Effect of stacked sodium bicarbonate loading on repeated all-out exercise

Sebastiaan Dalle¹, Stefan De Smet¹, Willem Geuns², Bart Van Rompaye³, Peter Hespel^{1, 2}, Katrien Koppo¹

¹ Dept. of Movement Sciences, KU Leuven, Leuven, Belgium

² Bakala Academy Athletic Performance Center, KU Leuven, Leuven, Belgium

³ Dept. of Applied Mathematics, Computer Science and Statistics, UGent, Gent, Belgium

Abstract

The purpose of this study was to evaluate whether NaHCO₃, administered via a 9-h stacked loading protocol (i.e. repeated supplementation with small doses in order to obtain a gradual increase in blood [HCO₃⁻]), has an ergogenic effect on repeated all-out exercise. Twelve physically active males were randomly assigned to receive either NaHCO₃ (BIC) or placebo (PL) in a double-blind cross-over design. NaHCO₃ supplementation was divided in three identical 3-h cycles: a 6.3g bolus at the start, followed by 2.1g doses at +1-h and +2-h, yielding a total NaHCO₃ intake of 0.4g·kg⁻¹ BM over 9h. At the end of each cycle, participants performed 2-min all-out cycling. Capillary blood samples were analysed for [HCO₃⁻], pH and [La⁻]. Pre-exercise blood [HCO₃⁻] in PL decreased from 25.6±0.2mmol·L⁻¹ in bout 1 to 23.6±0.2mmol·L⁻¹ in bout 4, whilst increasing from 25.5±0.2 to 31.2±0.4mmol·L⁻¹ in BIC (P<0.05). Concomitantly, pre-exercise pH values gradually decreased in PL (from 7.41±0.00 to 7.39±0.01) and increased in BIC (from 7.41±0.01 to 7.47±0.01; P<0.05). Mean power output of the 4 bouts was higher in BIC (428±20W) than in PL (420±20W; P<0.05). The ergogenic effect on repeated all-out exercise occurred in the absence of gastrointestinal distress.

Key words: **buffer capacity, muscle energetics, sprint performance, cycling**

Introduction

Numerous sports performances consist of repetitive short all-out exercise bouts that require a high fraction of energy input via anaerobic glyco(geno)lysis. This results in the accumulation of lactate anions (La⁻) and hydrogen protons (H⁺) in muscle cells and in the extracellular space. Some researchers challenge the central role of intramyocellular H⁺ accumulation in muscle fatigue(36). Shortly, it was argued that acidosis cannot be an important contributor to muscle fatigue as 1) some studies observed no temporal correlation between the extent of acidosis and the decline in contractile function(10), 2) muscle fatigue in single murine muscle fibers was little affected by pH at near-physiological temperatures(5) and 3) decreases in pH failed to decrease the rate of glycogenolysis/glycolysis during repeated contractions in humans(1). In contrast, others implicated a low cell pH as one of the fatigue inducing agents during high-intensity muscle contractions(12, 31). A low intramuscular acidity was reported to reduce cross-bridge force, velocity and power(12), and to depress myofibrillar Ca²⁺ sensitivity(29).

One strategy to attenuate fatigue development during anaerobic exercise is to inhibit H⁺ accumulation by increasing buffer capacity, for instance via oral NaHCO₃ supplementation(25). Indeed, increasing the alkaline reserve prior to exercise enables muscle to produce more H⁺ and La⁻ by increasing the gradient for efflux from the muscle(22). Nevertheless, evidence supporting the ergogenic effect of NaHCO₃ in short all-out exercise is equivocal. Literature inconsistencies could partly result from variations in dosage regimen. Doses investigated ranged from 0.1 to 0.5g NaHCO₃ per kg body mass (BM), with the optimal dosage for anaerobic

performances of ~1-min being $0.35\text{g}\cdot\text{kg}^{-1}$ BM(26). Furthermore, Saunders et al. (2014) showed that there is large inter-individual variability in the ergogenic response to sodium bicarbonate(32). This could be related to differences in time to peak alkalosis. Therefore, the timing of NaHCO_3 administration prior to exercise can be individualized to ensure that blood $[\text{HCO}_3^-]$ for each individual peaks at exercise onset(16). Unfortunately, predetermination of the time to peak blood $[\text{HCO}_3^-]$ is rather time consuming as it requires multiple visits to the laboratory. Also, the need of sophisticated devices raises additional costs. Furthermore, one single NaHCO_3 dose prior to the first of multiple exercise bouts is insufficient to increase blood $[\text{HCO}_3^-]$ prior to all bouts(37). Therefore, prolonging increased bicarbonate levels throughout a performance day might be a more straightforward strategy.

A recurring issue with NaHCO_3 supplementation is the gastrointestinal (GI) distress experienced by many athletes(7). These GI problems, mostly stomach cramping and diarrhea, may counteract the beneficial effect of induced alkalosis and preclude improvements in performance. It was reported that the incidence of GI distress is most prominent 90-min after ingestion(8) and that the complaints aggravated with doses above $0.3\text{g}\cdot\text{kg}^{-1}$ BM(26). To reduce the risk of GI distress during a competitive event, some researchers experimented with chronic loading and administered NaHCO_3 over several days or weeks(11, 24). The advantage of such an approach is that blood buffering capacity can be build up during the days before the race, thereby avoiding GI problems due to acute high-dose NaHCO_3 intake prior to exercise. However, this might be accompanied by a diminished HCO_3^- production by the kidneys on the long term and therefore abolish the physiological advantage. Stacked NaHCO_3 loading during the day of performance(s), on the other hand, might be of interest in many sport disciplines such as rowing, swimming, track cycling, athletic events, as their competition structure involves repeated qualification rounds throughout the day, which may gradually deplete the alkaline reserve and impair the performance in the final medal event.

Therefore, it is important to design a NaHCO_3 intake protocol that meets the intermittent structure of the aforementioned competition schedules, yet at the same time avoiding GI symptoms. However, research supporting such a gradual administration schedule is lacking. The aim of the present study is to assess the effect of stacked NaHCO_3 loading on blood acid-base balance, GI distress, and performance during a 9-h time window in which several distinct maximal exercise bouts are performed.

Materials and Methods

Participants

Twelve physically active males (mean $\pm$ SD; age: 21 ± 1 yr; height: 1.81 ± 0.10 m; BM: 74.4 ± 9.9 kg) volunteered to participate in this study. They were fully informed about the aim and the protocol of the study and signed a written informed consent approved by the Ethics Committee Research UZ/KU Leuven. Research was conducted in accordance with international standards for ethics in sport and exercise(18). A medical examination was performed by a GP prior to the start of the study to exclude participants with contra-indications for participation in strenuous exercise. All participants were non-smokers. They trained between 5-8h/week in a variety of disciplines (running, soccer, swimming, motocross, basketball) and had not been taking dietary supplements for a period of at least two months before the study. Participants were instructed not to change their training and dietary habits throughout the study.

Study design

This double-blind study with crossover design consisted of two experimental test days during which participants were randomly assigned to receive either NaHCO_3 or placebo (NaCl) with

a 7-day wash-out period in between. The effect of stacked NaHCO_3 loading was assessed in participants who performed four all-out cycling bouts throughout the day.

Supplementation protocol

All participants received 31.5g of NaHCO_3 (BIC) (which corresponded with an average relative dose of $0.43\text{g}\cdot\text{kg}^{-1}$ BM) in 700mg capsules spread over a 9-h period or an appearance-matched placebo (PL; NaCl) containing an equimolar amount of sodium (see Fig. 1). Doses were administered in three 3-h cycles. Each cycle started with a 6.3g dose administered with a light meal (850kcal; 62% carbohydrates, 16% proteins and 13% lipids), followed every hour by a 2.1g dose in conjunction with 0.25L water and a biscuit (125 kcal) to facilitate uptake(6).

Study protocol

The protocol consisted of four 2-min all-out cycling bouts interspersed by 3h intervals. One week prior to the start of the experimental sessions, participants completed a familiarisation session to get habituated with isokinetic cycling on an electromagnetically braked cycle ergometer (Avantronic Cyclus II, Leipzig, Germany). During this session the optimal bike positioning settings were also determined. After a 10-min warm-up, a maximal isokinetic 2-min bout was performed with a cadence fixed at 90rpm. On two following occasions, separated by one week, participants reported to the laboratory after an overnight fast and abstinence from severe exercise for at least 24-h. Every 3-h the following procedure was repeated: first, a 70 μ l capillary blood sample was taken from a preheated earlobe to determine blood $[\text{HCO}_3^-]$ and pH (ABL90 Flex analyzer, Radiometer Medical ApS, Copenhagen, Denmark) and blood $[\text{La}^-]$ (Lactate Pro 2, Arkray, Japan). Subsequently, after a 10-min warm-up, a 2-min all-out cycling bout was performed during which the mean power output (MPO) was calculated. After 2-min of passive recovery, another capillary blood sample was taken, whereafter participants cooled down for 10-min at 100W. Finally, GI distress was assessed before participants consumed a standardized meal during which the sodium bicarbonate supplementation protocol was started (see above, Fig. 1). GI distress was assessed by a standardized questionnaire, quantifying systemic, upper abdominal and lower abdominal problems on a scale ranging from 0-8 (with 0 being 'no problem' and 8 being 'unbearable') and a maximal total score of 96 (adapted from Pfeiffer et al. 2009)(30). Ratings of perceived exertion (RPE) were recorded using the 15 point graded category scale of Borg(3). The exercise test sessions were conducted at the same time of the day for each participant to account for any possible circadian rhythm effects.

Statistical analysis

Values are presented as means $\pm$ SEM. Differences in GI distress, in MPO and in blood $[\text{La}^-]$, $[\text{HCO}_3^-]$, pH and their respective Δ -values (=pre- vs. post-exercise) were analysed by a repeated measures ANOVA across conditions and time with a Bonferroni post-hoc test. Where relevant, Cohen's d was calculated as index of effect size (ES). Differences between values were considered to be significant for $P < 0.05$. Analyses were performed using R version 3.1.2 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Acid-base balance (Fig. 2, Table 1) - Baseline blood pH and $[\text{HCO}_3^-]$ were not significantly different between PL and BIC. In PL, because of the repetitive all-out bouts, pre-exercise pH and $[\text{HCO}_3^-]$ (i.e. the respective blood values measured before the start of each bout) decreased and did not return to the resting levels before the start of the next cycling bout, so that there was an overall decline over time. In BIC, pre-exercise pH and $[\text{HCO}_3^-]$ gradually increased during the 9-h stacked loading period. Higher values in BIC than in PL were observed for $\Delta[\text{HCO}_3^-]$

and $\Delta[\text{La}^-]$ ($P < 0.05$ for exercise bout 3 and 4), yet ΔpH was not significantly different between both conditions ($P = 0.49$). In BIC, $\Delta[\text{HCO}_3^-]$ and $\Delta[\text{La}^-]$ gradually increased over time (bout 1 < bout 3 and 4, bout 2 < bout 4; $P < 0.05$).

All-out 2-min sprint performance (Fig. 3) – MPO on average was higher in BIC than in PL, i.e., $428 \pm 20\text{W}$ vs. $422 \pm 20\text{W}$ ($P = 0.035$). The highest difference between conditions was observed in bout 3, where MPO was $\sim 3.2\%$ higher in BIC. Furthermore, a significant time effect was observed with a higher MPO in bout 4 than in bout 2 ($P = 0.021$).

Gastrointestinal symptoms - Most participants scored the majority of their GI symptoms at the low end of the scale ('no problem' - 'very minor problems'). Unexpectedly, the total GI distress score (sum of the registration moments) was elevated in PL compared to BIC, i.e. 13.5 ± 5.6 vs. 4.7 ± 1.8 ($P = 0.047$). This could mainly be explained by one outlier in PL, which reported flatulence, vomiting and diarrhea. After exclusion of this outlier, the GI distress score decreased to 8.2 ± 1.9 in PL, which is considered as 'low GI distress'.

Discussion

This is the first study to test the ergogenicity of a 9-h stacked NaHCO_3 ($0.4\text{g}\cdot\text{kg}^{-1}$ BM) loading protocol during which repeated all-out exercise bouts throughout the day are performed. We demonstrate that such a gradual loading strategy improves repetitive all-out exercise in the absence of GI distress, despite the total dose being higher than the prevailing recommendation of $0.3\text{g}\cdot\text{kg}^{-1}$ BM. The advantage of this loading protocol is that blood HCO_3^- levels remained elevated throughout the day.

Blood HCO_3^- levels gradually increased by $\sim 6\text{mmol}\cdot\text{L}^{-1}$ (+23%) during the 9-h loading period, which is $\sim 2\text{mmol}\cdot\text{L}^{-1}$ higher than values reported following a single $0.3\text{g}\cdot\text{kg}^{-1}$ BM NaHCO_3 dose (see Carr et al. (2011))(8). Also, the decrement of blood $[\text{HCO}_3^-]$ and increase of blood $[\text{La}^-]$ were higher in BIC than in PL, suggesting that there was a facilitated co-transport of H^+ and La^- out of the muscle cell during each cycling bout. Alternatively, the higher post-exercise blood $[\text{La}^-]$ in BIC might be due to reduced La^- clearance, as it was reported that La^- clearance by inactive skeletal muscle tissue is reduced following NaHCO_3 supplementation(17). In contrast to $\Delta[\text{HCO}_3^-]$ and $\Delta[\text{La}^-]$, the exercise-induced drop in blood pH was similar between BIC and PL, despite higher pre-exercise pH values in BIC, which is in agreement with other studies(20, 33, 35). The similar drop in pH during exercise in both conditions seems contra intuitive. However, the Henderson–Hasselbalch equation states that blood pH depends on the ratio between $[\text{HCO}_3^-]$ and pCO_2 . Prior to exercise, the higher pH values in BIC could be explained by elevated $[\text{HCO}_3^-]$, while the pCO_2 probably remained relatively unchanged since very little HCO_3^- was used at rest. During the exercise bouts, the drop in $[\text{HCO}_3^-]$ was larger in BIC than in PL. Given that the drop in pH was similar between both conditions, the drop in pCO_2 must have been higher in BIC compared to PL. Indeed, unpublished observations in our group showed that ΔpCO_2 following an all-out running bout (± 100 s) in BIC (5.3 ± 1.3 mmHg) tended to be higher than in PL (3.5 ± 1.1 mmHg; $p = 0.11$).

In quite a number of sports disciplines the competition schedule involves repetitive all-out exercise bouts to be performed throughout the day. Therefore, in the present study, four 2-min all-out exercise bouts with 3-h recovery intervals in between were used to evaluate the ergogenic potential of a novel stacked NaHCO_3 supplementation protocol. Interestingly, our results showed that NaHCO_3 supplementation significantly enhanced performance in 2-min all-out cycling bouts following both 6-h (+3.2%; ES: 0.20) and 9-h (+1.7%; ES: 0.10) of stacked

supplementation, but not in the earlier bouts. This is not surprising since less than 0.2g NaHCO₃ per kg BM was administered prior to bouts 1 (ES: 0.03) and 2 (ES: 0.03), which is too low to generate an ergogenic effect(26). Improved performance upon 6-h supplementation is interesting in a number of sport disciplines in which multiple competitions are scheduled during the day. It should be noted, however, that our participants were not elite athletes. Still, this does not exclude that our findings may be extrapolated to the elite. In fact, we extensively applied this protocol ‘in the field’ in a number of world-class track cyclists during omnium competition. These athletes experienced no GI discomfort at all, and generally performed well. One of the athletes set a new personal best on the 4K individual pursuit. Additionally, in their meta-analysis, Carr et al.(8) indicated that the inclusion of non-athletes had a small detrimental effect on the NaHCO₃-induced performance benefits. Unpublished data from our lab revealed that elite cyclists improved their 90s sprint performance to the same degree as in the current study. We therefore believe that the proposed supplementation protocol can be used in multiple competition contexts. For instance, in the omnium competition in track cycling, riders often participate in 4 events in one day (i.e. a scratch, elimination, tempo race, points race), but also in other sports disciplines such as swimming, judo, athletics, multiple qualification rounds are spread over the day, with medal events taking place in the evening. Athletes and coaches ought to consider the administration of (small) NaHCO₃ doses in between intermittent severe exercise bouts, taking into account 1) the personal preferences/GI sensitivity of the athlete, 2) the type of exercise and 3) the recovery time in between different bouts.

The effect of NaHCO₃ supplementation on intermittent short all-out cycling bouts was demonstrated in previous work(2, 9, 21, 23, 27, 28, 37, 38). However, in these studies the intermittent exercise protocol lasted 30-min or less, whilst in the present study, exercise bouts were spread over a 9-h period with 3-h intervals in between, which from a metabolic perspective is an entirely different situation. In short intermittent exercise the contribution of glycolytic ATP production gradually decreases as the number of exercise bouts increases(14). Conversely, repeated all-out exercise bouts with 3-h intervals in between allow for a higher glycolytic flux in each single bout, since intermediates and key enzymes of the anaerobic glycolysis are (partly) restored during the recovery time(19). Also, in none of the previous studies, NaHCO₃ was supplemented in between the all-out cycling bouts, which might explain why sometimes no ergogenic effect of sodium bicarbonate supplementation was observed. For instance, Zabala et al. (2011) supplemented 0.3g·kg⁻¹ BM 90-min prior to the first of three 30-s all-out cycling sprints, with 15-min recovery in between(37). While blood HCO₃⁻ levels significantly increased prior to sprint 1 (i.e. from ~24.5 to 28.5mmol·L⁻¹), the pre-exercise [HCO₃⁻] decreased below baseline levels at the start of sprint 2 (~18mmol·L⁻¹) and sprint 3 (~14.5mmol·L⁻¹). Future studies should therefore reveal whether small NaHCO₃ doses ingested during the rest interval between short maximal exercise bouts might improve pre-exercise buffering capacity, and thereby performance, in particular when the recovery time is relatively short (e.g. 15min).

Although it was previously reported that GI distress aggravates with acute NaHCO₃ doses exceeding 0.3g·kg⁻¹ BM(26), our stacked NaHCO₃ loading did not increase GI complaints, despite 0.4g·kg⁻¹ BM NaHCO₃ being administered over a 9-h period. Conversely, GI complaints were higher in PL than in BIC. However, this difference was due to one participant who reported upper GI distress both after the first and the second meal, and another participant with the same complaints after the last meal. None of these complaints were reported in BIC. The placebo capsules were identical to the capsules used in BIC, and were filled with an equimolar amount of Na⁺(2). Therefore, it is very unlikely that differences in upper GI complaints were due to Na⁺-induced disturbances. The particular reason for the differences in GI distress between both conditions is unclear. However, the most likely explanation is the more severe

exercise-induced acidosis in PL. The average post-exercise pH was 0.05 lower in BIC than in PL (7.23 ± 0.02 vs. 7.18 ± 0.01 , respectively). Following a performance predominantly relying on anaerobic glycolysis, systemic acidosis may cause vomiting as a physiological response to drain H^+ and thereby allow the stomach to add bicarbonate to the body(34). Despite the GI problems in PL, we assume that this did not affect performance as the participants with higher GI distress exhibited similar maximal $[La^-]$, RPE and performance compared to participants with minimal GI symptoms. Besides the implementation of a stacked loading strategy, we also tried to minimise GI distress by loading $NaHCO_3$ via capsules. In recent studies, Gough et al. (2017, 2018) and Freis et al. (2017) reported substantial GI discomfort following the intake of $0.3g \cdot kg^{-1}$ BM $NaHCO_3$ when dissolved in a solution(13, 15, 16). The authors suggested that the hypertonic $NaHCO_3$ solution might have resulted in excess fluid retention into the GI tract, which is likely to induce diarrhea(13). Furthermore, Breitzkreutz et al. (2007) mentioned that $NaHCO_3$ released in the acid environment of the stomach is transformed into carbon dioxide, causing abdominal pain and flatulence, and limiting its ergogenic potential(4). These incidents can be reduced by using capsules to postpone the release of $NaHCO_3$ to the small intestine, with minimal interference at the level of the stomach and thus less upper GI distress.

It is the prevailing opinion that the optimal time for $NaHCO_3$ administration is 60-90-min prior to exercise(24). Miller et al. (2016) observed that, in most of their participants, pH peaked between 60 and 90-min after ingestion of a single dose of $0.3g \cdot kg^{-1}$ BM $NaHCO_3$. They proposed this time to reach peak blood pH as the optimal time delay where the highest ergogenic effect might be expected(27). However, one should keep in mind that participants might also suffer from GI distress 60-90-min after consumption of $NaHCO_3$ (27), which might impair the beneficial effects of the induced alkalosis. Therefore, the stacked loading strategy applied here, may be a more effective approach to supplement a similar or even higher dose of $NaHCO_3$ in the absence of GI distress. Furthermore, such loading strategy extends the plateauing of peak blood $[HCO_3^-]$ providing a prolonged time window of ergogenicity.

Conclusion

The main finding of this study is that $0.4g \cdot kg^{-1}$ BM $NaHCO_3$, gradually supplemented over a 9-h time period, improved all-out performance in the absence of significant GI symptoms. Besides its ergogenic effect, the protocol is time effective since there is no need to predetermine the individualized time to peak HCO_3^- due to a sustained increase in blood bicarbonate. The proposed stacked loading strategy could be recommended in a variety of sports disciplines with multiple qualification rounds throughout the day. However, athletes and coaches should still take into account the competition schedule and the athlete's tolerance to $NaHCO_3$ to determine the appropriate loading strategy.

References

1. Bangsbo J, Madsen K, Kiens B, Richter EA. Effect of muscle acidity on muscle metabolism and fatigue during intense exercise in man. *J Physiol* 1996;495:587–96.
2. Bishop D, Edge J, Davis C, Goodman C. Induced metabolic alkalosis affects muscle metabolism and repeated-sprint ability. *Med Sci Sport Exerc* 2004;36:807–13.
3. Borg G. Perceived exertion as an indicator of somatic stress. *Scand J Rehabil Med* 1970;2:92–8.
4. Breitzkreutz J, Gan TG, Schneider B, Kalisch P. Enteric-coated solid dosage forms containing sodium bicarbonate as a drug substance: an exception from the rule? *J Pharm Pharmacol* 2007;59:59–65.
5. Bruton JD, La JAN, Joseph D, La J. Effects of CO_2 -induced acidification on the

- fatigue resistance of single mouse muscle fibers at 28°C. *J Appl Physiol* 1998;85:478–483.
6. Burke LM. Practical considerations for bicarbonate loading and sports performance. *Nestle Nutr Inst Workshop Ser* 2013;75:15–26.
 7. Burke LM, Pyne DB. Bicarbonate loading to enhance training and competitive performance. *Int J Sports Physiol Perform* 2007;2:93–7.
 8. Carr AJ, Hopkins WG, Gore CJ. Effects of acute alkalosis and acidosis on performance: A meta-analysis. *Sport Med* 2011;41:801–14.
 9. Costill D, Verstappen F, Kuipers H, Jansson E, Fink W. Acid-base balance during repeated bouts of exercise: influence of HCO₃. *Med Sci Sport Exerc* 1983;15:115–115.
 10. Degroot M, Massie BM, Boska M, Gober J, Miller RG, Weiner MW. Dissociation of [H⁺] from fatigue in human muscle detected by high time resolution 31P-NMR. *Muscle Nerve* 1993;16:91–8.
 11. 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;101:918–25.
 12. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 1994;74:49–94.
 13. Freis T, Hecksteden A, Such U, Meyer T. Effect of sodium bicarbonate on prolonged running performance: A randomized , double- blind , cross-over study. *PLoS One* 2017;12:e0182158.
 14. Gaitanos G, Williams C, Boobis L, Brooks S. Human muscle metabolism maximal exercise. *J Appl Physiol* 1993;75:712–9.
 15. Gough LA, Deb SK, Sparks AS, Mcnaughton LR. The reproducibility of blood acid base responses in male collegiate athletes following individualised doses of sodium bicarbonate: A randomised controlled crossover study. *Sport Med* 2017;47:2117–27.
 16. Gough LA, Deb SK, Sparks SA, Mcnaughton LR. Sodium bicarbonate improves 4 km time trial cycling performance when individualised to time to peak blood bicarbonate in trained male cyclists individualised to time to peak blood bicarbonate in trained male cyclists. *J Sports Sci* 2018;36:1705–12.
 17. Granier PL, Dubouchaud H, Mercier BM, Mercier JG, Ahmaidi S, Préfaut CG. Effect of NaHCO₃ on lactate kinetics in forearm muscles during leg exercise in man. *Med Sci Sport Exerc* 1996;28:692–7.
 18. Harriss D, Macsween A, Atkinson G. Standards for Ethics in Sport and Exercise Science Research: 2018 Update. *Int J Sport Med* 2017;38:1126–31.
 19. Krause U, Wegener G. Control skeletal of glycolysis in vertebrate muscle during exercise. *Am J Physiol Regul Integr Comp Physiol* 1996;270:R821–9.
 20. Kupcis PD, Slater GJ, Pruscino CL, Kemp JG. Influence of sodium bicarbonate on performance and hydration in lightweight rowing. *Int J Sport Physiol Perform* 2012;7:11–8.
 21. Lavender G, Bird SR. Effect of sodium bicarbonate ingestion upon repeated sprints. *Br J Sport Med* 1989;23:41–5.
 22. Mainwood G, Worsmey-Brown P. The effects of extracellular pH and buffer concentration on the efflux of lactate from frog sartorius muscle. *J Physiol* 1975;250:1–22.
 23. Mckenzie DC, Coutts KD, Stirling DR, Hoeben HH, Kuzara G. Maximal work production following two levels of artificially induced metabolic alkalosis. *J Sport Sci* 1986;4:35–8.
 24. Mcnaughton L, Backx K, Palmer G, Strange N. Effects of chronic bicarbonate ingestion on the performance of high-intensity work. *Eur J Appl Physiol* 1999;80:333–6.

25. McNaughton L, Curtin R, Goodman G, Perry D, Turner B, Showell C. Anaerobic work and power output during cycle ergometer exercise: effects of bicarbonate loading. *J Sport Sci* 1991;9:151–60.
26. McNaughton LR. Bicarbonate ingestion: effects of dosage on 60 s cycle ergometry. *J Sport Sci* 1992;10:415–23.
27. Miller P, Robinson AL, Sparks SA, Bridge CA, Bentley DJ, McNaughton LR. The effects of novel ingestion of sodium bicarbonate on repeated sprint ability. *J Strength Cond Res* 2016;30:561–8.
28. Mündel T. Sodium bicarbonate ingestion improves repeated high-intensity cycling performance in the heat. *Temperature* 2018;1–5.
29. Nelson CR, Fitts RH. Effects of low cell pH and elevated inorganic phosphate on the pCa-force relationship in single muscle fibers at near-physiological temperatures. *Am J Physiol Cell Physiol* 2014;306:C670–8.
30. Pfeiffer B, Cotterill A, Grathwohl D, Stellingwerff T, Jeukendrup AE. The effect of carbohydrate gels on gastrointestinal tolerance during a 16-km run. *Int J Sport Nutr Exerc Metab* 2009;19:485–503.
31. Sahlin K. Muscle fatigue and lactic acid accumulation. *Acta Physiol Scand Suppl* 1986;556:83–91.
32. Saunders B, Sale C, Harris RC, Sunderland C. Sodium Bicarbonate and High-Intensity-Cycling Capacity: Variability in Responses. *Int J Sports Physiol Perform* 2014;9:627–32.
33. Siegler J, Gleadall-Siddall D. Sodium bicarbonate ingestion and repeated swim sprint performance. *J Strength Cond Res* 2010;24:3105–11.
34. Valeur J, Julsrud J. Vomiting: a physiological response to acidosis? *Scand J Gastroenterol* 2013;48:1103–4.
35. Vanhatalo A, McNaughton LR, Siegler J, Jones AM. Effect of induced alkalosis on the power-duration relationship of “all-out” exercise. *Med Sci Sports Exerc* 2010;42:563–70.
36. Westerblad H. Acidosis is not a significant cause of skeletal muscle fatigue. *Med Sci Sport Exerc* 2016;48:2339–42.
37. Zabala M, Peinado AB, Calderon FJ, Sampedro J, Castillo MJ, Benito PJ. Bicarbonate ingestion has no ergogenic effect on consecutive all out sprint tests in BMX elite cyclists. *Eur J Appl Physiol* 2011;111:3127–34.
38. Zabala M, Requena B, Sanchez-Munoz C, et al. Effects of sodium bicarbonate ingestion on performance and perceptual responses in a laboratory-simulated BMX cycling qualification series. *J Strength Cond Res* 2008;22:1645–53.

Figure 1. Schematic presentation of the study protocol.

Participants ($n = 12$) performed 4 all-out cycling bouts over a 9-h time window. They received sodium bicarbonate or placebo in a randomised double-blind cross-over design. Every 3-h, a 6.3g dose (***) with standardized meal (🍴) was followed by 2 smaller dosages of 2.1g (*). Capillary blood samples and a questionnaire for gastrointestinal (GI) side-effects were taken at regular intervals.

Figure 2. Effects of sodium bicarbonate intake on blood acid-base balance.

Data are mean $\pm$ SEM ($n=12$) for blood bicarbonate (left panel) and blood pH (right panel) before the start of a 2-min all-out exercise bout after 0, 3, 6 and 9-h of supplementation with either placebo (□) or sodium bicarbonate (■). The black vertical bars represent the 2-min all-out exercise bouts. * $P < 0.05$ compared with PL. § $P < 0.05$ compared with baseline (0h).

Figure 3. Effects of sodium bicarbonate intake on performance.

Data are mean $\pm$ SEM ($n=12$) for mean power output of the 4 cycling bouts after 0, 3, 6 and 9-h of supplementation with either placebo (□) or sodium bicarbonate (■). * $P < 0.05$ compared with PL.

		PL			BIC			ES		
		HCO ₃ ⁻ (mmol·L ⁻¹)	pH	La ⁻ (mmol·L ⁻¹)	HCO ₃ ⁻ (mmol·L ⁻¹)	pH	La ⁻ (mmol·L ⁻¹)	HCO ₃ ⁻	pH	La ⁻
Bout 1	Pre	25.6±0.2	7.41±0.00	1.0±0.1	25.5±0.2	7.41±0.01	0.9±0.1	0.12	0.00	0.30
	Post	14.1±0.3	7.19±0.01	10.3±0.5	13.9±0.4	7.17±0.01	9.7±0.6	0.21	0.37	0.32
Bout 2	Pre	25.2±0.3	7.40±0.00	1.1±0.1	27.8±0.3*§	7.43±0.00*§	1.2±0.1	1.56	1.54	0.18
	Post	14.2±0.4	7.19±0.01	10.3±0.6	15.7±0.4*§	7.23±0.01*§	11.5±0.4*§	0.97	1.04	0.71
Bout 3	Pre	24.3±0.2§	7.39±0.00	0.9±0.0	29.5±0.4*§	7.46±0.01*§	1.0±0.1	1.82	1.76	0.43
	Post	14.0±0.6	7.18±0.02	10.2±0.9	16.3±0.5*§	7.26±0.01*§	12.6±0.4*§	1.01	1.22	0.94
Bout 4	Pre	23.6±0.2§	7.39±0.01	0.9±0.1	31.2±0.4*§	7.47±0.01*§	0.9±0.1	1.88	1.71	0.09
	Post	13.2±0.3	7.17±0.01	11.0±0.4	16.8±0.6*§	7.27±0.02*§	13.1±0.5*§	1.48	1.33	1.10

Table 1. Blood bicarbonate, pH and lactate pre and post each all-out cycling bout.

Data are mean ± SEM (n=12) for blood bicarbonate (HCO₃⁻), pH and lactate (La⁻) for each 2-min all-out exercise bout after 0, 3, 6 and 9-h of supplementation with either placebo or sodium bicarbonate. ES = the Cohen's d effect size for all blood parameters. * P < 0.05 compared with PL. § P < 0.05 compared with baseline (0-h). All HCO₃⁻, pH and La⁻ values significantly differed between pre and post for every exercise bout, but for clarity reasons this is not indicated in the table.