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Effects of Sodium Bicarbonate Supplementation on Muscular Strength and Endurance: A Systematic Review and Meta-analysis

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Effects of sodium bicarbonate supplementation on muscular strength and endurance: a systematic review and meta-analysis

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Key points

1. This meta-analysis found significant ergogenic effects of sodium bicarbonate supplementation on muscular endurance of both small and large muscle groups.
2. No significant ergogenic effects of sodium bicarbonate were found for muscular strength.
3. No significant linear trends in the effects of timing of sodium bicarbonate ingestion or acute increase in blood bicarbonate concentrations on muscular endurance or muscular strength were found.

Background: The effects of sodium bicarbonate on muscular strength and muscular endurance are commonly acknowledged as unclear due to the contrasting evidence on the topic.

Objective: To conduct a systematic review and meta-analysis of studies exploring the acute effects of sodium bicarbonate supplementation on muscular strength and endurance.

Methods: A search for studies was performed using five databases. Meta-analyses of standardized mean differences (SMDs) were performed using a random-effects model to determine the effects of sodium bicarbonate supplementation on muscular strength (assessed by changes in peak force [N], peak torque [N·m], or maximum load lifted [kg]) and muscular endurance (assessed by changes in the number of repetitions performed or time to maintain isometric force production). Subgroup meta-analyses were conducted for the muscular endurance of small vs. large muscle groups and muscular strength tested in a rested vs. fatigued state. A random-effects meta-regression analysis was used to explore possible trends in the effects of: (a) timing of sodium bicarbonate ingestion; and (b) acute increase in blood bicarbonate concentration (from baseline to pre-exercise), on muscular endurance and muscular strength.

Results: Thirteen studies explored the effects of sodium bicarbonate on muscular endurance and 11 on muscular strength. Sodium bicarbonate supplementation was found to be ergogenic for muscular endurance (SMD = 0.37; 95% confidence interval [CI]: 0.15, 0.59; $p = 0.001$). The performance-enhancing effects of sodium bicarbonate were significant for both small (SMD = 0.31; 95% CI: 0.04, 0.59; $p = 0.025$) and large muscle groups (SMD = 0.40; 95% CI: 0.13, 0.66; $p = 0.003$). Sodium bicarbonate ingestion was not found to enhance muscular strength (SMD = –0.03; 95% CI: –0.18, 0.12; $p = 0.725$). No significant effects were found regardless of whether the testing was carried out in a rested (SMD = 0.02; 95% CI: –0.09, 0.13; $p = 0.694$) or fatigued (SMD = –0.16; 95% CI: –0.59, 0.28; $p = 0.483$) state. No significant linear trends in the effects of timing of sodium bicarbonate ingestion or acute increase in blood bicarbonate concentrations on muscular endurance or muscular strength were found.

Conclusions: Overall, sodium bicarbonate supplementation acutely improves muscular endurance of small and large muscle groups, but no significant ergogenic effect on muscular strength was found.

1 Introduction

The 2018 International Olympic Committee consensus statement classified sodium bicarbonate as a supplement with good evidence of benefits for exercise performance [1]. The most pronounced effects of sodium bicarbonate supplementation are observed for high-intensity tasks lasting between 1 and 10 minutes [1]. There is strong evidence that sodium bicarbonate enhances performance during multiple bouts of high-intensity exercise that have a high anaerobic metabolic demand, such as judo, swimming, and boxing [1, 2-5]. Sodium bicarbonate elicits ergogenic effects by increasing the concentration of blood bicarbonate, a buffer that can help to maintain extracellular and intracellular pH [6]. During exercise, greater levels of circulating bicarbonate following sodium bicarbonate ingestion are accompanied by: (a) increased blood pH; and (b) increased transport of hydrogen ions (H^+) and lactate out of the working muscle into the circulation [6-11]. This increase in the rate of H^+ removal from the active muscles delays exercise-induced metabolic acidosis, which has been associated with delayed exercise-induced fatigue [6].

While the general ergogenic effect of sodium bicarbonate supplementation and its physiological mechanisms are well established, its effects on resistance exercise performance are less clear. Two of the most important muscular qualities in resistance exercise are muscular strength and muscular endurance. Muscular strength can be defined as “the capacity to exert force under a particular set of biomechanical conditions” [12]. Muscular endurance represents the ability of a muscle or a group of muscles to maintain force production at a given percentage of maximum or to repeat contractions against a load for an extended time [13].

Supplementation with sodium bicarbonate may enhance muscular endurance given that such tasks may result in a high production of H^+ [14]. Given its buffering effects, the ingestion of sodium bicarbonate before exercise may attenuate and delay fatigue during exercise. Nonetheless, the evidence on this topic remains equivocal, with some studies reporting increases in muscular endurance following sodium bicarbonate ingestion, while others report that muscular endurance performance is unaffected by prior sodium bicarbonate ingestion [15-18]. Regarding muscular strength, a study using perfused rat hind-limb muscles reported that increases in bicarbonate concentration did not result in changes in tetanic force [19]. These results observed in animal models suggest that sodium bicarbonate supplementation and the subsequent increases in blood bicarbonate may not result in acute increases in muscular strength in humans – a hypothesis in line with findings from several studies [20, 21]. Specifically, one study included 12 resistance-trained men and reported that acute ingestion of 0.3 $g{\cdot}kg^{-1}$ of sodium bicarbonate 60 minutes pre-exercise did not significantly enhance muscular strength of the knee extensors [20]. Ansdell et al. [21] also did not find improvements in muscular strength following the ingestion of 0.4 $g{\cdot}kg^{-1}$ sodium bicarbonate 90 and 60 minutes pre-exercise in basketball players. Nonetheless, Coombs et al. [17] reported that the ingestion of 0.3 $g{\cdot}kg^{-1}$ of sodium bicarbonate enhanced knee extension peak torque by 8% in a sample of nine male physical education students, even though the exact mechanisms underpinning this increase remain unclear.

Factors such as absolute changes in circulating bicarbonate, ingestion timing, the exercise task performed, and the training status of the participants may explain some of the differences in findings [22]. Besides these factors, possibly even more important is that studies in sports nutrition tend to be performed in small participant samples, and therefore may have a low statistical power [1, 23]. A meta-analysis may help to overcome the low generalizability of findings from individual studies and clarify equivocal findings on a given topic. Even though several meta-analyses [2, 24-28] have explored the effects of acute sodium bicarbonate ingestion on various aspects of exercise performance (e.g., single and repeated sprint performance, intermittent exercise performance), none of these meta-analyses focused specifically on muscular strength or muscular endurance outcomes. Therefore, the objective of this study was to conduct a systematic review of studies examining the acute effects of sodium bicarbonate supplementation on muscular strength and endurance and to synthesize their results using a meta-analysis.

2 Methods

2.1 Search strategy

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [29]. The search for studies was conducted on July 31st 2019 in the following databases: Open Access Theses and Dissertations, PubMed/MEDLINE, Scopus, SPORTDiscus, and Web of Science (including all Web of Science Core Collection: Citation Indexes). The following search syntax was used: ("sodium bicarbonate" OR NaHCO3) AND ("muscle strength" OR "muscular strength" OR "muscle endurance" OR "muscular endurance" OR "isometric" OR "isokinetic" OR "resistance exercise" OR "resistance training" OR "strength exercise" OR "strength training" OR "MVC" OR "torque" OR "maximal voluntary contraction" OR "1RM" OR "1 RM" OR "one repetition maximum" OR "1 repetition maximum" OR "bench press" OR "squat" OR "leg press"). No year restrictions were applied in the search. Secondary searches were performed by: (a) examining reference lists of the included studies and relevant review papers [1, 2, 15, 22, 28, 30]; and (b) examining the studies that cited the included studies (i.e., forward citation tracking) through Scopus and Google Scholar. The search for studies was performed independently by two authors (JG and RFR).

2.2 Inclusion criteria

Studies were included in the review if they satisfied the following criteria: (a) published in English; (b) included apparently healthy humans as participants; and (c) utilized a crossover study design to explore the acute effects of sodium bicarbonate supplementation on muscular strength or muscular endurance. For muscular endurance, studies were considered if they used resistance exercise sets performed for a maximal number of repetitions with a given load or isometric tests that included time to maintain force production at a given percentage of maximum. For muscular strength, studies were included if they tested muscular strength using isometric or isokinetic tests of maximal voluntary contraction or tests that included a repetition maximum (RM) component such as 1RM. Studies that did not satisfy these criteria were excluded. Typical reasons for exclusion were not assessing muscular strength or endurance, presenting duplicate (i.e., previously published) data, or performed using animal models.

2.3 Data extraction

Two authors (JG and RFR) extracted the following data from the included studies: (a) study authors and publication year; (b) participants characteristics, such as sex and training status; (c) the test(s) used for examining muscular performance; (d) the protocol for sodium bicarbonate supplementation, including the dose, timing and form of administration; (e) pH and blood bicarbonate values pre and post sodium bicarbonate and placebo ingestion; (f) side-effects associated with sodium bicarbonate supplementation; and (g) main findings regarding the effects of sodium bicarbonate on muscular strength and/or endurance performance. If the study results were reported in a figure only, the Web Plot Digitizer software Version 4.2 (https://automeris.io/WebPlotDigitizer/) was used to extract the data. The data extraction file can be found in Electronic Supplementary Material Appendix S1.

2.4 Methodological quality assessment

In order to assess the methodological quality of the included studies, the 11-item Physiotherapy Evidence-Based Database (PEDro) checklist was used [31]. The 11 items on this checklist include a "Yes/No" response scale and are related to various aspects of the study design, including eligibility criteria, randomization and blinding (of both participants and assessors), attrition, and the reporting of data. According to the established PEDro checklist guidelines [31], all items except the first one are included in the calculation of the summary score. A "Yes" response to a given item adds one point to the summary score. Based on the summary scores, the studies were classified as being of "excellent quality" (9 to 10 points), "good quality" (6 to 8 points), "fair quality" (4 to 5 points) or "poor" methodological quality (≤3 points) [32-34]. Two authors of the review (JG and AG) independently conducted the quality assessment; any discrepancies between the authors in the scores were resolved through discussion and agreement.

2.5 Statistical analysis

A random-effects meta-analysis was used to pool the effect sizes from the included studies. This model was used as it accounts for differences between studies that could have affected the treatment effect [35]. For the analysis, muscular performance data (e.g., number of performed repetitions, total time to maintain force production at a given percentage of maximal voluntary contraction [MVC], maximal force [N], peak torque [N·m], or total load lifted [kg]) from the included studies were converted to standardized mean differences (SMDs) using: (a) exercise performance means and standard deviations of the sodium bicarbonate and placebo conditions; (b) study sample size; and (c) inter-trial correlation. As inter-trial correlation was not presented in the included studies, the formula presented in the *Cochrane Handbook for Systematic Reviews of Interventions* [36] was used to estimate the correlation: $r' = \frac{s_{placebo}^2 + s_{treatment}^2 - s_D^2}{2 \cdot s_{placebo} \cdot s_{treatment}}$, where $s_{placebo}$ is the standard deviation of the placebo trial score, $s_{treatement}$ is the standard deviation of the sodium bicarbonate trial score, and s_D is the standard deviation of the change score calculated as: $s_D = \left(\frac{s_{placebo}^2}{n} + \frac{s_{treatment}^2}{n}\right)^{1/2}$. For the studies that explored the effects of sodium bicarbonate on performance in several exercises, SMDs and variances were calculated for each exercise separately and the average SMD and variance values were used for the analysis [32-34, 37]. Two main meta-analyses were performed: (a) for the effect of sodium bicarbonate on muscular endurance; and (b) for the effect of sodium bicarbonate on muscular strength. For muscular endurance, a sensitivity analysis was performed by excluding a study [20] that was classified as an outlier through visual examination of the forest plot. Specifically, this study reported a substantially larger effect size than the remaining studies. Additionally, as it has been suggested that the effects of sodium bicarbonate on might be greater on muscular endurance of small muscle groups [38], subgroup meta-analysis examined the effect of sodium bicarbonate on muscular endurance of: (a) large muscle groups; and (b) small muscle groups. For muscular strength, some studies explored the effects of sodium bicarbonate before an exercise protocol (i.e., in a rested state) and after an exercise protocol (i.e., in a fatigued state, defined by force output reductions caused by the exercise task preceding the strength assessment). We, therefore, performed a subgroup meta-analysis for the effects of sodium bicarbonate on muscular strength in: (a) a rested state; and (b) a fatigued state. A subgroup meta-analysis was also conducted to examine the effects of sodium bicarbonate on muscular endurance and muscular strength for the studies that provided supplementation at one time point vs. the studies that split the total dose and administered it at multiple time points. A subgroup analysis for dose could not be done given that 19 out of the 20 included studies used a sodium bicarbonate dose of 0.3 $g·kg^{-1}$ (Table 1).

A random-effects meta-regression analysis was conducted to explore possible trends in the effects of: (a) timing of sodium bicarbonate ingestion; and, (b) acute increases in blood bicarbonate concentration (from baseline to pre-exercise) on muscular strength and muscular endurance. In the meta-regression on timing of ingestion, only studies that used sodium bicarbonate supplementation provided at one time point were included. In the meta-regression on acute increases in blood bicarbonate concentration, only studies that collected blood samples and reported pre and post values were included.

The pooled effects sizes were categorized as “trivial” (<0.20), “small” (0.20 to 0.39), “medium” (0.40 to 0.59), “large” (0.60 to 0.79), and “very large” (≥0.80). The I^2 statistic was used to explore heterogeneity. I^2 values of <50%, 50 to 75%, and >75% were considered to represent low, moderate and high levels of heterogeneity, respectively. The statistical significance threshold was set at $p < 0.05$. All analyses were performed using the Comprehensive Meta-Analysis software, version 2 (Biostat Inc., Englewood, NJ, USA). The data files used for the meta-analyses on muscular endurance and muscular strength can be found in Electronic Supplementary Material Appendix S2 and Electronic Supplementary Material Appendix S3, respectively.

3 Results

3.1 Search results

The primary search resulted in 229 documents (Figure 1). Of the 229 search results, 27 full-text papers were read and 17 studies were included in the review. Secondary searches produced another 1460 search results. The secondary search resulted in the inclusion of three additional studies. Therefore, the final number of included studies was 20 [16-18, 20, 21, 23, 38-51]. Thirteen studies explored the effects of sodium bicarbonate on muscular endurance while 11 examined the effects of the supplement on muscular strength, with some assessing both outcomes (Table 1).

3.2 Study characteristics

The total number of participants across all studies was 192 (184 men and 8 women). Studies either used mixed-sex samples (three studies) or included only men (17 studies). The median number of participants per study was 10. Studies included athletes (male basketball players in one study [21] and male club triathletes in another study [42]) or resistance-trained men, although several studies included participants classified as recreationally active or untrained. Out of the 20 included studies, 19 used a sodium bicarbonate dose of 0.3 $g{\cdot}kg^{-1}$ and one study used the dose of 0.4 $g{\cdot}kg^{-1}$. The timing of ingestion ranged from 60 minutes pre-exercise up to 180 minutes pre-exercise. In some studies, the dose of sodium bicarbonate was provided at one time point, with other studies splitting up the total dose and administering it at multiple time points (e.g., 90, 60, and 30 minutes pre-exercise; see Table 1 for details). None of the studies utilized individual time-to-peak bicarbonate supplementation protocols.

3.3 Methodological quality

Studies were classified as being either excellent (15 studies), good (4 studies), or fair methodological quality (1 study). None of the included studies were rated as being of poor methodological quality (Table 2).

3.4 Effect of sodium bicarbonate supplementation on muscular endurance

The pooled number of participants in the analysis for muscular endurance was n = 113. There was a significant effect of sodium bicarbonate on muscular endurance, compared to placebo (SMD = 0.37; 95% CI: 0.15, 0.59; p = 0.001; I^2 = 70%; Figure 2). Upon exclusion of one study that reported a very large effect size, the pooled SMD still remained significant, even though it decreased to 0.20 (95% CI: 0.05, 0.36). The subgroup analysis for muscle size found a significant effect of sodium bicarbonate for muscular endurance of large (SMD = 0.40; 95% CI: 0.13, 0.66; p = 0.003; I^2 = 75%) and small muscle groups (SMD = 0.31; 95% CI: 0.04, 0.59; p = 0.025; I^2 = 0%). The subgroup analysis for the protocol of supplementation found a significant effect of sodium bicarbonate on muscular endurance for the studies that used one time point of ingestion (SMD = 0.53; 95% CI: 0.14, 0.93; p = 0.008; I^2 = 69%) and for the studies that split the dose across multiple time points (SMD = 0.23; 95% CI: 0.05, 0.42; p = 0.014; I^2 = 5%). The meta-regression analyses for timing and acute increase in blood bicarbonate concentration did not show significant linear trends (p = 0.194 and p = 0.311, respectively; Electronic Supplementary Material Appendix S4 and Electronic Supplementary Material Appendix S5).

3.5 Effects of sodium bicarbonate supplementation on muscular strength

The pooled number of participants in the analysis for muscular strength was n = 110. There was no significant difference in muscular strength between the sodium bicarbonate and placebo trials (SMD = –0.03; 95% CI: –0.18, 0.12; p = 0.725; I^2 = 45%; Figure 3). The subgroup analysis found no significant effects of sodium bicarbonate on muscular strength in a rested state (SMD = 0.02; 95% CI: –0.09, 0.13; p = 0.694; I^2 = 15%) or a fatigued state (SMD = –0.16; 95% CI: –0.59, 0.28; p = 0.483; I^2 = 50%). The subgroup analysis for protocol of supplementation found no significant effect of sodium bicarbonate on muscular strength for studies that used one time point of ingestion (SMD = –0.14; 95% CI: –0.50, 0.21; p = 0.427; I^2 = 48%) and for studies that used multiple time points (SMD = 0.04; 95% CI: –0.06, 0.14; p = 0.405; I^2 = 0%). The meta-regression analyses for timing and specific levels of acute increase in blood bicarbonate concentrations did not show significant linear trends (p = 0.058 and p = 0.135, respectively; Electronic Supplementary Material Appendix S6 and Electronic Supplementary Material Appendix S7).

4 Discussion

The findings of this review indicate that sodium bicarbonate supplementation elicits acute ergogenic effects on muscular endurance of both small and large muscle groups. Sodium bicarbonate ingestion may increase the number of repetitions performed with a given load or the time to maintain isometric force production at a given percentage of maximum. These findings are based on studies that used sodium bicarbonate dose of 0.3 $g \cdot kg^{-1}$ provided from 60 to 180 minutes before exercise. Improvements in muscular endurance with sodium bicarbonate were found for studies that used one time point of ingestion and for studies that used multiple time points (e.g., ingestion at 90, 60, and 30 min before exercise). No significant ergogenic effect of sodium bicarbonate supplementation on muscular strength was found. No significant linear trends in the effects of timing of sodium bicarbonate ingestion or acute increase in blood bicarbonate concentration on muscular endurance and muscular strength were found. The results of this meta-analysis may help to develop evidence-based guidelines regarding sodium bicarbonate supplementation in the context of resistance exercise and also to inform future studies.

4.1 Effects of sodium bicarbonate supplementation on muscular endurance

The favorable effect of sodium bicarbonate supplementation on muscular endurance can be explained by the suggested physiological mechanisms of this supplement. Specifically, sodium bicarbonate elicits its performance-enhancing effect on exercise tasks that produce a substantial increase in H^+ [6, 22, 52]. H^+ accumulation is theorized to inhibit actomyosin cross-bridge attachment and thus impair force production and/or inhibit PFK and phosphorylase, which regulate glycolysis and re-synthesis of ATP [6, 53, 54]. Muscular endurance tasks can result in high production of H^+ [14], and, therefore, consuming sodium bicarbonate should, in theory, increase the body's buffering capacity and lead to better maintenance of cellular pH, which would, in turn, improve performance [6, 53, 54].

Even though sodium bicarbonate may enhance muscular endurance, the duration of the task is one component to consider here. Generally, sodium bicarbonate is considered ergogenic for activities that are of high-intensity and that last longer than 30 seconds but less than 10 minutes [1]. Indeed, McNaughton et al. [52] observed a performance-enhancing effect of sodium bicarbonate ingestion on cycling exercise lasting 120 and 240 seconds, while high-intensity cycling exercise lasting 10 and 30 seconds was not affected. In this context, most studies included in the present review used muscular endurance tests lasting more than 30 seconds. For example, a study where the participants were required to perform 60 repetitions of knee flexion/extension, and total work was used as a proxy of muscular endurance [17]. The total duration of this test was around 85 seconds, and a test with this intensity and duration would result in a high production of H^+. However, the duration of the exercise does not seem to be the sole determinant for the ergogenic effect of sodium bicarbonate as some of the included studies used exercise tasks lasting over 30 seconds but did not find significant ergogenic effects and their effect sizes were around zero (Figure 2). This is likely because sodium bicarbonate may act through multiple mechanisms and not only buffering of H^+ [1, 38]. Future studies are warranted to elucidate the exact mechanisms by which sodium bicarbonate enhances muscular endurance.

In order for sodium bicarbonate to be ergogenic, it has been hypothesized that a 5 $mmol \cdot L^{-1}$ and 6 $mmol \cdot L^{-1}$ increase in blood bicarbonate (from baseline levels) is required to have a *potential* and *almost certain* ergogenic effect on exercise performance, respectively [2, 22]. However, meta-regression found no significant linear trends in the effects of acute increases in blood bicarbonate on muscular strength and muscular endurance (Electronic Supplementary Material Appendix S5). One limitation of these findings is that not all studies included in the review assessed changes in blood bicarbonate (Table 1). Therefore, future research is needed to explore if there is a threshold of blood bicarbonate increase following sodium bicarbonate ingestion above which there is an increased likelihood of experiencing an ergogenic effect on muscular endurance.

Sostaric et al. [38] suggested that the effects of sodium bicarbonate might be greater for exercises that activate small muscle groups. This hypothesis is based on the suggested higher blood flow in small muscle groups that occurs during exercise, which potentially results in a greater ion exchange within the muscle. While our results suggest that the effectiveness of sodium bicarbonate is not impacted by muscle group size, it should be noted that only three studies were included in the subgroup analysis for small muscle groups. Therefore, a degree of caution must be exercised when interpreting these findings. Future studies should consider exploring this topic further, preferably by comparing the effects of sodium bicarbonate on muscular endurance of small and large muscle groups in the same group of participants.

4.2 Effects of sodium bicarbonate supplementation on muscular strength

The pooled SMD for the effect of sodium bicarbonate on muscular strength was very close to zero, with both the upper and lower limit of CI within the range of trivial effects. This suggests that, even if an effect exists (regardless of whether it is positive or negative), it is most likely practically negligible. From a physiological perspective, these results are not surprising given that muscular strength tests consist of maximal exertion that is of very short duration (e.g., a 1RM test may only last a couple of seconds). Subgroup analyses suggested that sodium bicarbonate is not ergogenic when muscular strength is tested in a rested state nor after exercise-induced fatigue. Nonetheless, there were only four studies that explored the effects of sodium bicarbonate on strength in a fatigued state. Given that one study [21] reported possible benefits of sodium bicarbonate in attenuating the fatigue-induced decline of muscular strength, future research on this topic is warranted. Compared to testing in a rested state, ergogenic effects of sodium bicarbonate on muscular strength might be more likely in a fatigued state due to possible H^+ accumulation from the previous exercise. However, such effects would be dependent on the amount of fatigue induced during the prior exercise (i.e., not all fatigue-states would expect an improvement). Future studies may consider exploring the effects of sodium bicarbonate on muscular strength after exercise protocols that induce different amounts of fatigue and/or different degrees of H^+ accumulation.

4.3 Side-effects associated with sodium bicarbonate supplementation

Potential gastrointestinal side-effects are important to consider in relation to sodium bicarbonate supplementation. The buildup of CO_2 in the gut, as a result of supplementation with sodium bicarbonate, may cause bloating, nausea, vomiting, and abdominal pain [55, 56]. Some of these side-effects were reported in the included studies (Table 1) although it was not possible to determine whether this influenced the outcome of studies. The seriousness and types of side-effects vary greatly between individuals; some experience symptoms and others do not. While our main findings refer to average responses, sodium bicarbonate supplementation can be ergolytic in those who experience gastric discomfort [56]. Thus, experimentation is needed to determine the individual response, and to then assess whether the benefits outweigh the costs for a given person. The incidence of gastrointestinal side-effects associated with sodium bicarbonate can be reduced by using delayed-release capsules, as shown by Hilton and colleagues [57]. Therefore, individuals prone to these side-effects might consider using delayed-release capsules when supplementing with sodium bicarbonate [57].

4.4 Methodological quality

Most studies included in this review used a double-blind study design, which is identified as the “gold standard” study design in this line of research [1]. However, none of the included studies explored the effectiveness of the blinding by asking the participants to indicate which trial was the sodium bicarbonate and which was the placebo. Given that sodium bicarbonate is also associated with side-effects such as gastrointestinal issues (Table 1), it is possible that some participants were able to identify the study treatments correctly. This may be important to explore in future studies and consider in the interpretation of the results, given that correct supplement identification may influence the outcomes of a given exercise task and, therefore, lead to bias in the results [58]. Future studies may consider exploring the effectiveness of the blinding to the placebo and sodium bicarbonate conditions and to compare the results between individuals who are able to identify the sodium bicarbonate with those that are not.

4.5 Strengths and limitations

The key strengths of this review are: (a) the use of a broad search syntax; (b) the search for published literature in five bibliographic databases; (c) the comprehensive forward and backward citation tracking; and (d) following a strict protocol for systematic reviews. The main limitation of this review is that, out of the total of 192 participants included in the primary studies, only eight were females. Furthermore, the included studies focused on young individuals, while none of them included older adults. Therefore, future studies in women and/or older adults are warranted. It also needs to be mentioned that there are cases in which isolated sodium ingestion has be reported to be ergogenic for exercise performance [59]. Therefore, to isolate the effects of bicarbonate, some studies use sodium-matched placebos [60]. Out of the 20 studies included in this review, only three [21, 40, 43] matched the sodium content between placebo and sodium bicarbonate conditions. This aspect, therefore, needs to be highlighted as another potential limitation of the review. Finally, in the present review, we were not able to explore the influence of sodium bicarbonate dose on muscular strength and endurance. Out of the 20 included studies, 19 used a dose of 0.3 $g \cdot kg^{-1}$, and only one study used 0.4 $g \cdot kg^{-1}$ (Table 1). Future dose-response studies are needed to explore the minimal effective and optimal doses of sodium bicarbonate.

4.6 Recommendations for future research

The findings presented in this review highlight the potential of sodium bicarbonate to acutely enhance muscular endurance. Given these acute benefits, future long-term studies are needed to explore if chronic supplementation also enhances hallmark adaptations to resistance training, such as hypertrophy and strength. Some studies using long-term sodium bicarbonate supplementation suggest that supplementing with sodium bicarbonate before each training session may enhance endurance training adaptations [61, 62]. Therefore, it is reasonable to speculate that the long-term use of sodium bicarbonate may enhance adaptations during resistance training programs. However, in the only study that examined this in the context of resistance training, 10-weeks of sodium bicarbonate supplementation did not enhance muscular strength adaptations [51]. This study, however, included had a small sample size ($n = 8$) [51]. Future studies with larger sample sizes are needed to explore this topic further.

A relevant outcome that has received relatively little attention in research is the rate of force development (RFD). Currently, only three studies explored the effects of sodium bicarbonate supplementation on RFD [41, 48, 50]. Two studies reported that RFD was not significantly affected by the prior ingestion of sodium bicarbonate, while one study [48] showed that RFD was significantly higher following the ingestion of sodium bicarbonate, as compared to placebo. Given that the RFD is associated with several aspects of athletic performance, future research is needed to explore the effects of sodium bicarbonate on this specific outcome [63].

All included studies employed a standardized supplementation protocol at a uniform timing of ingestion (e.g., all participants took the supplement 90 minutes pre-exercise). However, studies show a wide variation in peak bicarbonate concentration between individuals [22, 56, 64, 65]. Following the ingestion of 0.1, 0.2 and 0.3 $g \cdot kg^{-1}$ of sodium bicarbonate, the participants experienced peak bicarbonate concentration between 30 and 150, 40 and 165, and 75 and 180 minutes [64]. Theoretically, the highest probability of experiencing a performance-enhancing effect following sodium bicarbonate supplementation would be at the moment of peak circulating bicarbonate [22]. Despite this notion, none of the included studies determined individual time-to-peak bicarbonate levels and utilized individual time-to-peak bicarbonate protocols of supplementation [22]. Future studies may consider (a) using individualized time-to-peak protocols when exploring the effects of sodium bicarbonate supplementation on muscular endurance; and (b) comparing the effects of sodium bicarbonate supplementation on muscular qualities at different stages relative to the individually determined peak circulating bicarbonate concentrations. Future research also needs to consider that the time-to-peak blood bicarbonate concentration may vary based on the form of ingestion. For example, time-to-peak concentration was 120 ± 29 min and 72 ± 18 min following the ingestion of sodium bicarbonate as an aqueous solution or in delayed-release capsules, respectively [57].

4.7 Practical implications

Individuals interested in acute enhancement of muscular endurance during resistance exercise may consider supplementing with sodium bicarbonate. Practically speaking, sodium bicarbonate supplementation may lead to a small increase in the number of performed repetitions at a given load or the time to maintain an isometric action at a given percentage of maximum. Sodium bicarbonate may be effective for improvements in muscular endurance of both large and small muscle groups. These findings are based on studies that used 0.3 $g \cdot kg^{-1}$ of sodium bicarbonate ingested between 60 to 180 minutes before exercise. Significant ergogenic effects on muscular endurance were found for ingesting the whole dose of sodium bicarbonate at once and for splitting up the total amount and ingesting it at multiple time points (e.g., 0.1 $g.kg^{-1}$ ingested 90, 60, and 30 min before exercise). Sodium bicarbonate does not seem to be ergogenic for muscular strength and does not appear to be a worthwhile supplementation strategy for athletes competing in sports where strength is an important muscular quality.

5 Conclusions

Our findings indicate that supplementation with sodium bicarbonate acutely improves muscular endurance. The ergogenic effect is moderate and its magnitude does not seem to be dependent on the size of the activated muscles. Improvements in muscular endurance following sodium bicarbonate were found for studies that used one time point of ingestion and for studies that used multiple time points. However, no significant ergogenic effects of sodium bicarbonate supplementation on muscular strength were found, regardless of whether the testing was done in a rested or in a fatigued state. For both muscular strength and muscular endurance, no significant linear trends in the effects of timing of sodium bicarbonate ingestion or acute increase in blood bicarbonate concentrations were found.

Data availability statement

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Notes

Compliance with Ethical Standards

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Conflict of Interest

Jozo Grgic, Ramon F. Rodriguez, Alessandro Garofolini, Bryan Saunders, David J. Bishop, Brad J. Schoenfeld and Zeljko Pedisic have no conflicts of interest that are directly relevant to the content of this article.

Author Contributions

JG conceived the idea for the review. JG and RFR conducted the study selection and data extraction. JG and AG conducted the quality assessment. JG conducted the statistical analyses. JG drafted the initial manuscript. RFR, AG, BS, DJB, BJS, and ZP contributed to writing the manuscript. All authors approved the final version of the manuscript.

References

1. Maughan RJ, Burke LM, Dvorak J, et al. IOC consensus statement: dietary supplements and the high-performance athlete. Br J Sports Med. 2018;52(7):439–55.
2. Carr AJ, Hopkins WG, Gore CJ. Effects of acute alkalosis and acidosis on performance: a meta-analysis. Sports Med. 2011;41(10):801–14.
3. Artioli GG, Gualano B, Coelho DF, et al. Does sodium-bicarbonate ingestion improve simulated judo performance? Int J Sport Nutr Exerc Metab. 2007;17(2):206–17.
4. Lindh AM, Peyrebrune MC, Ingham SA, et al. Sodium bicarbonate improves swimming performance. Int J Sports Med. 2008;29(6):519–23.
5. Siegler JC, Hirscher K. Sodium bicarbonate ingestion and boxing performance. J Strength Cond Res. 2010;24(1):103–8.
6. Lancha Junior AH, Painelli Vde S, Saunders B, et al. Nutritional strategies to modulate intracellular and extracellular buffering capacity during high-intensity exercise. Sports Med. 2015;45(Suppl 1):S71–81.
7. Mainwood GW, Worsley-Brown PA. The effect of extracellular pH and buffer concentration on the efflux of lactate from frog sartorius muscle. J Physiol. 1975;250(1):1–22.
8. Mainwood GW, Cechetto D. The effect of bicarbonate concentration on fatigue and recovery in isolated rat diaphragm muscle. Can J Physiol Pharmacol. 1980;58(6):624–32.
9. Roth D. The sarcolemmal lactate transporter: transmembrane determinants of lactate flux. Med Sci Sports Exerc. 1991;23(8):925–34.
10. Ren JM, Henriksson J, Katz A, et al. NADH content in type I and type II human muscle fibres after dynamic exercise. Biochem J. 1988;251(1):183–7.

11. Bangsbo J, Aagaard T, Olsen M, et al. Lactate and H+ uptake in inactive muscles during intense exercise in man. J Physiol. 1995;488(1):219–29.
12. Carroll TJ, Riek S, Carson RG. Neural adaptations to resistance training: implications for movement control. Sports Med. 2001;31(12):829–40.
13. Kell RT, Bell G, Quinney A. Musculoskeletal fitness, health outcomes and quality of life. Sports Med. 2001;31(12):863–73.
14. Bangsbo J, Johansen L, Graham T, et al. Lactate and H+ effluxes from human skeletal muscles during intense, dynamic exercise. J Physiol. 1993;462:115–33.
15. Requena B, Zabala M, Padial P, et al. Sodium bicarbonate and sodium citrate: ergogenic aids? J Strength Cond Res. 2005;19(1):213–24.
16. Carr BM, Webster MJ, Boyd JC, et al. Sodium bicarbonate supplementation improves hypertrophy-type resistance exercise performance. Eur J Appl Physiol. 2013;113(3):743–52.
17. Coombes J, McNaughton LR. Effects of bicarbonate ingestion on leg strength and power during isokinetic knee flexion and extension. J Strength Cond Res. 1993;7(4):241–49.
18. Siegler JC, Marshall P, Pouslen MK, et al. The effect of pH on fatigue during submaximal isometric contractions of the human calf muscle. Eur J Appl Physiol. 2015;115(3):565–77.
19. Spriet LL, Lindinger MI, Heigenhauser GJ, et al. Effects of alkalosis on skeletal muscle metabolism and performance during exercise. Am J Physiol. 1986;251(5 Pt 2):R833–9.
20. Casarin CAS, Battazza RA, Lamolha MA, et al. Sodium bicarbonate supplementation improves performance in isometric fatigue protocol. Rev Bras Med Esporte. 2019;25(1):40–4.

21. Ansdell P, Dekerle J. Sodium bicarbonate supplementation delays neuromuscular fatigue without changes in performance outcomes during a basketball match simulation protocol. J Strength Cond Res. 2017. doi: 10.1519/JSC.0000000000002233
22. Heibel AB, Perim PHL, Oliveira LF, et al. Time to optimize supplementation: modifying factors influencing the individual responses to extracellular buffering agents. Front Nutr. 2018;5:35.
23. Webster MJ, Webster MN, Crawford RE, et al. Effect of sodium bicarbonate ingestion on exhaustive resistance exercise performance. Med Sci Sports Exerc. 1993;25(8):960–5.
24. Matson LG, Tran ZV. Effects of sodium bicarbonate ingestion on anaerobic performance: a meta-analytic review. Int J Sport Nutr. 1993;3(1):2–28.
25. Lopes-Silva JP, Reale R, Franchini E. Acute and chronic effect of sodium bicarbonate ingestion on Wingate test performance: a systematic review and meta-analysis. J Sports Sci. 2019;37(7):762–771.
26. Lopes-Silva JP, Choo HC, Franchini E, et al. Isolated ingestion of caffeine and sodium bicarbonate on repeated sprint performance: A systematic review and meta-analysis. J Sci Med Sport. 2019;22(8):962–72.
27. Grgic J, Garofolini A, Pickering C, et al. Isolated effects of caffeine and sodium bicarbonate ingestion on performance in the Yo-Yo test: A systematic review and meta-analysis. J Sci Med Sport. 2019. doi: 10.1016/j.jsams.2019.08.016
28. Peart DJ, Siegler JC, Vince RV. Practical recommendations for coaches and athletes: a meta-analysis of sodium bicarbonate use for athletic performance. J Strength Cond Res. 2012;26(7):1975–83.
29. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6(7):e1000097.

30. McNaughton LR, Gough L, Deb S, et al. Recent developments in the use of sodium bicarbonate as an ergogenic aid. Curr Sports Med Rep. 2016;15(4):233–44.
31. Maher CG, Sherrington C, Herbert RD, et al. Reliability of the PEDro scale for rating quality of randomized controlled trials. Phys Ther. 2003;83(8):713–21.
32. Grgic J, Trexler ET, Lazinica B, et al. Effects of caffeine intake on muscle strength and power: a systematic review and meta-analysis. J Int Soc Sports Nutr. 2018;15:11.
33. Grgic J, Pickering C. The effects of caffeine ingestion on isokinetic muscular strength: a meta-analysis. J Sci Med Sport. 2019. 2019;22(3):353–60.
34. Grgic J. Caffeine ingestion enhances Wingate performance: a meta-analysis. Eur J Sport Sci. 2018;18(2):219–25.
35. Borenstein M, Hedges LV, Higgins JP, et al. A basic introduction to fixed-effect and random-effects models for meta-analysis. Res Synth Methods. 2010;1(2):97–111.
36. Higgins JPT, Deeks JJ, Altman DG, on behalf of the Cochrane Statistical Methods Group, editors. Chapter 16.1.3.2. Imputing standard deviations for changes from baseline. In: Higgins JP, Green S, editors. Cochrane handbook for systematic reviews of interventions. Version 5.1.0 (updated March 2011). Cochrane Collaboration, Chichester, UK; 2011.
37. 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(7):1375–87.
38. Sostaric SM, Skinner SL, Brown MJ, et al. Alkalosis increases muscle K+ release, but lowers plasma [K+] and delays fatigue during dynamic forearm exercise. J Physiol. 2006;570(Pt 1):185–205.
39. Balberman SE. The effects of induced alkalosis and acidosis on the work output of the knee extensor and flexor muscle groups [Masters thesis]. The University of Arizona; 1983.

40. Duncan MJ, Weldon A, Price MJ. The effect of sodium bicarbonate ingestion on back squat and bench press exercise to failure. J Strength Cond Res. 2014;28(5):1358–66.
41. Farney TM, MacLellan MJ, Hearon CM, et al. The effect of aspartate and sodium bicarbonate supplementation on muscle contractile properties among trained men. J Strength Cond Res. 2018. doi: 10.1519/JSC.0000000000002692.
42. Hunter AM, De Vito G, Bolger C, et al. The effect of induced alkalosis and submaximal cycling on neuromuscular response during sustained isometric contraction. J Sports Sci. 2009;27(12):1261–9.
43. Materko W, Santos EL, Novaes JDS. Effect of bicarbonate supplementation on muscular strength. J Exerc Physiol Online. 2008;11(6):25–33.
44. Maughan RJ, Leiper JB, Litchfield PE. The effects of induced acidosis and alkalosis on isometric endurance capacity in man. In: Dotson CO, Humphrey JH (eds). Exercise physiology, current selected research, vol. 2. AMS Press, New York; 1986. p. 73–82.
45. Page R, Siegler JC. The effects of sodium bicarbonate ingestion on exhaustive bench press performance. Med Sci Sports Exerc. 2011;43(S5):847–8.
46. Portington KJ, Pascoe DD, Webster MJ, et al. Effect of induced alkalosis on exhaustive leg press performance. Med Sci Sports Exerc. 1998;30(4):523–8.
47. Raymer GH, Marsh GD, Kowalchuk JM, et al. Metabolic effects of induced alkalosis during progressive forearm exercise to fatigue. J Appl Physiol. 2004;96(6):2050–6.
48. Siegler JC, Marshall PW, Raftry S, et al. The differential effect of metabolic alkalosis on maximum force and rate of force development during repeated, high-intensity cycling. J Appl Physiol. 2013;115(11):1634–40.
49. Siegler JC, Marshall P. The effect of metabolic alkalosis on central and peripheral mechanisms associated with exercise-induced muscle fatigue in humans. Exp Physiol. 2015;100(5):519–30.

50. Siegler JC, Mudie K, Marshall P. The influence of sodium bicarbonate on maximal force and rates of force development in the triceps surae and brachii during fatiguing exercise. Exp Physiol. 2016;101(11):1383–91.

51. Siegler JC, Marshall PWM, Finn H, et al. Acute attenuation of fatigue after sodium bicarbonate supplementation does not manifest into greater training adaptations after 10-weeks of resistance training exercise. PLoS One. 2018;13(5):e0196677.

52. McNaughton LR. Sodium bicarbonate ingestion and its effects on anaerobic exercise of various durations. J Sports Sci. 1992;10(5):425–35.

53. Donaldson SK, Hermansen L, Bolles L. Differential, direct effects of H+ on Ca2+-activated force of skinned fibers from the soleus, cardiac and adductor magnus muscles of rabbits. Pflugers Arch. 1978;376(1):55–65.

54. Fabiato A, Fabiato F. Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiac and skeletal muscles. J Physiol. 1978;276:233–55.

55. Carr AJ, Slater GJ, Gore CJ, et al. Effect of sodium bicarbonate on [HCO3-], pH, and gastrointestinal symptoms. Int J Sport Nutr Exerc Metab. 2011;21(3):189–94.

56. Saunders B, Sale C, Harris RC, et al. Sodium bicarbonate and high-intensity cycling capacity: variability in responses. Int J Sports Physiol Perform. 2014;9(4):627–32.

57. Hilton NP, Leach NK, Sparks SA, et al. A novel ingestion strategy for sodium bicarbonate supplementation in a delayed-release form: a randomised crossover study in trained males. Sports Med Open. 2019;5(1):4.

58. Saunders B, de Oliveira LF, da Silva RP, et al. Placebo in sports nutrition: a proof-of-principle study involving caffeine supplementation. Scand J Med Sci Sports. 2017;27(11):1240–47.

59. Mora-Rodriguez R, Hamouti N. Salt and fluid loading: effects on blood volume and exercise performance. Med Sport Sci. 2012;59:113–9.
60. Bishop D, Claudius B. Effects of induced metabolic alkalosis on prolonged intermittent-sprint performance. Med Sci Sports Exerc. 2005;37(5):759–67.
61. Edge J, Bishop D, Goodman C. Effects of chronic NaHCO3 ingestion during interval training on changes to muscle buffer capacity, metabolism, and short-term endurance performance. J Appl Physiol. 2006;101(3):918–25.
62. Bishop DJ, Thomas C, Moore-Morris T, et al. Sodium bicarbonate ingestion prior to training improves mitochondrial adaptations in rats. Am J Physiol Endocrinol Metab. 2010;299(2):E225–33.
63. Tillin NA, Pain MT, Folland J. Explosive force production during isometric squats correlates with athletic performance in rugby union players. J Sports Sci. 2013;31(1):66–76.
64. Jones RL, Stellingwerff T, Artioli GG, et al. Dose-response of sodium bicarbonate ingestion highlights individuality in time course of blood analyte responses. Int J Sport Nutr Exerc Metab. 2016;26(5):445–53.
65. Gough LA, Deb SK, Sparks SA, et al. Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time to peak blood bicarbonate in trained male cyclists. J Sports Sci. 2018;36(15):1705–12.

Figure 1. Flow diagram of the literature search and selection process. After reviewing a total of 1689 search records, 20 studies were included in the review

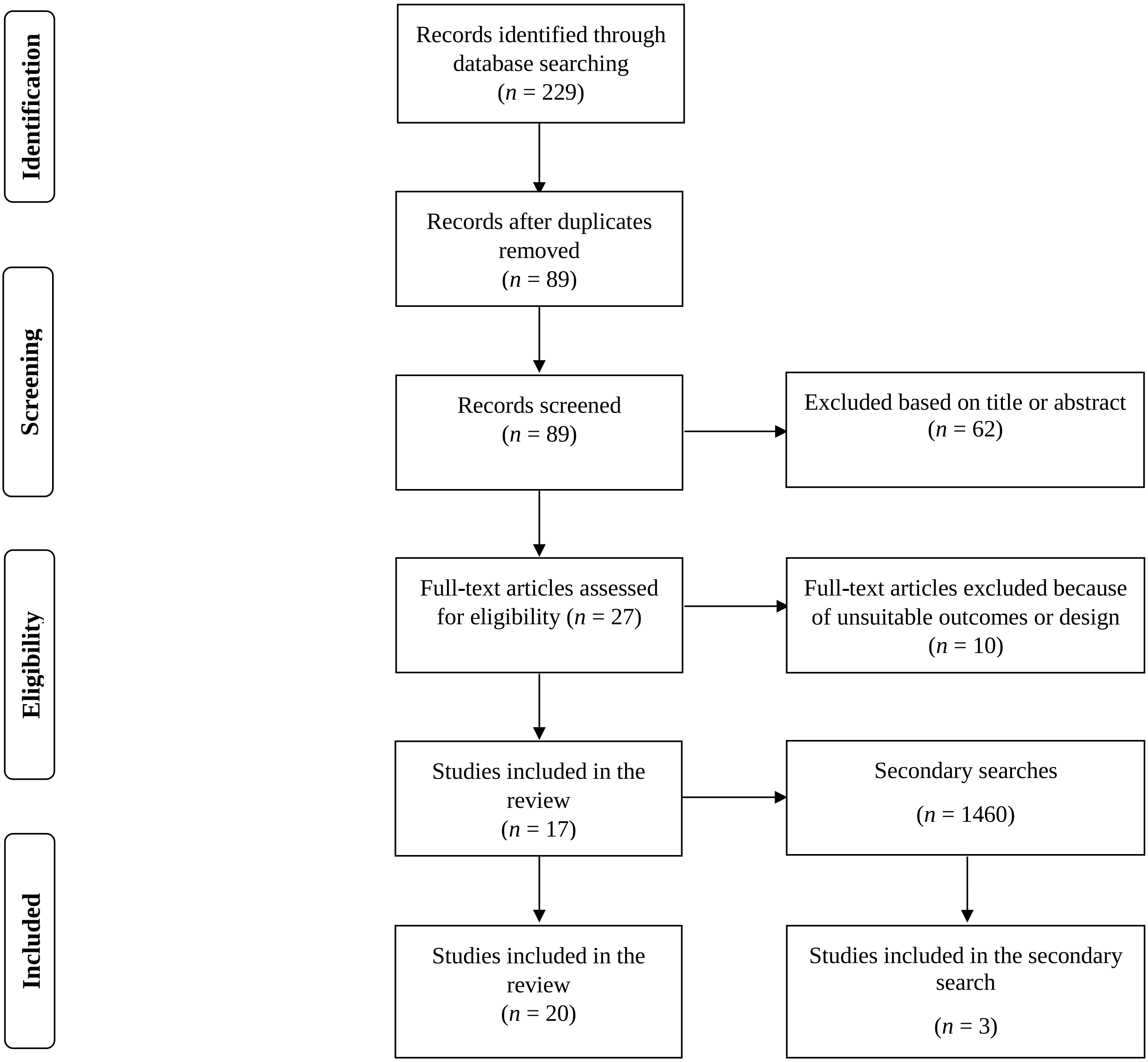

Figure 2. Results of the meta-analysis on the effect of sodium bicarbonate supplementation on muscular endurance. The numbers on the x-axis denote the standardized mean differences (SMD) between the sodium bicarbonate and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI). Upon exclusion of one study that reported a very large effect size, the pooled SMD still remained significant, even though it decreased to 0.20 (95% CI: 0.05, 0.36).

Study	SMD	Lower limit	Upper limit	p-value
Balberman [39]	0.03	-0.22	0.29	0.812
Carr et al. [16]	0.42	0.34	0.51	0.000
Casarin et al. [20]	2.85	2.35	3.35	0.000
Coombes et al. [17]	0.42	0.13	0.71	0.005
Duncan et al. [40]	0.24	-0.02	0.51	0.070
Maughan et al. [44]	0.12	-0.13	0.37	0.343
Portington et al. [46]	-0.03	-0.09	0.03	0.312
Raymer et al. [47]	0.47	0.08	0.85	0.017
Siegler et al. [18]	0.02	-0.28	0.33	0.887
Siegler et al. [51]	0.00	-0.27	0.27	1.000
Sostaric et al. [38]	0.44	0.26	0.61	0.000
Webster et al. [23]	0.15	-0.05	0.34	0.139
Pooled effect	0.37	0.15	0.59	0.001

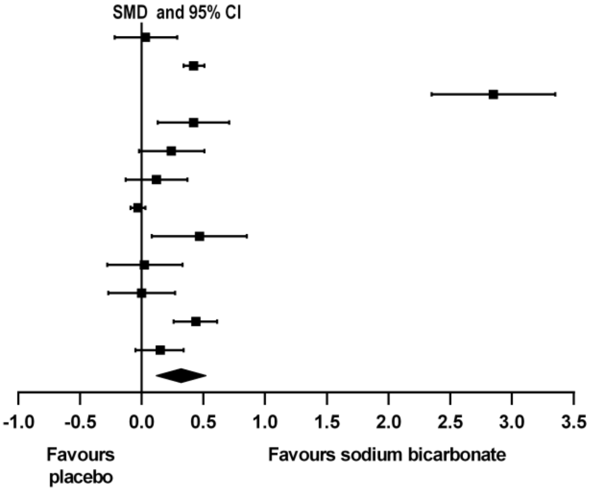

Figure 3. Results of the meta-analysis on the effect of sodium bicarbonate supplementation on muscular strength. The numbers on the *x*-axis denote the standardized mean differences (SMD) between the sodium bicarbonate and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI)

Study	SMD	Lower limit	Upper limit	p-value
Ansdell et al. [21]	0.18	-0.10	0.46	0.203
Casarin et al. [20]	0.00	-0.20	0.20	1.000
Coombes et al. [17]	0.43	0.14	0.72	0.004
Farney et al. [41]	-0.14	-0.37	0.09	0.237
Hunter et al. [42]	-1.17	-1.61	-0.73	0.000
Materko et al. [43]	0.00	-0.20	0.20	1.000
Maughan et al. [44]	-0.04	-0.28	0.20	0.744
Siegler et al. [48]	0.01	-0.25	0.27	0.939
Siegler and Marshall [49]	0.00	-0.23	0.23	1.000
Siegler et al. [18]	0.17	-0.11	0.45	0.229
Siegler et al. [50]	-0.07	-0.27	0.13	0.484
Pooled effect	-0.03	-0.18	0.12	0.725

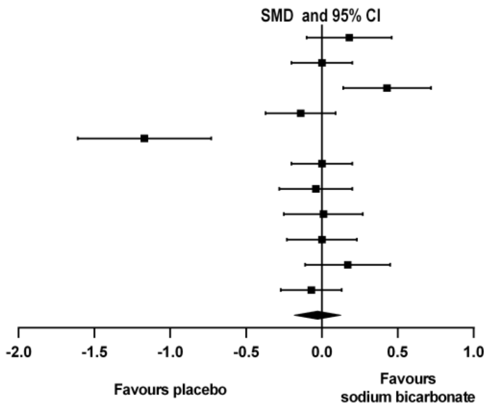

Table 1. Summary of the included studies that explored the effects of sodium bicarbonate supplementation on muscular strength and/or endurance

Reference; study design	**Study sample and supplement protocol**	**Performance assessment**	**Changes in pH and blood bicarbonate**	**Reported side-effects**
Ansdell et al. [21]; RDB	10 male basketball players ingested a dose of 0.4 g/kg 90 to 60 minutes pre-exercise in liquid form	Knee extension MVC before a basketball game, and after each quarter	Not assessed	None reported
Balberman [39]; RDB	10 male university students ingested a dose of 0.3 g/kg 180 minutes pre-exercise in capsule form	Isokinetic knee flexion and extension total work	**pH** *Pre-supplementation* Placebo: 7.44 ± 0.02 Sodium bicarbonate: 7.44 ± 0.02 *Pre-exercise* Placebo: 7.45 ± 0.02 Sodium bicarbonate: 7.51 ± 0.02	"Many of the subjects suffered from diarrhea"
Carr et al. [16]; RDB	12 resistance-trained men ingested a dose of 0.3 g/kg 80 to 50 minutes pre-exercise in capsule form	4 sets of squat, leg press, and leg extension exercise performed to muscle failure; 1 additional sets of leg extensions performed to muscle failure with lower loads	**pH** *Pre-supplementation* Placebo: 7.42 ± 0.02 Sodium bicarbonate: 7.43 ± 0.02 *Pre-exercise* Placebo: 7.42 ± 0.02 Sodium bicarbonate: 7.49 ± 0.02 **Bicarbonate** *Pre-supplementation* Placebo: 25.7 ± 2.3 Sodium bicarbonate: 26.2 ± 2.1 *Pre-exercise* Placebo: 25.4 ± 1.8 Sodium bicarbonate: 31.5 ± 2.6	Lightheadedness and eructation in one participant
Casarin et al. [20]; RDB	12 resistance-trained men ingested a dose of 0.3 g/kg 60 minutes pre-exercise in capsule form	Knee extension MVC and time to maintain 50% above MVC	**pH** *Pre-exercise* Placebo: 7.40 ± 0.02	None reported

			Sodium bicarbonate: 7.60 ± 0.02	
Coombes et al. [17]; RDB	9 male physical education students ingested a dose of 0.3 g/kg 90 minutes pre-exercise in liquid form	Isokinetic knee flexion and extension peak torque and total work	**pH** *Pre-supplementation* Placebo: 7.33 ± 0.04 Sodium bicarbonate: 7.33 ± 0.03 *Pre-exercise* Placebo: 7.33 ± 0.06 Sodium bicarbonate: 7.39 ± 0.04 **Bicarbonate** *Pre-supplementation* Placebo: 23.8 ± 1.8 Sodium bicarbonate: 25.9 ± 2.5 *Pre-exercise* Placebo: 26.7 ± 2.1 Sodium bicarbonate: 32.3 ± 4.0	None reported
Duncan et al. [40]; RDB	8 resistance-trained men ingested a dose of 0.3 g/kg 60 minutes pre-exercise in liquid form	3 sets of squat and bench press at 80% 1RM performed to muscle failure	**pH** *Pre-supplementation* Placebo: 7.4 ± 0.01 Sodium bicarbonate: 7.4 ± 0.01 *Pre-exercise* Placebo: 7.4 ± 0.03 Sodium bicarbonate: 7.4 ± 0.01 **Bicarbonate** *Pre-supplementation* Placebo: 25.5 ± 1.1 Sodium bicarbonate: 24.6 ± 1.6 *Pre-exercise* Placebo: 23.1 ± 4.8 Sodium bicarbonate: 30.6 ± 2.5	Gastrointestinal distress in three participants

Farney et al. [41]; RSB	11 recreationally active men ingested a dose of 0.3 g/kg 60 minutes pre-exercise in liquid form	Isometric mid-thigh pull test	Not assessed	Gastrointestinal track complications in one participant
Hunter et al. [42]; DB	8 male triathletes ingested a dose of 0.3 g/kg 180 minutes pre-exercise in capsule form	Knee extension MVC	**pH** *Pre-supplementation* Placebo: 7.43 ± 0.03 Sodium bicarbonate: 7. 43 ± 0.03 *Pre-exercise* Placebo: 7.43 ± 0.02 Sodium bicarbonate: 7.48 ± 0.04 **Bicarbonate** *Pre-supplementation* Placebo: 25.0 Sodium bicarbonate: 26.0 *Pre-exercise* Placebo: 26.0 Sodium bicarbonate: 29.6	None reported
Materko et al. [43]; RDB	11 resistance-trained men ingested a dose of 0.3 g/kg 120 minutes pre-exercise in liquid form	10RM bench press and pull press	Not assessed	None reported
Maughan et al. [44]; RDB	10 untrained men ingested a dose of 0.3 g/kg 150 minutes pre-exercise (at 15 minutes intervals) in capsule form	MVC and time to maintain MVC at 20%, 50%, and 80% of MVC	**pH** *Pre-supplementation* Placebo: 7.38 ± 0.03 Sodium bicarbonate: 7.39 ± 0.03 *Pre-exercise* Placebo: 7.39 ± 0.02 Sodium bicarbonate: 7.42 ± 0.04 **Bicarbonate** *Pre-supplementation* Placebo: 24.1 ± 2.7 Sodium bicarbonate: 24.1 ± 2.1 *Pre-exercise*	Minor gastrointestinal distress

			Placebo: 24.9 ± 2.2 Sodium bicarbonate: 27.0 ± 3.3	
Page et al. [45]; RSB[a]	8 resistance-trained men ingested a dose of 0.3 g/kg 120 minutes pre-exercise in capsule form	3 sets of bench press performed to muscle failure	Not reported	None reported
Portington et al. [46]; RDB	15 resistance-trained men ingested a dose of 0.3 g/kg 105 minutes pre-exercise in capsule form	5 sets of leg press performed to muscle failure	**pH** *Pre-supplementation* Placebo: 7.40 Sodium bicarbonate: 7.40 *Pre-exercise* Placebo: 7.40 Sodium bicarbonate: 7.48 **Bicarbonate** *Pre-supplementation* Placebo: 23.0 Sodium bicarbonate: 22.8 *Pre-exercise* Placebo: 22.9 Sodium bicarbonate: 27.9	Slight gastrointestinal distress in four participants
Raymer et al. [47][b]	6 recreationally active men ingested a dose of 0.3 g/kg 90 minutes pre-exercise in capsule form	Wrist flexion to muscle failure	**pH** *Pre-exercise* Placebo: 7.43 ± 0.01 Sodium bicarbonate: 7.48 ± 0.01 **Bicarbonate** *Pre-exercise* Placebo: 31.9 ± 2.6 Sodium bicarbonate: 39.0 ± 2.5	None reported
Siegler et al. [48]; RDB	8 recreationally active men and 2 recreationally active women ingested a dose of 0.3 g/kg 90 to 30 minutes pre-exercise in capsule form	Knee extension MVC pre-exercise as well as between cycling tasks	**pH** *Pre-supplementation* Placebo: 7.38 ± 0.04 Sodium bicarbonate: 7.40 ± 0.01 *Pre-exercise*	None reported

			Placebo: 7.37 ± 0.04 Sodium bicarbonate: 7.46 ± 0.03 **Bicarbonate** *Pre-supplementation* Placebo: 23.4 ± 2.0 Sodium bicarbonate: 24.6 ± 1.1 *Pre-exercise* Placebo: 22.8.6 ± 1.8 Sodium bicarbonate: 29.4 ± 2.3	
Siegler and Marshall [49]; RDB	11 recreationally active men ingested a dose of 0.3 g/kg 90 to 30 minutes pre-exercise in capsule form	Knee extension MVC with and without cuffs	**pH** *Pre-supplementation* Placebo: 7.40 ± 0.01 Sodium bicarbonate: 7.40 ± 0.02 *Pre-exercise* Placebo: 7.42 ± 0.02 Sodium bicarbonate: 7.47 ± 0.03 **Bicarbonate** *Pre-supplementation* Placebo: 24.3 ± 1.0 Sodium bicarbonate: 24.6 ± 0.7 *Pre-exercise* Placebo: 24.9 ± 1.0 Sodium bicarbonate: 28.8 ± 1.9	None reported
Siegler et al. [18]; RDB	8 recreationally active men ingested a dose of 0.3 g/kg taken at 90 to 30 minutes pre-exercise in capsule form	Plantar flexion MVC (pre-exercise and after each minute during the 5 minutes of exercise) and time to maintain MVC	**pH** *Pre-supplementation* Placebo: 7.41 ± 0.02 Sodium bicarbonate: 7.39 ± 0.03 *Pre-exercise* Placebo: 7.41 ± 0.04 Sodium bicarbonate: 7.46 ± 0.03 **Bicarbonate** *Pre-supplementation*	None reported

			Placebo: 24.8 ± 1.2 Sodium bicarbonate: 24.0 ± 1.5 *Pre-exercise* Placebo: 25.4 ± 2.4 Sodium bicarbonate: 28.9 ± 2.3	
Siegler et al. [50]; RDB	10 resistance-trained men ingested a dose of 0.3 g/kg 90 to 30 minutes pre-exercise in capsule form	Plantar flexion and elbow extension and MVC	**pH (triceps surae)** *Pre-exercise* Placebo: 7.42 ± 0.02 Sodium bicarbonate: 7.48 ± 0.02 **Bicarbonate (triceps surae)** *Pre-exercise* Placebo: 25.8 ± 1.5 Sodium bicarbonate: 30.5 ± 1.3 **pH (triceps brachii)** *Pre-exercise* Placebo: 7.42 ± 0.3 Sodium bicarbonate: 7.48 ± 0.2 **Bicarbonate (triceps brachii)** *Pre-exercise* Placebo: 25.7 ± 1.8 Sodium bicarbonate: 30.2 ± 1.9	Not explored
Siegler et al. [51]; RDB	6 resistance-trained men and 2 resistance-trained women ingested a dose of 0.3 g/kg 90 to 30 minutes pre-exercise in capsule form	5 sets of leg extensions performed to muscle failure and knee extension MVC	**pH** *Pre-exercise* Placebo: 7.42 ± 0.02 Sodium bicarbonate: 7.46 ± 0.02 **Bicarbonate** *Pre-exercise* Placebo: 24.9 ± 1.0 Sodium bicarbonate: 28.1 ± 1.1	None reported
Sostaric et al. [38]; RDB	5 untrained men and 4 untrained women ingested a dose of 0.3 g/kg in	Finger flexions performed to muscle failure	**Bicarbonate** *Pre-exercise* Placebo: 27.4 ± 1.0	None reported

	5 intervals starting at 180 minutes pre-exercise in capsule form		Sodium bicarbonate: 31.0 ± 1.0	
Webster et al. [23][b]	6 resistance-trained men ingested a dose of 0.3 g/kg 105 minutes pre-exercise in capsule form	1 set of leg press performed to muscle failure	**pH** *Pre-supplementation* Placebo: 7.40 ± 0.02 Sodium bicarbonate: 7.39 ± 0.02 *Pre-exercise* Placebo: 7.39 ± 0.02 Sodium bicarbonate: 7.46 ± 0.02 **Bicarbonate** *Pre-supplementation* Placebo: 23.8 Sodium bicarbonate: 22.9 *Pre-exercise* Placebo: 22.7 ± 1.0 Sodium bicarbonate: 27.2 ± 1.3	"Upset stomach" after the testing in one participants

MVC: maximal voluntary contraction; RM: repetition maximum; RDB: randomized double-blind; RSB: randomized single-blind; DB: double-blind

[a]this study was not included in the meta-analysis due to the lack of reported data

[b]crossover study without any blinding

Table 2. Results of the methodological quality assessment using the Physiotherapy Evidence-Based Database (PEDro) scale. All but one study had a score of ≥7 which indicates good to excellent quality

Reference	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Summary score
Ansdell et al. [21]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Balberman [39]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Carr et al. [16]	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Casarin et al. [20]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Coombes et al. [17]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Duncan et al. [40]	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Farney et al. [41]	Yes	Yes	Unclear	Yes	Yes	No	No	Yes	Yes	Yes	Yes	7
Hunter et al. [42]	No	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	8
Materko et al. [43]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Maughan et al. [44]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Page et al. [45]	No	Yes	Unclear	Yes	Yes	No	No	Yes	Yes	Yes	Yes	7
Portington et al. [46]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Raymer et al. [47]	No	Unclear	Unclear	Yes	Unclear	Unclear	Unclear	Yes	Yes	Yes	Yes	5
Siegler et al. [48] 2013	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Siegler and Marshall [49] 2015	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Siegler et al. [18] 2015	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Siegler et al. [50] 2016	No	Yes	Unclear	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	8
Siegler et al. [51] 2018	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Sostaric et al. [38]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Webster et al. [23]	No	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9

Yes: criterion is satisfied; No: criterion is not satisfied; Unclear: unable to rate