day (Week 4) 6.4 g/day (Week 5–10)	Maltodextrin equivalent	10 weeks	Total work done	Cycle capacity tests at 110% Wmax	N/A	Significantly improved total work done by 16.2% for the BA group
Kim et al. (2018)	Randomized, double-blind controlled trial	19 amateur male boxers	BA: $n = 9$, 23.00 (±1.82) years PL: $n = 10$ 22.20 (±2.21) years	4.9 g/day for 49 kg –69 kg, and –5.4 g/day for –75 kg to + 91 kg	Maltodextrin in a similar manner	10 weeks	Maximal and isokinetic strength (leg and trunk), peak, and mean power	Bench press and back squat dynamometer at an angular velocity of 30°/s and 60°/s 30 s Wingate test, Sargent jump test	10-week training	Significant improvement in lower-body peak power (6.06%) and upper-body power drop (3.20%), as well as nonsignificant improvement in maximal strength (squat 4.21% and bench press 5.18%) in BA group
Saunders et al. (2017)	Randomized double-blind controlled trial	25 active males	Two participants were allocated in BA for each participant in PL Age: 27 (±4) years	6.4 g/day	Maltodextrin equivalent	24 weeks	Time to exhaustion	Cycle capacity tests at 110% Wmax	N/A	Time to exhaustion significantly improved in BA group with possible to almost certain improvements across all weeks (96%–100%) but not in PL group

Note. BA = beta-alanine; PL = placebo: N/A = not applicable: 1RM = one-repetition maximum: HIIT = high-intensity interval training: TT = time trial: TTE = time to exhaustion: TBA = trained + beta-alanine: TPL = trained + placebo: NTBA = nontrained + beta-alanine: NTPL = nontrained + placebo: BAE = beta-alanine elite participants: PLE = placebo elite participants: BANE = beta-alanine nonelite participants: PLNE = placebo nonelite participants: SB = sodium bicarbonate: BAWR = beta-alanine collegiate wrestlers/players: PLWR = placebo collegiate wrestlers/players: BAFB = beta-alanine football players: PLFB = placebo football players: Wmax = maximum power: RAST = radioallergosorbent.

Study Characteristics

A total of 331 participants were pooled together across the studies included in the meta-analysis, with similar numbers in the beta-alanine group ($n = 166$) and the PL group ($n = 165$). Sporting background of the participants varied: track and field ($n = 25$); cyclists ($n = 47$); runners ($n = 18$); team sports including football, soccer, basketball, hockey, and rugby ($n = 68$); recreationally active ($n = 58$); water polo ($n = 22$); amateur boxers ($n = 19$); resistance-trained ($n = 49$); alpine skiers ($n = 9$); and competitive rowers ($n = 16$).

Dosage of beta-alanine varied between studies, from 3.9 g per day to 6.4 g per day. Studies were grouped as low (3.9–4.6 g per day, $n = 4$), medium (4.7–5.5 g per day, $n = 2$), and high dose (5.6–6.4 g per day, $n = 12$). These groupings (low/medium/high) are arbitrary, serving to differentiate between dose magnitudes for this review only, and are not representative of the general dose considerations found in the literature, although these groupings may be useful in practical terms, as they often approximate dose ranges available for commercial use. Supplementation protocols lasted from 4 to 10 weeks for the studies analyzed, grouped into duration of 4 weeks ($n = 9$) and 5–10 weeks ($n = 9$). For the test durations, studies analyzed were grouped as 0–1 ($n = 8$), 1–4 ($n = 7$), and 4–10 min ($n = 3$).

Effect of Beta-Alanine on Maximal Intensity Exercise

The main analysis of this review included 18 studies. Five studies measured power output (Brisola et al., 2018; Ducker et al., 2013a; Gross et al., 2014; Howe et al., 2013; Turcu et al., 2022), five measured muscle strength (Askari & Rahmaninia, 2018; de Camargo et al., 2023; Freitas et al., 2019; Kim et al., 2018; Smith et al., 2019), one measured work done (Hill et al., 2007), six measured time taken to complete an exercise task (Bellinger & Minahan, 2016a, 2016b; Derave et al., 2007; Ducker et al., 2013b, 2013c; Jagim et al., 2013), and one measured total work sets completed (Maté-Muñoz et al., 2018). Since outcomes were measured using different methods and units of measurement, utilizing mean differences (MD) would have been inappropriate; therefore, global output was expressed as the composite score of all measures using SMD.

Figure 2 shows that supplementation with beta-alanine had small to moderate but significant positive effects on maximal exercise (SMD: 0.39, 95% CI [0.09, 0.69]; $p = .01$), compared with PL. The studies reviewed in this analysis displayed low to moderate heterogeneity ($I^2 = 44\%$, $p = .02$). Fourteen of the 18 studies showed beta-alanine supplementation having a beneficial effect on maximal exercise (Bellinger & Minahan, 2016a, 2016b; Brisola et al., 2018; Derave et al., 2007; Ducker et al., 2013a, 2013b, 2013c; Freitas et al., 2019; Hill et al., 2007; Howe et al., 2013; Kim et al., 2018; Maté-Muñoz et al., 2018; Smith et al., 2019; Turcu et al., 2022) with the study by Hill et al. (2007) displaying a large effect size (3.59). The remaining four studies showed a neutral or small detrimental effect of supplementation (Askari & Rahmaninia, 2018; de Camargo et al., 2023; Gross et al., 2014; Jagim et al., 2013). As described in the Methods, a second meta-analysis using identical data, but assuming r to be .50, was also performed for comparison (Figure 3).

Subgroup Analysis: Supplementation Duration

To investigate the effect of duration of beta-alanine supplementation, a subgroup analysis was performed between studies in which supplementation lasted for 4 weeks ($n = 9$; Bellinger & Minahan, 2016a, 2016b; Brisola et al., 2018; Derave et al., 2007; Ducker et al., 2013a, 2013b, 2013c; Freitas et al., 2019; Howe et al., 2013) or 5–10 weeks ($n = 9$; Askari & Rahmaninia, 2018; de Camargo et al., 2023; Gross et al., 2014; Hill et al., 2007; Jagim et al., 2013; Kim et al., 2018; Maté-Muñoz et al., 2018; Smith et al., 2019; Turcu et al., 2022; Figure 4). The lower, 4-week, duration of supplementation showed a smaller but significant effect on maximal intensity exercise (SMD: 0.34, 95% CI [0.02, 0.67]; $p = .04$)

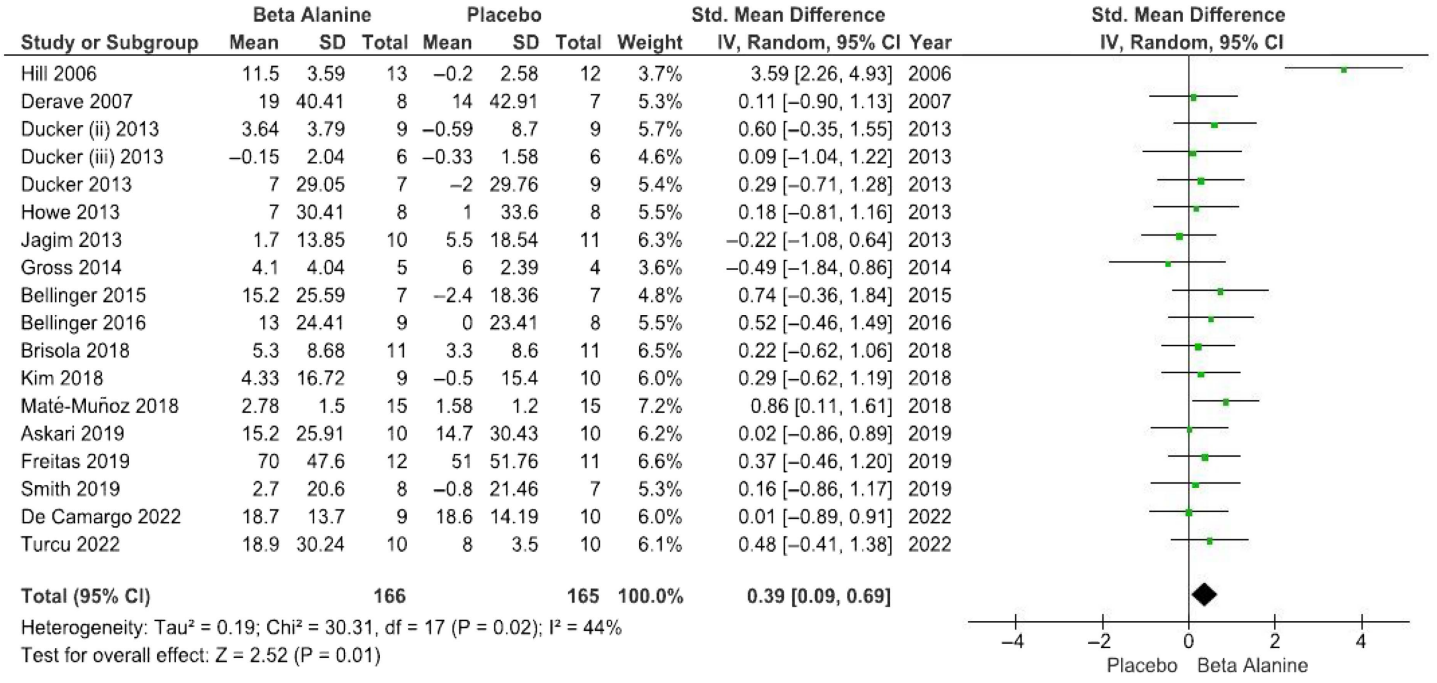

Figure 2 — Forest plot comparing the effects of beta-alanine supplementation on maximum intensity exercise.

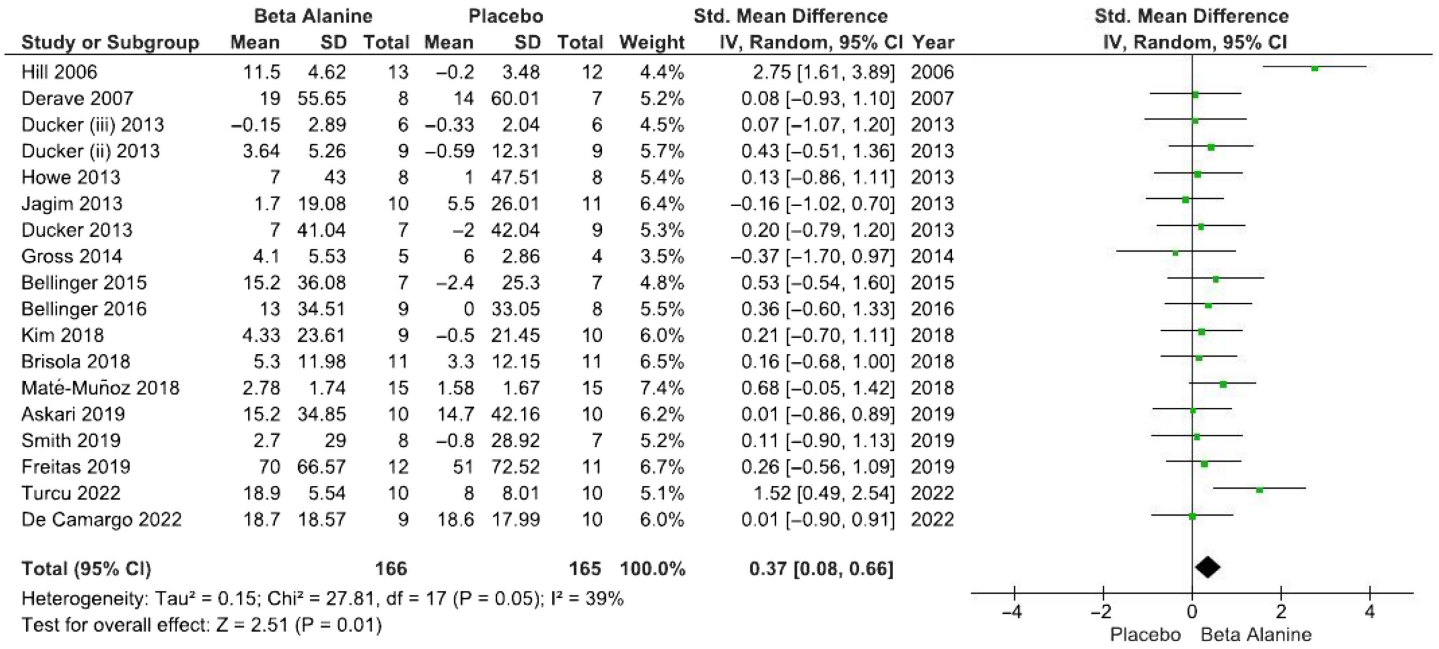

Figure 3 — Forest plot comparing the effects of beta-alanine supplementation on maximum intensity exercise assuming *r* to be .5.

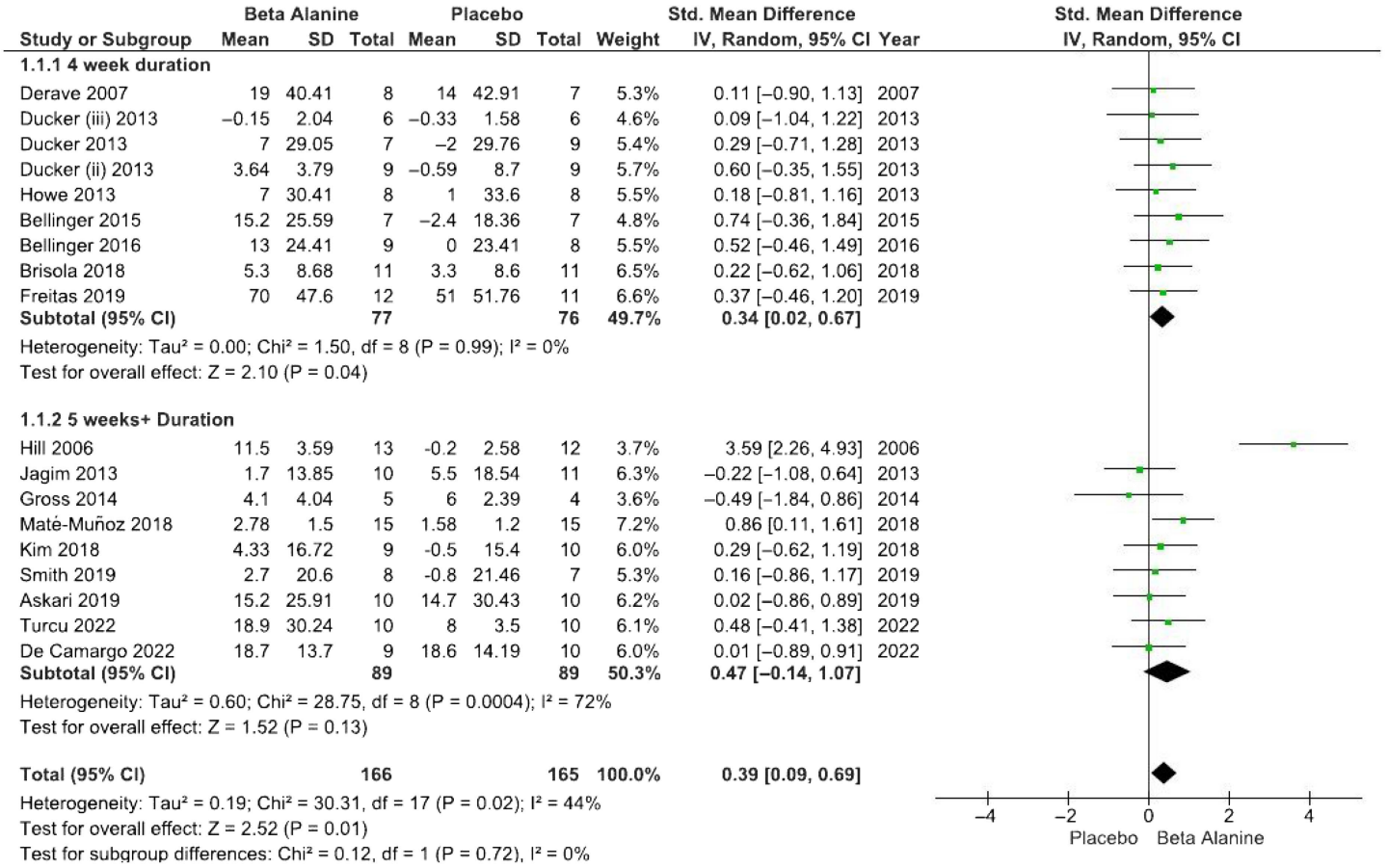

Figure 4 — Forest plot comparing the effects of beta-alanine supplementation duration on maximum intensity exercise.

when compared to PL, and displayed no heterogeneity ($I^2 = 0\%$, $p = .99$), compared with the higher, 5–10 weeks duration of supplementation which showed a larger but statistically insignificant effect (SMD: 0.47, 95% CI [–0.14, 1.07]; $p = .13$) compared with PL, and moderate to large homogeneity ($I^2 = 72\%$, $p < .0004$).

We performed further analysis on the 5–10 weeks group, splitting them into groups that provided beta-alanine for 5–6 weeks ($n = 4$) or 8–10 weeks ($n = 5$). This analysis showed a small (SMD: 0.18, 95% CI [–0.43, 0.79]; $p = .57$) and moderate (SMD: 0.79, 95% CI [–0.24, 1.82]; $p = .13$) effect when compared to PL, respectively, but was not significantly different. The 5–6 weeks group showed low heterogeneity ($I^2 = 38\%$, $p = .18$), and the 8–10 weeks group showed high heterogeneity ($I^2 = 83\%$, $p = .0001$).

All studies in the 4-week group reported that beta-alanine supplementation was beneficial, while five of the nine studies in the 5–10 weeks group showed beneficial effects. The remaining four studies showed neutral or small detrimental effects on maximal intensity exercise.

Subgroup Analysis: Exercise Test Duration

To investigate whether beta-alanine supplementation changed maximal exercise output relative to the duration of the test, a subgroup analysis was conducted, in which the studies were divided into those which used tests lasting 0–1 ($n = 8$), 1–4 ($n = 7$), and 4–10 min ($n = 3$) (Figure 5).

The 0–1 min group showed a small insignificant effect on maximal output (SMD: 0.13, 95% CI [–0.22, 0.47]; $p = .98$) with no heterogeneity ($I^2 = 0\%$, $p = .98$). Despite a moderate effect size, there was no significant effect in the 1–4 min test duration group (SMD: 0.72, 95% CI [–0.03, 1.47]; $p = .06$), and heterogeneity was high ($I^2 = 75\%$, $p = .0005$). Finally, the 4–10 min group showed a moderate and significant effect of beta-alanine supplementation on maximal output (SMD: 0.55, 95% CI [0.07–1.04]; $p = .03$) with no heterogeneity ($I^2 = 0\%$, $p = .58$). All results are compared with PL.

Of the eight studies included in the 0–1 min group, five showed beneficial effects and the remaining three showed neutral or detrimental effects. Six of the seven studies in the 1–4 min group showed positive effects on maximal output, and all three studies in the 4–10 min group showed beneficial effects.

Subgroup Analysis: Dosage

A subgroup analysis on the influence of beta-alanine dosage on maximal intensity exercise revealed significant increases with a

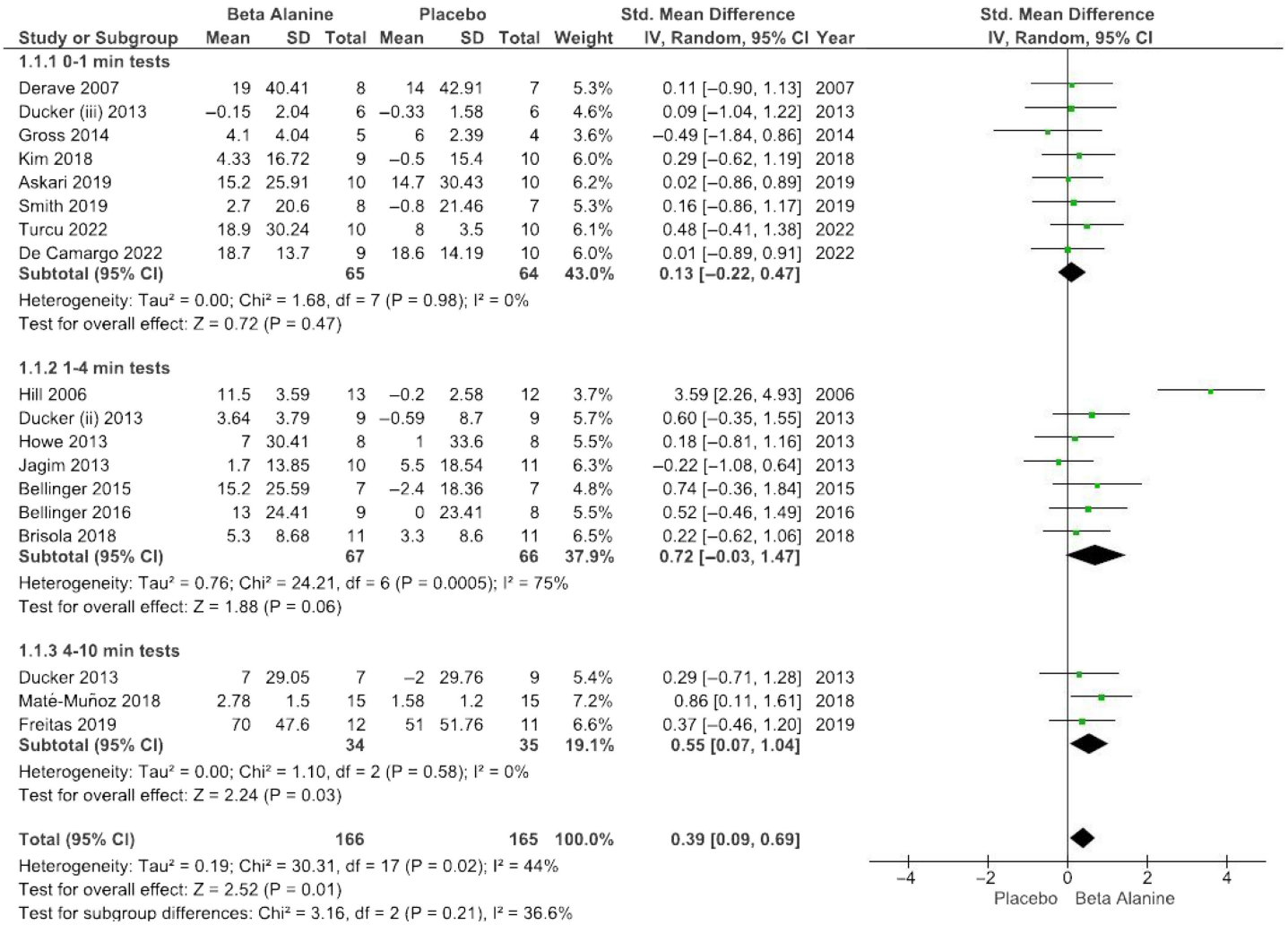

Figure 5 — Forest plot comparing the effects of beta-alanine supplementation on exercise test duration.

high dose ($n = 12$, 5.6–6.4 g per day; SMD: 0.35, 95% CI [0.09, 0.62]; $p = .009$). Low ($n = 4$, 3.9–4.6 g per day) and medium ($n = 2$, 4.7–5.5 g per day) dosages had no statistically significant effects, with large (SMD: 0.82, 95% CI [–0.78, 2.43]; $p = .32$) and small (SMD: 0.15, 95% CI [–0.48, 0.78]; $p = .65$) effect sizes, respectively (Figure 6). All results are compared with PL.

One of the studies in the low-dosage group showed detrimental effects on output (Gross et al., 2014), one study (Askari & Rahmaninia, 2018) included in the medium dosage protocol displayed a neutral outcome, and two studies in the high-dosage protocol (de Camargo et al., 2023; Jagim et al., 2013) reported detrimental or neutral effects. The heterogeneity between subgroups was insignificant ($I^2 = 0\%$, $p = .70$).

Risk of Bias

Quality assessment and risk of bias performed according to the Revised Cochrane Collaboration's tool for assessing risk of bias in randomized trials (RoB2; Higgins et al., 2019) demonstrated that the overall risk of bias of the included studies is low. Bias results are presented in Figure 7.

Discussion

Effect of Beta-Alanine on Maximal Intensity Exercise

This review aimed to evaluate the effects of beta-alanine supplementation on maximal intensity exercise. There was a small (0.39), significant effect in favor of beta-alanine supplementation on maximal intensity exercise. The duration of beta-alanine supplementation showing the greatest ergogenic benefits was 4 weeks, with the administered dosage ranging from 5.6 to 6.4 g per day. Beta-alanine supplementation was most effective for exercise lasting 4–10 min.

Our review's results are in agreement with previous systematic reviews (Berti Zanella et al., 2017; Quesnele et al., 2014) that also found improvements in the same parameters. Beyond that, our results indicate that beta-alanine supplementation can enhance both exercise performance and capacity, agreeing with previous research (Saunders et al., 2017). An older systematic review and meta-analysis by Hobson et al. (2012) found that beta-alanine supplementation had a significant effect on capacity but did not improve performance-based measures. The difference in results

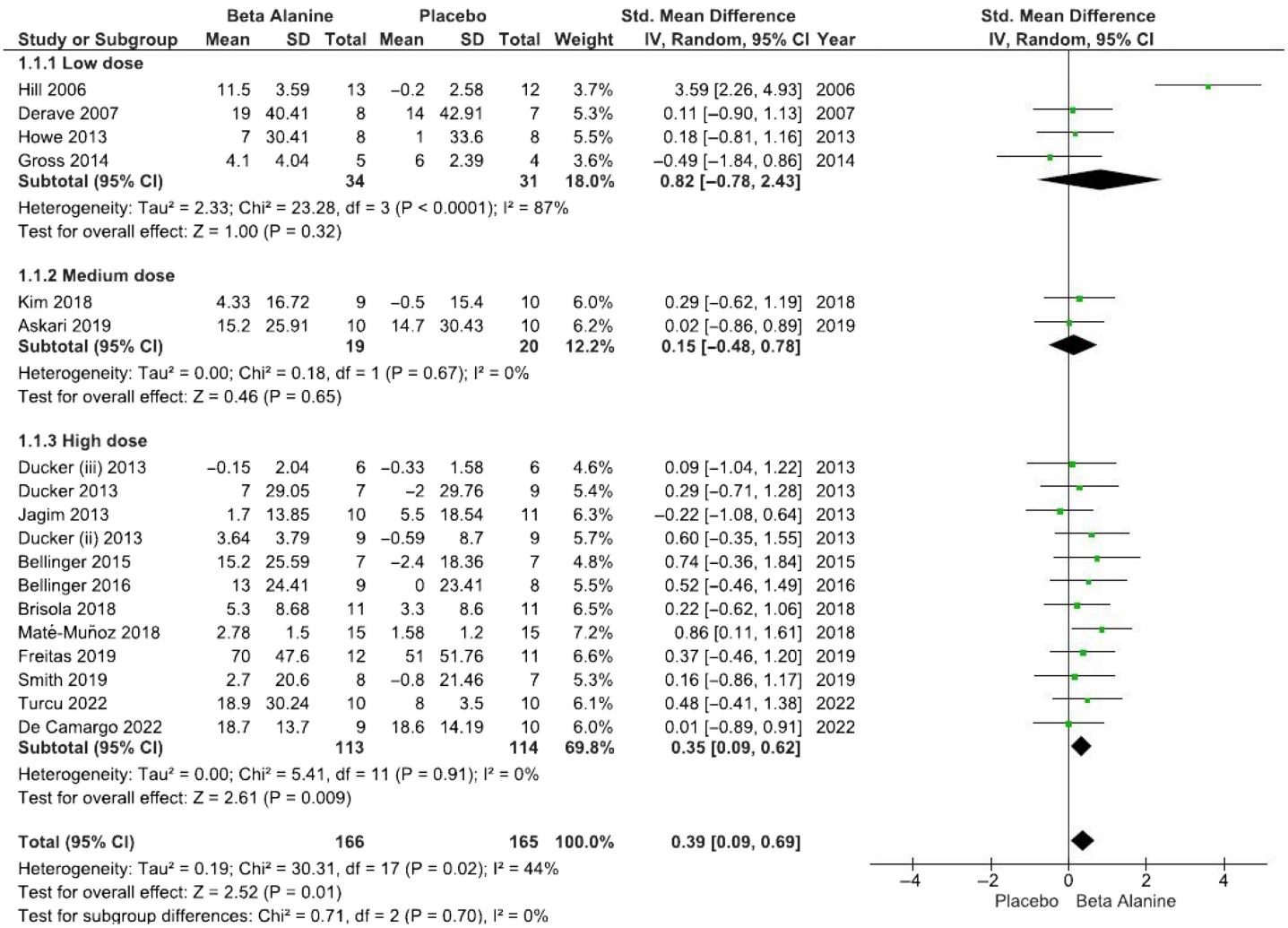

Figure 6 — Forest plot comparing the effects of beta-alanine supplementation dosages on maximum intensity exercise.

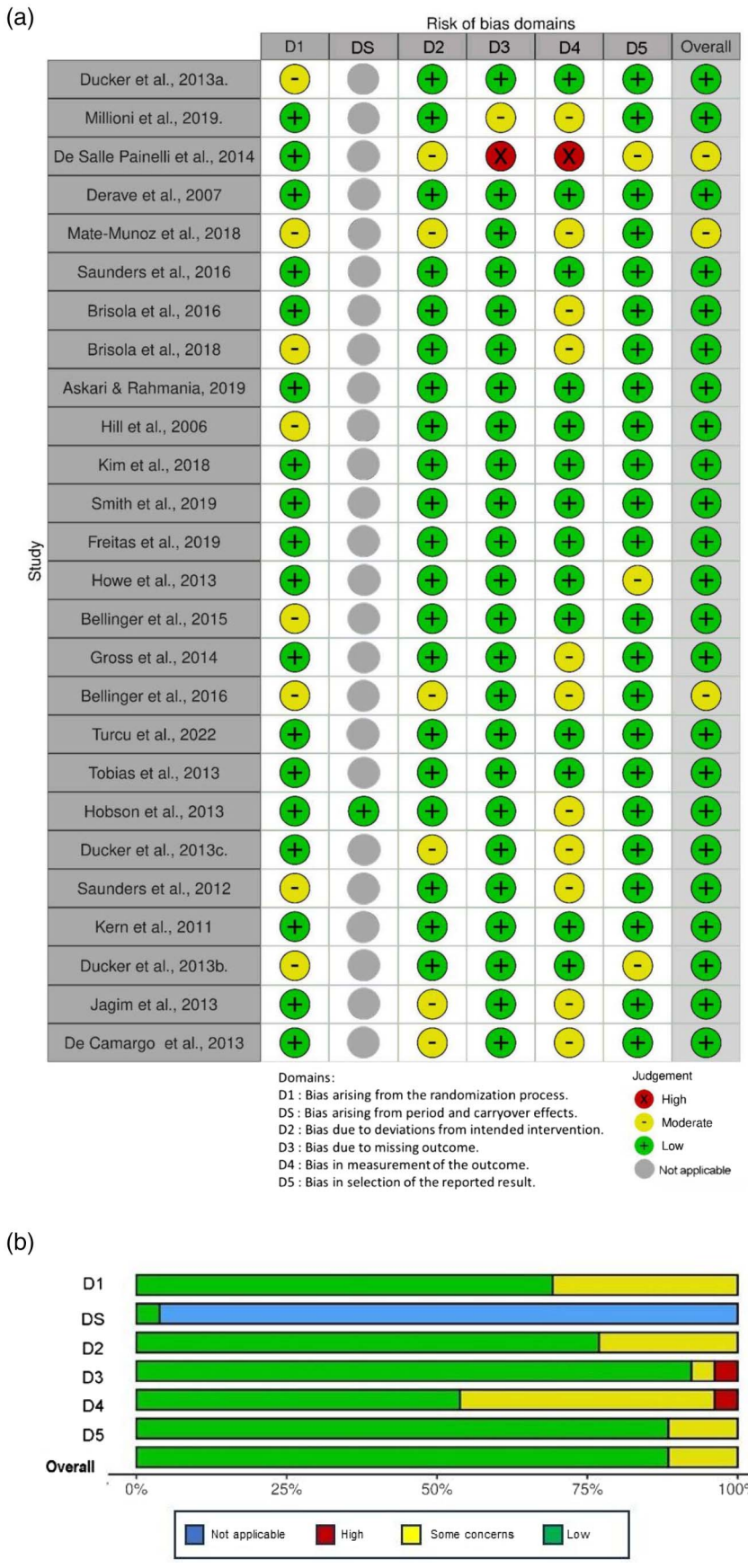

Figure 7 — Assessment of bias of the randomized studies according to RoB 2 tool: (a) traffic light plot and (b) summary plot.

could be due to the lack of studies incorporating performance measures at the time, as the authors have acknowledged (Saunders et al., 2017).

Several studies in this review showed that supplementation with beta-alanine improved short-term, high-intensity exercise. Specifically, studies reported significant improvements in total work done and power, which are capacity measures (Askari & Rahmaninia, 2018; De Salles Painelli et al., 2014; Derave et al., 2007; Ducker et al., 2013c; Gross et al., 2014; Hill et al., 2007; Kim et al., 2018; Maté-Muñoz et al., 2018; Turcu et al., 2022), and improvements in performance measures, such as time to completion/exhaustion (Bellinger & Minahan, 2016a, 2016b; Ducker et al., 2013a, 2013c; Milioni et al., 2019; Saunders et al., 2017). However, some studies reported no significant improvements in performance or capacity after beta-alanine supplementation. Ducker et al. (2013b) and Saunders et al. (2012) reported no changes in performance time in a repeated sprint test. No effect of beta-alanine supplementation was observed by Freitas et al. (2019) on maximal strength, and other authors also reported no effect (Hobson et al., 2013; Howe et al., 2013; Tobias et al., 2013). Potential explanations are discussed within their respective sections in the following paragraph.

From a mechanistic perspective, beta-alanine supplementation has been demonstrated to increase muscle carnosine levels (Culbertson et al., 2010; Varanoske et al., 2017). Carnosine is an important buffer of hydrogen ions (H+), a fatiguing metabolite which accumulates during high-intensity exercise, altering muscle pH from ~7.05 to as low as ~6.5 (Allen et al., 2008; Sweeney et al., 2010) negatively affecting exercise output (Culbertson et al., 2010; Ducker et al., 2013a). In addition, carnosine can increase calcium (Ca^{2+}) release from the sarcoplasmic reticulum, increasing muscular contractility and delaying fatigue, thus enhancing output (Dutka et al., 2012; Ojeda et al., 2020).

Effect of Beta-Alanine Supplementation Duration on Maximal Intensity Exercise

Our analysis suggests that the duration of beta-alanine supplementation providing the greatest relative benefit to improving exercise output is 4 weeks. Indeed, a longer duration of supplementation did not appear to augment effects. Furthermore, when subjects were tested on a supramaximal cycling test, data suggested that the greatest enhancement in output was achieved at the end of 4 weeks of supplementation (Hill et al., 2007). Shorter supplementation periods (<4 weeks) did not significantly improve maximal intensity exercise; however, a trend toward improvements in exercise performance with smaller dosage periods has been suggested (Hoffman et al., 2008).

It is not yet clear what the optimal duration period is for increasing intramuscular carnosine concentrations (Trexler et al., 2015), but we can speculate why the 4 weeks duration may have led to the greatest benefits; beta-alanine shares the same transporter to the cell with taurine therefore prolonged supplementation with beta-alanine may affect homeostasis (Artioli et al., 2010; Dolan, Swinton, et al., 2019). This in turn can reverse beta-alanine's influence, as reported in a study where participants were ingesting 6.4 g per day of beta-alanine for 24 weeks (Dolan, Swinton, et al., 2019).

Mediation of Beta-Alanine's Effect by Test Duration

Meta-analysis results demonstrated that beta-alanine supplementation improved exercise output in tests lasting 4–10 min, but not for tests lasting 0–1 min or 1–4 min, although the SMD was moderate for the latter. These results are in contrast to previous research indicating that tests lasting from 1 to 4 min benefited most from beta-alanine supplementation (Hobson et al., 2012; Saunders et al., 2017). During exercise of this duration at high intensity, the predominant energetic pathway is the anaerobic-glycolytic pathway, where H+ is generated, leading to a decrease in pH, that can precipitate fatigue (Ojeda et al., 2020).

A possible explanation for our findings could be the nature of the tests employed in studies. Performance tests were intermittent, relying upon pacing strategies. They included short periods of maximal intensity exercise followed by light-intensity recovery periods, possibly masking beta-alanine's ergogenic effect at the early stages of the tests. Maximal blood H+ accumulation occurs after approximately 4 min of intense exercise (Saunders et al., 2017). When maximal exercise is intermittent, it takes longer for H+ to accumulate, extending the time needed for beta-alanine supplementation to manifest its effects.

Beta-alanine supplementation did not enhance performance in shorter tests lasting 0–1 min, possibly because exercise of this duration is not limited by acidosis (Artioli et al., 2010). According to (Saunders et al., 2017), a 0.5- to 10-min time frame could be more applicable for carnosine's acid buffering role since physical activity lasting 7–8 min still relies heavily on energy from glycolysis. Total anaerobic energy contribution during a 4-km cycling test lasting around 6 min is about 25%, while total energy contribution from glycolysis during 2,000 m rowing, lasting >7 min, is about 12% (Saunders et al., 2017).

In addition, it is worth mentioning that duration of the tests itself may have an effect on the reliability of precision of the assessments. Hopkins et al. (2001) showed that measures of reliability can vary based on the nature of the tests being conducted (i.e., field test of sprint running vs. mean power on isokinetic ergometers) as a function of measurement error, expressed as coefficient of variation. It stands to reason that similar effects may be observed as the duration of a test varies, and more research on this topic is required.

Effect of Beta-Alanine Dosage

Dosages were categorized into three groups, low (3.9–4.6 g per day), medium (4.7–5.5 g per day), and high (5.6–6.4 g per day). The most significant changes in exercise output were observed with high dosages of beta-alanine supplementation, at 5.6–6.4 g per day. This dosage range has been shown to increase muscle carnosine concentrations by up to 64% and 80% at 4 weeks and 10 weeks, respectively (Trexler et al., 2015).

This is in line with research that demonstrated carnosine synthesis in human skeletal muscle is dependent on beta-alanine availability (Sale et al., 2010). Additionally, in the absence of a known threshold of intramuscular carnosine storage, it is reasonable to assume that higher beta-alanine dosages result in higher muscle carnosine concentrations, and this equates to greater muscle buffering capacity during high-intensity exercise (Hobson et al., 2012). Estimations suggest that carnosine contributes up to 10% of the total buffering capacity in muscle (Artioli et al., 2010). After beta-alanine supplementation, total buffering capacity can reach up to 15%, and if only Type II muscle fibers are taken into consideration, carnosine contribution can be >25% (Artioli et al., 2010).

However, Ojeda et al. (2020) found in their systematic review and meta-analysis that even dosages as low as 1.5 g per day could

result in changes in physical output. This variability in results regarding beta-alanine dosage could be due to the exercise test or outcomes measured and requires further research. Ducker et al. (2013a) state that a range of 3–6 g per day of beta-alanine supplementation for a duration of 4 weeks can increase intramuscular carnosine concentrations from 30% to 80%, with the range of dosage supplementation likely being proportional to carnosine concentration increase.

Strengths and Limitations

To date, this is the most comprehensive meta-analysis on the effects of beta-alanine supplementation, covering a generalized analysis as well as various subgroupings including supplementation duration, exercise test duration, and dosage. A major strength of this research is the high quality of the studies included. Overall, the included studies had a low risk of bias, with only one study exhibiting a high risk of bias, in just two domains. Almost all of the studies mention that they controlled for nutritional supplementation and ergogenic aid use during the intervention period, and excluded participants that consumed any supplement that could affect the results of the intervention 3 months prior to the study.

Females may have been excluded because they inherently have lower levels of carnosine (Baguet et al., 2010); therefore, mixed gender groups could bias results. Furthermore, all studies excluded vegetarians, as they may have lower basal carnosine stores (Baguet et al., 2010). The findings of this review are therefore only applicable to omnivorous males. A limitation is the low number of studies available for review that provided beta-alanine, without the addition of other ingredients. Additionally, any conclusions from this investigation only pertain to maximal intensity outcomes, such as strength, power, and performance time, as this review did not focus on submaximal outcomes, or exercise lasting 0.5 min or >10 min in duration.

Practical Applications

Based on our findings, beta-alanine supplementation could be used by coaches, strength and conditioning trainers, and athletes across a broad spectrum of sports and activities as an ergogenic aid to enhance physical exercise output. Supplementation is likely to be most beneficial for athletes in high-intensity sports lasting from 4 to 10 min, such as middle-distance runners, rowers, swimmers, and combat sports' athletes. For maximal benefits, the dosage should range from 5.6 to 6.4 g per day, for a supplementation period of 4 weeks. In order to avoid paresthesia that may occur after beta-alanine supplementation, it is recommended to ingest beta-alanine in smaller doses of 1.6 g throughout the day (Trexler et al., 2015) and to consume 2 g/kg of carbohydrates an hour before beta-alanine supplementation (Ojeda et al., 2020). This study can also serve as a foundation for further research into those areas of beta-alanine supplementation which still need clarification, such as acute dosing protocols, and whether or not upper limits to cellular carnosine saturation exist, and their subsequent effects on exercise/sports performance and physiology.

Conclusions and Future Perspectives

This systematic review and meta-analysis demonstrated that beta-alanine supplementation can significantly enhance maximal intensity exercise, as measured by changes in power, strength, work done, performance time, and total sets performed. Our analysis suggests that such effects are observed with a dosage of 5.6 g–6.4 g per day for 4 weeks, when exercise performance lasts 4–10 min. This highlights the need for more high-quality, newer systematic reviews since the 4–10 min time frame is not in agreement with previous systematic reviews (Hobson et al., 2012; Saunders et al., 2017).

Nevertheless, heterogeneous results from individual studies necessitate the need for further research. Also, some studies suggest that beta-alanine supplementation can enhance maximal intensity exercise with lower, acute doses (Ducker et al., 2013a; Ojeda et al., 2020) even when ingested 1 hr prior to testing (Ojeda et al., 2020). Therefore, dosage and duration of beta-alanine supplementation need to be further investigated, as well as the minimal effective acute dose. More research should be conducted with female participants, both athletes and sports enthusiasts, since studies concerning beta-alanine supplementation in females are currently scarce compared with those in males.

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