BRIEF REVIEW

PRACTICAL RECOMMENDATIONS FOR COACHES AND ATHLETES: A META-ANALYSIS OF SODIUM BICARBONATE USE FOR ATHLETIC PERFORMANCE

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ABSTRACT

Peart, DJ, Siegler, JC, and Vince, RV. Practical recommendations for coaches and athletes: A meta-analysis of sodium bicarbonate use for athletic performance. *J Strength Cond Res* 26(7): 1975–1983, 2012—Sodium bicarbonate ($NaHCO_3$) is a buffering agent that is suggested to improve performance by promoting the efflux of hydrogen ions from working cells and tissues. Research surrounding its efficacy as an ergogenic aid is conflicting, making it difficult to draw conclusions as to its effectiveness for training and competition. This study performed a meta-analysis of relevant research articles to allow the development of concise practical recommendations for coaches and athletes. The overall effect size for the influence of $NaHCO_3$ on performance was moderate, and was significantly lower for specifically trained as opposed to recreationally trained participants.

KEY WORDS buffering, alkalosis, ergogenic aid, nutrition

INTRODUCTION

The use of ergogenic aids to improve performance is widespread (10,54,69), though their use is only recommended after a careful cost-benefit analysis (45). Alkalizing substances have been researched extensively for their potential to improve performance by minimizing the extent of metabolic acidosis, a contributor to fatigue during high-intensity exercise. One such agent that has attracted a wealth of attention is sodium bicarbonate ($NaHCO_3$), which has been featured in the literature since as early as the 1930s (17) and regularly since the 1970s. The ingestion of $NaHCO_3$ increases the level of bicarbonate (HCO_3^-) in the blood, a natural buffer that works by accepting a proton to form carbonic acid:

$$H^+ + HCO_3^- \leftrightarrow H_2CO_3 \leftrightarrow CO_2 + H_2O$$

The additional HCO_3^- promotes a greater extracellular efflux of H^+ and lactate, as demonstrated by a commonly reported higher blood lactate after exercise with $NaHCO_3$ ingestion (74,86,95). Although there is a large body of evidence to support the use of $NaHCO_3$ for sports performance, its use has been associated with possible gastrointestinal side effects (11). There is also conflicting research challenging its efficacy as an ergogenic aid, as highlighted in a number of review articles (9,52,65,71). Such reviews are essential because they summarize existing research and allow recommendations for evidence-based practice. However, the conclusions from review articles are susceptible to the opinions of the authors, because no statistical methods are used to support the arguments presented. A meta-analysis from almost 2 decades ago (43) reported only a moderate overall effect size (ES) for the effect of $NaHCO_3$ on anaerobic performance. The analytical methods of this review allow a greater insight into the efficacy of $NaHCO_3$ for sport performance; however, it was limited to the research of the time because there were few studies using trained subjects and no studies implementing prolonged protocols. There has since been a wealth of research articles on this topic, and therefore, a more up-to-date meta-analysis is needed to inform coaches, nutritionists, and athletes alike. The purpose of this study is to perform a meta-analysis to include more contemporary research. This will assist in the quantification of the efficacy of $NaHCO_3$ ingestion for sports performance and provide practitioners a tool for the implementation of an effective cost-benefit analysis, that is, ergogenic potential vs. possible gastrointestinal distress.

METHODS

Data Sources

A computer search for relevant peer-reviewed articles (excluding abstracts and unpublished theses and dissertations) was performed in January 2012 by entering various combinations of the following key words into PubMed, SPORTDiscus and Google Scholar; 'sodium bicarbonate,' 'bicarbonate ingestion,' 'preexercise alkalosis,' 'ergogenic aids,' 'induced alkalosis,' 'acid-base balance,' 'sport nutrition,' 'sport performance,' 'sport,' and 'exercise.' A manual

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TABLE 1. Summary of research articles used for analysis (chronological order).*

Study	Subjects	Exercise	Effect size	Ergogenic effect? (Y/N)
Wilkes et al. (92)	6 Trained male runners	800-m Run	PT = 0.46	Y
Katz et al. (32)	8 Male participants	Ride to exhaustion at 125% max	TEX = 0.35	N
Parry-Billings and MacLaren (55)	6 Male participants	3 × 30-s Wingate tests separated by 6 min	AP = 0.09†	N
			PP = 0.15†	N
Robertson et al. (68)	10 Male participants	Arm ergometry 80% max	TW = 0.96	Y
		Cycle ergometry 80% max	TW = 0.94	Y
		Arm and cycle ergometry 80% max	TW = 1.67	Y
Goldfinch et al. (22)	6 Male participants	400-m Run	PT = 0.75	Y
Brien and McKenzie (8)	6 Trained male rowers	6-min Rowing; 4-min 80% max and 2-min all-out	TW = −0.05	N
Iwaoka et al. (28)	6 Male participants	Ride to exhaustion at 95% max	TEX = 2.23	Y
Lavender and Bird (37)	8 Female and 15 male participants	10 × 10-s cycle sprints with 50-s recovery	PP = 0.06†	Y
Linderman et al. (38)	8 Male trained cyclists	Cycle to exhaustion at 70 rpm, 100% max	TEX = 0.15	N
McNaughton (50)	9 Male participants	1. 60-s Cycle ergometry (200 mg)	TW = 1.21	N
			PP = 0.11	N
		2. 60-s Cycle ergometry (300 mg)	TW = 2.10	Y
			PP = 0.94	Y
		3. 60-s Cycle ergometry (400 mg)	TW = 2.03	Y
			PP = 0.39	Y
Coombes and McNaughton (15)	9 Male participants	Isokinetic leg press exercise	TW = 0.47	Y
Webster et al. (89)	6 Trained male participants	Leg-press exercise to fatigue	FREQ = 0.52	N
Bird et al. (4)	10 Male runners	1,500-m Run	PT = 0.24	Y
Potteiger et al. (58)	7 Trained male participants	Treadmill run; 30-min at LT followed by time to exhaustion at 110% LT	TEX = 0.62	N
Portington et al. (57)	15 Male participants	5 Sets of maximal leg press performance	FREQ = −0.05	N
McNaughton et al. (49)	10 Trained male cyclists	60-min Cycling time trial	AP = 1.28	Y
			PP = 0.04	N
Aschenbach et al. (2)	8 Male wrestlers	8 × 15-s Maximal arm ergometry separated by 20-s active recovery	TW = −0.2	N
Stephens et al. (78)	6 Trained male cyclists	60-min Cycling; 30-min 80% max and 30-min performance trial	PT = 0.15	N
Price et al. (60)	8 Male participants	30-min Intermittent cycling	TW = 0.11	N
Bishop et al. (6)	10 Active female participants	5 × 6-s Cycle sprints with 30-s recovery	TW = 0.27	Y
Raymer et al. (63)	6 Moderately active male participants	Ramped forearm resistance training	TEX = 0.79	Y
			PP = 0.9	Y
Bishop and Claudius (5)	7 Female team sports players	Intermittent cycle test to mimic demands of field hockey	TW = 0.13†	N
Robergs et al. (66)	12 Male cyclists	Cycling at 110% PPO until fatigue	TEX = −0.03	N
Artioli et al. (1)	23 Trained judo competitors	1. Judo specific test	FREQ = 1.18	Y

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		2. Upper limb Wingate test	AP = 0.55†	Y
			PP = 0.43†	Y
Lindh et al. (39)	9 Trained male swimmers	200-m Freestyle swim	PT = 0.05	Y
Materko et al. (42)	11 Experienced male participants	1. 10 Repetition max bench press	PP = −0.02‡	N
		2. 10 Repetition max pull press	PP = 0.05‡	N
Pruscino et al. (62)	6 Trained male swimmers	2 × 200-m Freestyle swim	PT = 0.34†	N
Siegler et al. (74)	9 Male participants	Cycling at 120% PPO until fatigue	TEX = 0.09	N
Zabala et al. (95)	9 Trained male cyclists	3 × 30-s Wingate tests separated by 30 min	AP = −0.06	N
			PP = −0.03	N
Cameron et al. (11)	25 Trained male rugby players	Rugby-specific training and rugby-specific repeated-sprint test	PT = 0.25	N
Price and Simons (61)	8 Male participants	20 × 24-s Runs at 100% v-$\dot{V}O_2$; O_2max followed by 120% v-$\dot{V}O_2$; O_2max to fatigue	TEX = 0.14	N
Siegler et al. (75)	9 Male participants	1. 3 × 30-s Sprints separated by 3-min active recovery	TW = 0.12§	N
		2. 3 × 30-s Sprints separated by 3-min passive recovery	TW = 0.18§	N
Siegler and Gleadall-Siddall (72)	6 Male and 8 female swimmers	8 × 25-m Front crawl sprints	PT = 0.15	Y
Siegler and Hirscher (73)	10 Trained male boxers	4 × 3-min Rounds of sparring	FREQ = 0.44†	Y
Tan et al. (83)	12 Trained female water-polo players	Simulated water-polo match	PT = −0.11	N
Vanhatalo et al. (86)	8 Active male participants	3-min All-out cycling	TW = −0.01	N
Carr et al. (12)	6 Male and 2 female trained rowers	2,000-m Rowing ergometry	PT = −0.05	N
			AP = 0.07	N
Joyce et al. (30)	8 Trained male swimmers	200-m Swim	PT = 0.17	N
Zabala et al. (94)	10 Trained male cyclists	3 × 30-s Wingate tests separated by 15 min	AP = −0.07	N
			PP = −0.06	N
Kupcis et al. (36)	7 Trained male rowers	2,000-m Rowing ergometry	PT = 0.07	N

*PP = peak power; AP = average power; PT = performance time; TW = total work; TEX = time to exhaustion; FREQ = frequency; LT = lactate threshold; PPO = peak power output; $\dot{V}O_2$max = velocity at $\dot{V}O_2$max.

†Signifies that a grand mean and pooled *SD* were used to calculate the effect size.

‡Categorized as PP to allow comparison.

§Categorized as TW to allow comparison.

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cross-reference of relevant articles and review articles was also performed (9,52,65,71).

Inclusion Criteria and Excluded Studies

The retrieved articles were then selected for the meta-analysis according to the following inclusion criteria: (a) An acute dosage employed of 0.2–0.4 $g \cdot kg^{-1} \cdot body\ weight^{-1}$ 60–120 minutes before exercise. This was chosen to take into account recommendations from recent research examining ingestion protocols (13,64,76). (b) Placebo-controlled, randomized, blinded, and repeated measures design. (c) Relevant raw data provided, that is, performance means and *SD*s. If the required raw data were not available in the article, then an attempt was made to contact the authors. (d) Human participants. (e) The main aim of the research was to examine the influence of $NaHCO_3$ on performance. This was to assist clarity and allow recommendations to be made for performance. (f) Substance not combined with any other nutritional product and ergogenic aid.

All the studies that met these criteria are summarized in Table 1. The following studies were consequently excluded: (3,7,14,16–18,20,21,23–27,29,33–35,40,41,44,46,48,51,53,56,59,70,77,79,80,84,85,87,88,91,93,96) because they did not meet the inclusion criteria.

Coding and Classification of Variables

The articles selected that met the inclusion criteria were coded so as to categorize into the following characteristics: (a) *Exercise type:* Defined as either a single bout of exercise or a repeated bout exercise (e.g., repeated-sprints and sport-specific simulations). (b) *Performance measure:* Time to exhaustion, average and peak power, performance time, total work and distance completed and frequency of events. (c) *Approximate exercise time:* In studies employing a period of submaximal exercise before performance trial, only the performance aspect was counted. Recovery periods in repeated-sprint protocols were not included, and if a grand mean was calculated for repeated sprints, then the duration of 1 sprint and repetition was counted (see statistical analysis). (d) *Training status of the participants:* A trained participant refers to an athlete whose training plan is relevant for the respective exercise task, for example, Wilkes et al. (92) observing runners perform/compete in an 800-m race and Zabala et al. (94) observing BMX cyclists. Those participants described as healthy, active, and recreationally trained were classified as untrained. No sedentary participants were included. (e) *Induced alkalosis:* Calculated as the change in blood pH preingestion-postingestion in the experimental trial. To ensure consistency, only capillary blood results were analyzed because these were most common. (f) *Induced acidosis:* Calculated as the change in blood pH preexercise-postexercise in the placebo trial. To ensure consistency, only capillary blood results were analyzed because these were most common.

Statistical Analyses

The effectiveness of the $NaHCO_3$ supplementation was quantified by determining the ES for each variable, which can be categorized as small (0.2), moderate (0.5), or high (0.8). This was calculated using the following equation:

$$\mathrm{ES} = (\text{Mean of } \mathrm{NaHCO_3} - \text{Mean of placebo}) \div \textit{SD of placebo}.$$

This equation was reversed in the case of those studies employing performance time as the performance measure, as a lower number would be considered beneficial. An ES for studies using repeated-sprint protocols was calculated from the total work/distance completed in all of the sprints. When these data were not available, a grand mean and pooled *SD* from the sprints was calculated. A weighted ES was then calculated to account for changes in individual sample sizes as described in Matson and Tran (43):

$$\text{Weighted ES} = \sum[(\mathrm{ES})(n)] \div \sum n.$$

The effect of training status, ingestion type, and exercise type on the ES were analyzed using a Mann-Whitney *U* test, and exercise duration using the Kruskal-Wallis test as the analysis of *Z*-scores demonstrated an absence of normal distribution. Differences between performance measures were analyzed using a 1-way analysis of variance. Pearson correlation coefficients were used to analyze the nature and magnitude of relationships between variables. No statistics were employed when observing the differences between trained and untrained subjects in each performance measure and exercise duration category because of the varied data sets available.

Results

There were 40 research articles that met the inclusion criteria for the meta-analysis, allowing the analysis of

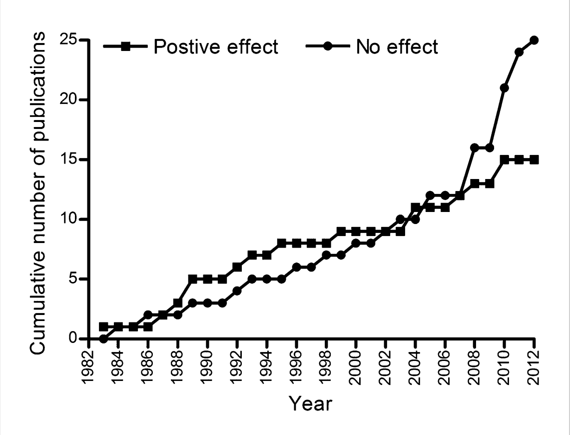

Figure 1. The publication rate of included studies reporting an ergogenic and no ergogenic effect of $NaHCO_3$.

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58 ESs from 395 participants (348 men and 47 women). Of the articles included, 15 (38%) reported an ergogenic benefit. A tracking of positive and no effect publications by year is presented in Figure 1, with only those studies selected for inclusion in the meta-analysis shown to allow comparison within similar ingestion protocols. The summary of all the ESs is available in Table 2. The overall ES for the influence of $NaHCO_3$ on performance regardless of performance measure, duration, and training status was 0.41 (weighted mean = 0.36). The overall ES was significantly higher in untrained participants compared with trained participants ($p = 0.007$), and higher in single bout as opposed to repeated bout exercises ($p = 0.013$). The ES was higher in studies administering $NaHCO_3$ as a liquid solution as opposed to capsules but not significantly so ($p = 0.457$).

Exercise protocols employing a time to exhaustion or total work performance measure resulted in a much higher ES than the overall ES (0.60 and 0.63, respectively). The time to exhaustion ES however was lowered when the weighted mean is observed (0.50). In contrast, those studies using performance time or power as a performance measure resulted

Table 2. Summary of ES sizes.*

		ES			
Measure (subject numbers)	No. of ES	Mean	*SD*	95% CI	Weighted mean ES
Overall (395)	58	0.41	0.59	0.25, 0.56	0.36
Trained (248)	32	0.20	0.36	0.13, 0.33	0.18
Untrained (147)	26	0.65	0.72	0.36, 0.95	0.59
Liquid solution (242)	37	0.46	0.61	0.25, 0.66	0.41
Trained (122)	15	0.22	0.45	−0.03, 0.47	0.17
Untrained (120)	22	0.62	0.66	0.32, 0.91	0.61
Capsule ingestion (144)	21	0.32	0.56	0.06, 0.57	0.25
Trained (117)	17	0.19	0.26	0.06, 0.32	0.20
Untrained (27)	4	0.86	1.11	−0.92, 2.63	0.49
Single bout (221)	38	0.54	0.66	0.32, 0.75	0.52
Trained (111)	16	0.23	0.38	0.26, 0.43	0.23
Untrained (110)	22	0.76	0.73	0.44, 1.09	0.71
Repeated bout (174)	20	0.16	0.32	0.01, 0.30	0.13
Trained (137)	16	0.18	0.35	−0.01, 0.37	0.15
Untrained (37)	4	0.05	0.11	−0.12, 0.22	0.05
Time to exhaustion (71)	9	0.60	0.71	0.05, 1.15	0.50
Trained (27)	3	0.25	0.33	−0.58, 1.07	0.19
Untrained (44)	6	0.78	0.81	−0.07, 1.63	0.69
Total work (84)	16	0.63	0.77	0.22, 1.04	0.68
Trained (31)	4	0.04	0.20	−0.18, 0.25	0.05
Untrained (53)	12	0.82	0.79	0.32, 1.32	0.86
Performance time (117)	12	0.17	0.30	−0.02, 0.36	0.09
Trained (111)	11	0.12	0.25	−0.05, 0.29	0.05
Untrained (6)	1	0.75	N/A	N/A	N/A
Power (106)	18	0.27	0.40	0.07, 0.47	0.25
Trained (62)	11	0.20	0.41	−0.08, 0.48	0.22
Untrained (44)	7	0.38	0.36	0.04, 0.71	0.31
Frequency (40)	4	0.41	0.69	−0.69, 1.51	0.26
Trained (25)	3	0.71	0.41	−0.29, 1.72	0.72
Untrained (15)	1	−0.5	N/A	N/A	N/A
Short, ≤2 min (179)	27	0.51	1.14	0.05, 0.96	0.45
Trained (111)	13	0.07	0.10	0.01, 0.14	0.08
Untrained (68)	14	0.91	1.50	0.04, 1.77	0.87
Medium, 2–10 min (120)	15	0.40	0.60	0.06, 0.73	0.34
Trained (97)	12	0.30	0.34	0.08, 0.52	0.29
Untrained (23)	3	0.77	1.26	−2.37, 3.91	0.61
Long, ≥10 min (45)	8	0.42	0.50	−0.02, 0.85	0.42
Trained (23)	4	0.40	0.59	−0.53, 1.34	0.46
Untrained (22)	4	0.43	0.49	−0.47, 1.33	0.37

*ES = effect size.

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in much lower ESs of 0.17 and 0.27, respectively, with performance time reducing to 0.09 after weighting. Despite this, there were no significant differences in ESs between performance measures ($F = 2.03, p = 0.12$). None of the differences between exercise duration were significant ($p = 0.501$).

There was a moderate but significant overall relationship between ES and the state of induced alkalosis ($n = 27$, $r = 0.45$, $p = 0.02$), and this relationship was stronger in trained than in untrained participants ($n = 15$, $r = 0.56$, $p = 0.03$ and $n = 12$, $r = 0.50$, $p = 0.10$, respectively). The overall relationship between ES and the state of induced acidosis was weak and insignificant ($n = 24$, $r = 0.25$, $p = 0.237$).

DISCUSSION

A moderate overall weighted ES for the impact of $NaHCO_3$ on performance was calculated (0.36), lower than that reported by Matson and Tran in 1993 (0.44). This is possibly because of the increased number of publications challenging its efficacy as an ergogenic aid in recent years (Figure 1). Another explanation for this may be the greater number of trained participants in this review as a significantly lower ES was observed for this group. This finding is in contrast to previous opinion, with Webster et al. (89) claiming that the use of trained subjects was a factor consistently associated with improved performance with $NaHCO_3$. Requena et al. (65) supported this suggestion claiming that more highly trained subjects have a higher maximal rate of anaerobic glycolysis, allowing alkaline treatment to have a more significant effect. It may instead be the case that training adaptations such as increased density of monocarboxylate transporter proteins (31) and improved muscle buffering capacity (19,90) are more effective than $NaHCO_3$ administration for trained athletes, whereas their lesser trained counterparts are more reliant on the extra buffering capacity afforded by the $NaHCO_3$. This is supported by the relationship observed between induced alkalosis and ES, as the correlation was statistically significant in trained but not untrained participants, suggesting that only greater inductions of alkalosis has the potential to influence performance in trained individuals as Zabala et al. suggested recently (94). It must be considered that these relationships are limited to the studies included in the meta-analysis and of capillary blood and also that a significant correlation does not represent causation.

A number of research articles have reported ergogenic effects for $NaHCO_3$ when using repeated-sprint exercises, however, not until after the first (37) or second repetition (1,6,88). These studies suggest that a single bout exercise is unlikely to benefit from $NaHCO_3$ administration, because its benefit arises from the improvement in acid-base recovery allowed between bouts (74). However, this study found a statistically higher performance ES in single bout as opposed to repeated bout exercises. It must be considered though that there are different proportions of trained to untrained participants in these categories, and ESs are similar when only taking into account trained participants.

The overall ES was higher in studies employing time to exhaustion or total work completed as a performance measure rather than performance time or power. However, the time to exhaustion and total work groups had a high proportion of untrained subjects, whereas the performance time group had a high proportion of trained subjects (only 1 untrained ES in group), therefore influencing the overall ESs. It is interesting that trained subjects in the performance time group had one of the lowest ESs, because it could be argued that this combination would be most applicable to elite sporting performance. Despite the differences between performance measures, there were no statistically significant differences in overall ESs. The absence of statistical differences between performance measures could be because of the differences in the size of the data sets between groups, coupled with the large confidence intervals, which often resulted in negative values at the lower 95% limit.

The most common duration of exercise protocols used to investigate the use of $NaHCO_3$ was up to approximately 120 seconds (Table 2). This is presumable because high-intensity efforts of this duration are predominantly associated with anaerobic glycolysis. However, the overall ES for this duration of exercise was no different to medium (2–10 minutes) and long (>10-minute) duration protocols. Within the short duration category, the ES is much higher in untrained than in trained subjects, again suggesting that untrained subjects are more reliant on the extra buffering potential afforded by $NaHCO_3$. However, once more, the confidence intervals must be taken into consideration. The similar overall ESs across exercise durations may suggest that the extra buffering capacity is not the sole mechanism behind its potential effect on performance. There has been some work to suggest that $NaHCO_3$ may improve perceptual responses to exercise, which could account for the similarly moderate ES for longer exercise protocols (67,81,82). However, as with most research regarding $NaHCO_3$, there is also a wealth of evidence on the contrary (1,60,78,93,95).

It should be considered when interpreting our findings that although the $NaHCO_3$ dosages were similar in the observed studies, the method of administration differed. The majority of the studies administered the buffer in liquid solutions including water, flavored water, fruit juice and soup, whereas the other method used capsules. We have anecdotal evidence from our laboratory and others (94) that some side effects are induced by the taste of $NaHCO_3$ in a liquid solution and that it is easier to tell the difference between placebo and $NaHCO_3$ when ingested in a liquid solution as opposed to capsules. This is problematic for research design because there is a strong placebo effect associated with this particular buffer (47). The mean ES reported in this study is higher in those studies administering $NaHCO_3$ in solution compare to capsules (0.46 and 0.32, respectively), particularly when observing the weighted mean (0.41 and 0.25, respectively) (Table 2). However, it must be added that there were no significant

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differences between said ESs. Future work should not only compare the incidence and severity of side effects between ingesting $NaHCO_3$ in solution and capsules (as recently done by Carr et al. [13]) but also any potential differences in athletic performance.

PRACTICAL APPLICATIONS

The ergogenic potential of $NaHCO_3$ had an overall moderate ES and appeared to be more effective in recreationally as opposed to specifically trained participants. This ES however was highly variable when considering the 95% confidence intervals. Coaches and athletes can take the following practical applications from the results of this review: (a) The use of $NaHCO_3$ should be made on an individual basis as although negative ESs were in the minority (Table 1), a number of the ESs had negative lower confidence intervals (Table 2), meaning a potentially adverse performance effect in some athletes. (b) Care should be taken when evaluating results from studies using performance measures and participants unrelated to their field. (c) The combination of trained participants and performance time resulted in a very weak weighted ES (0.05). (d) Potential performance improvements may not be limited to short exercise protocols. (e) Although it appears that only minor benefits are afforded to trained individuals, such small margins may be significant at the elite level. If $NaHCO_3$ is to be used then it is suggested to experiment with loading protocols to develop an individual specific routine to achieve a peak alkalosis and minimize the risk of potential side effects (13). A recommended starting dosage is 0.2–0.4 $g \cdot kg^{-1} \cdot$body weight^{-1} and 60–120 minutes preexercise in flavored water or capsules.

Future research should focus where possible on trained subjects performing sport-specific tasks, such as those studies on boxing (73), water polo (83), rugby (11), judo (1), and BMX cycling (94,95). Such research would avoid inflating the efficacy of $NaHCO_3$ with untrained subjects who are unlikely to use it and so allow coaches, nutritionists, and athletes to make more informed decisions about their respective sport.

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