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ORIGINAL RESEARCH

Oral but Not Topical Sodium Bicarbonate Improves Repeated Sprint Performance During Simulated Soccer Match Play Exercise in Collegiate Athletes

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This study investigated the effect of oral and topical sodium bicarbonate (SB) on soccer-specific performance during simulated soccer exercise. In a block randomized, double-blind, crossover design, 10 collegiate male soccer players (stature: 181.7 ± 3.2 cm, body mass: 81.7 ± 10.5 kg) performed soccer-specific performance tests (countermovement jumps, Illinois agility, 8 × 25 m repeated sprints) throughout a 90-min soccer-specific aerobic field test (SAFT90) following 0.3 g/kg body mass SB in capsules (SB-ORAL), 0.9036 g/kg body mass PR Lotion (SB-LOTION), or placebo capsules and lotion (PLA). Soccer-specific performance tests were conducted pre-SAFT90, during half-time and post-SAFT90. Blood samples were analyzed for acid–base balance (pH; bicarbonate, HCO_3^-) and strong ions (sodium, Na^+; potassium, K^+). Average sprint times were quicker for SB-ORAL than PLA during half-time (3.7%; $p = .049$; $g = .57$) and post-SAFT90 (4.9%; $p = .041$; $g = .66$). SB-ORAL increased pH and HCO_3^- prewarm-up and during half-time ($p < .05$), and lowered K^+ during half-time ($p = .035$) compared with PLA. SB-LOTION increased pH ($p = .019$) and lowered K^+ ($p = .012$) during half-time compared with PLA. SB-LOTION increased Na^+ postexercise compared with PLA ($p = .008$). Repeated sprint times during simulated soccer exercise improved for SB-ORAL, which might have been mechanistically underpinned by elevated blood buffering capacity and greater regulation of strong ion concentration. Consuming SB in capsules is a more effective strategy than topical SB application for improving blood buffering capacity and repeated sprint performance throughout competitive soccer matches.

Keywords: acid–base balance, strong ions, ergogenic aids, lotion, agility

Sodium bicarbonate (SB) is an ergogenic aid for athletes during repeated bouts of high-intensity exercise (Carr et al., 2011). Substantial anaerobic energy demand causes excessive accumulation of hydrogen cations (H^+) within active muscles, leading to declining intramuscular pH (Sahlin, 2014). Ingestion of 0.3 g/kg body mass (BM) SB raises blood bicarbonate (HCO_3^-) by ~5.0–6.0 mmol/L, elevating the pH gradient between intra- and extracellular environments (Bishop et al., 2004). This accelerates removal of H^+ from within the muscle and protects against intramuscular acidosis that inhibits adenosine triphosphate production via anaerobic glycolysis (Messonnier et al., 2007; Spriet et al., 1989). Ingesting SB also alters strong ion concentration (i.e., sodium, Na^+; potassium, K^+), which preserves muscle excitability and excitation–contraction coupling (Sostaric et al., 2006). Disruptions to these biochemical processes contribute toward skeletal muscle fatigue (Fitts, 2016); therefore, SB supplementation may sustain force generating capacity and offset fatigue during sporting disciplines comprising repeated high-intensity efforts.

Competitive soccer matches are characterized by repeated bouts of high-intensity exercise (i.e., two or more successive sprints) across ~90 min (two 45 min halves) that are interspersed with short recovery periods (~30 s; Spencer et al., 2005). Elite soccer players perform up to 25 sprint efforts during matches (Gabbett et al., 2013), resulting in the accumulation of H^+ within muscles (Bangsbo et al., 2007). Previous work in hockey and cycling demonstrated elevated HCO_3^- after SB ingestion during exercise lasting between 60 and 180 min (Dalle et al., 2021; Macutkiewicz & Sunderland, 2018), but it remains unclear whether increased HCO_3^- would be maintained throughout a competitive soccer match. Theoretically, SB could be an ergogenic strategy for soccer players if enhanced extracellular buffering protects against declining intramuscular pH from repetitive sprint efforts. A few studies have examined the effect of SB during soccer-specific exercise. Gurton, Greally, et al. (2023) showed a 1.8% improvement ($p = .023$, $d = .38$) in 8 × 25 m repeated sprint times after SB. Krustrup et al. (2015) and Marriott et al. (2015) found SB to increase distance covered during the Yo-Yo Intermittent Recovery

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Test Level 2 by 14% ($p = .04$) and 23% ($p < .05$), respectively. In contrast, Guimarães et al. (2020) reported no improvements for 6×35 m repeated sprint time following SB (1.2 s faster, $p = .553$).

Factors such as differences in exercise protocol, participant characteristics, and ingestion timing/dosage likely contribute to equivocal effects of SB during soccer-specific exercise. Inconsistent results might also be explained by gastrointestinal discomfort after SB ingestion (Cameron et al., 2010). One alternative could be PR Lotion (Momentous), which is a topically applied muscle cream purported to deliver SB into systemic circulation via the transdermal route (Prausnitz & Langer, 2008). Gurton, Greally, et al. (2023) reported a 1.9% improvement ($p = .036$, $d = .34$) for 8×25 m repeated sprint times after PR Lotion. On the other hand, McKay et al. (2020) found PR Lotion did not increase average power during 3×30 s Wingate cycling tests ($p = .108$). Despite contradictory findings, a strong rationale exists for using PR Lotion over traditional SB ingestion approaches, as if it was proven effective, it would eliminate concerns about gastrointestinal side effects. Further placebo-controlled research trials are warranted before conclusions can be drawn regarding PR Lotions' efficacy.

While oral and topical SB have been shown to improve soccer-specific performance, it is not known whether benefits exist during ecologically valid match play exercise. An athletes' ability to repeat high-intensity efforts is a key determinant of success in soccer, but it declines toward the latter stages of matches (Bradley et al., 2010). Additional work is needed examining whether oral or topical SB elevate HCO_3^- throughout soccer matches and subsequently improve performance before either should be incorporated into nutritional regimes. Therefore, the aim of this study was to investigate the effect of oral and topical SB (PR Lotion) on soccer-specific performance (countermovement jumps, CMJ; Illinois agility test, IAT; 8×25 m repeated sprints) during simulated soccer match play exercise.

Methods

Experimental Design

A randomized, double-blind, placebo-controlled, crossover design was employed. Three treatments (oral SB, topical SB, and placebo) were allocated to be received by four participants first, second, and third during experimental trials using a 3×3 block randomization design. Sequence order was randomly assigned using an online generator (www.randomization.com).

Participants

Our a priori sample size calculation conducted on G*Power (version 3.1.9.4) revealed that 10 participants were needed to achieve statistical power ($\beta = 0.80$; $\alpha = .05$). This assumed that repeated measures analyses of variance (ANOVA; within-factors) would be used to analyze sprint times (primary outcome) with a medium effect size (partial eta squared, $\eta_P^2 = .06$) expected. Correlation between repeated measures ($r = .85$) was estimated using data for the repeated sprint protocol (Gurton, Greally, et al., 2023). Twelve participants were recruited; however, two withdrew due to time commitments. Therefore, 10 collegiate male soccer players (age: 24 ± 3 years, stature: 1.82 ± 0.03 m, BM: 81.7 ± 10.5 kg, training per week: 5 ± 1 hr) completed the study. Participants were aged 18–35 years and played soccer in the British Universities and Colleges Sport leagues. They were excluded if they had used SB in the previous 6 months or were allergic to any ingredients in PR Lotion. The study was performed in accordance with the Declaration of Helsinki (World Medical Association, 2013) and approved by the Institutional Ethics Committee (ER51987898). Participants were informed of any risks associated with the study before providing written informed consent.

Preexperimental Phase

Participants were instructed to avoid vigorous exercise, alcohol, caffeine, and foods with a high potential renal acid load 24 hr before each session (Maughan et al., 2004). During familiarization, a 24-hr dietary recall was conducted using self-report food diaries, with participants asked to replicate nutritional intake before subsequent visits. Participants were asked to attend in a 3-hr postprandial state to minimize the influence of potential renal acid load on acid–base balance (Remer, 2001). Visual inspection of food diaries (consistency of food choice, patterns, and portion sizes) by the principal investigator revealed that compliance to dietary controls was met. Experimental trials were separated by 5–7 days to ensure sufficient recovery and washout of interventions. Testing was conducted at a similar time (±2 hr) to control for confounding effects of circadian rhythms on exercise performance (Reilly, 1990).

Familiarization to Soccer-Specific Exercise

Participants performed a 10-min team sport-specific warm-up (Gurton, Greally, et al., 2023). Familiarization involved conducting performance tests and one block of the SAFT90. Three CMJs were performed on an optical measurement system (OptoJump Next, Microgate), with 1 min separating each jump. Next, participants carried out three IAT followed by 8×25 m repeated sprints. During both tests, repeated efforts were separated by 30 s, with completion times recorded via light gates (Brower Timing Systems, Draper) placed at the start and end points. Participants then undertook one 15-min block of the SAFT90, including a soccer-specific eccentric movement pattern circuit (IAT, 10 m sprint, 5 m sidestepping, three headers, backwards running, and a shooting drill) designed to increase ecological validity of our study protocol. The SAFT90 comprised shuttle running and utility movements over a 20-m distance, with participants first sidestepping around one pole (2 m distance) before running forwards through the course, navigating a further three poles (9, 10, and 11 m distance; Small et al., 2010). An audio compact disk was used to provide verbal signals to control the exercise intensity ("stand," "walk," "jog," "stride," "sprint") and activity ("upwards," "sideways").

Experimental Procedures

Participants performed three separate experimental trials, with an overview of timings and measurements outlined in Figure 1. On arrival to the laboratory, baseline capillary blood samples were analyzed for acid–base balance, strong ions, and lactate. Gastrointestinal discomfort and cooling sensations questionnaires were also completed. Participants then received either oral SB, topical SB or placebo, and a carbohydrate-rich meal (1.5 g/kg BM; biscuits, gels, cereal bars, and cornflakes with milk) over 30 min. They were not permitted to consume any additional food. Water was consumed ad libitum ($1{,}115 \pm 465$ ml) during the first trial, with equal volumes provided during subsequent sessions. Gastrointestinal discomfort, cooling sensations, and blinding questionnaires were completed postsupplementation and prewarm-up. Capillary blood samples were repeated prewarm-up. Participants started the warm-up 105 min postsupplementation, with the first bout of

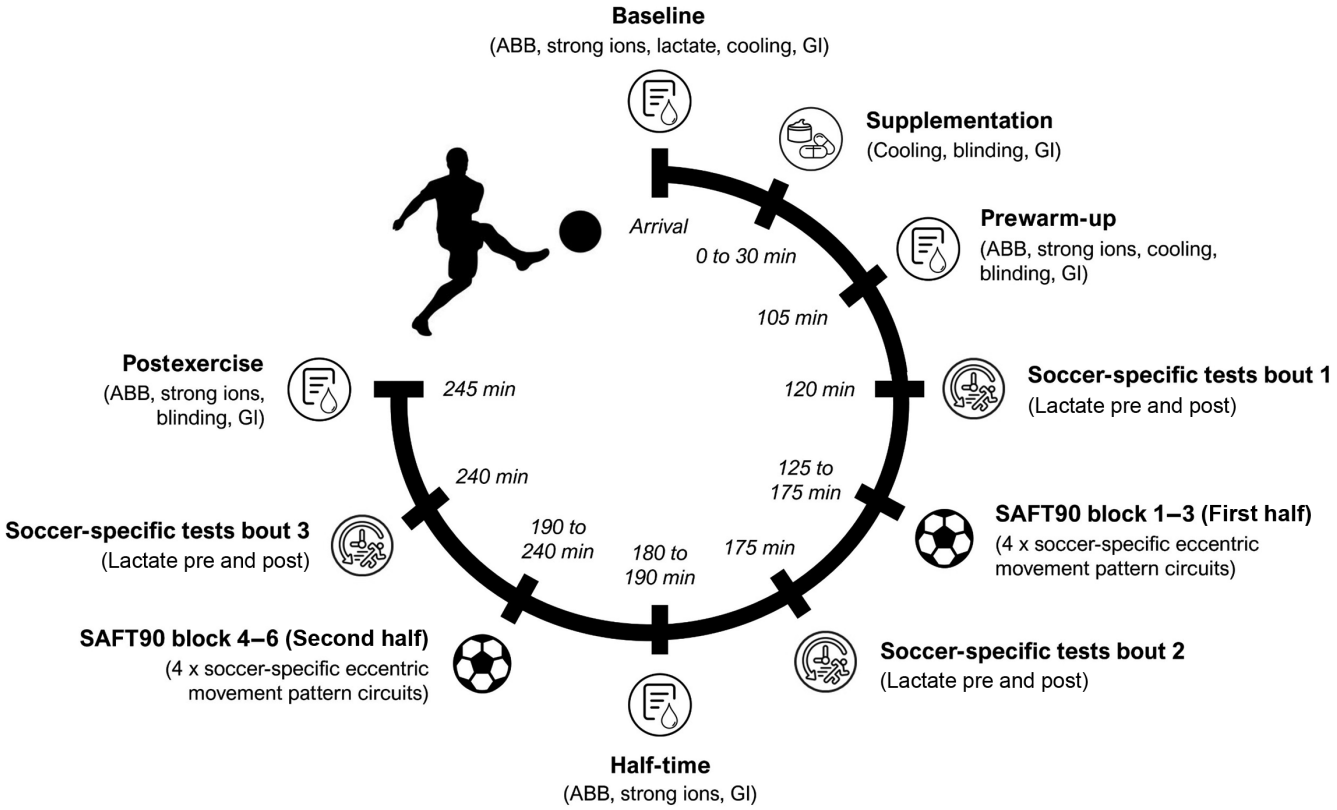

Figure 1 — Experimental schematic showing timings and measurements during simulated soccer match play exercise protocol (~4 hr). Soccer-specific exercise tests included three countermovement jumps, three Illinois agility circuits, and eight 25-m repeated sprints. Supplements were given as three separate doses across the 30-min window. ABB = acid–base balance (blood pH, bicarbonate), strong ions (sodium, potassium, calcium); GI = gastrointestinal discomfort questionnaire (visual analog scales for eight symptoms).

performance tests (pre-SAFT90) commencing 120 min postsupplementation. This time frame was chosen as peak changes in blood pH are thought to occur ~120 min after applying PR Lotion (Gibson et al., 2023). Participants performed six 15-min blocks of the SAFT90 (~100 min total exercise time with soccer-specific movement patterns). Blocks 1–3 and 4–6 were separated by a 15-min recovery period to simulate half-time. Soccer-specific movement patterns were completed before and after each block. Participants repeated performance tests at half-time and post-SAFT90. Capillary blood samples were measured again for acid–base balance and strong ions during half-time and postexercise. Additional blood samples were analyzed for lactate postwarm-up, after performance tests, and following both halves of the SAFT90. Gastrointestinal discomfort was measured during half-time and postexercise. Blinding questionnaires were repeated postexercise.

Supplementation Protocol

During experimental trials, participants received either: (a) 0.3 g/kg BM SB in capsules and 0.9036 g/kg BM placebo lotion (SB-ORAL), (b) placebo capsules and 0.9036 g/kg BM PR Lotion (SB-LOTION), and (c) placebo capsules and 0.9036 g/kg BM placebo lotion (PLA). Supplements were prepared by a laboratory technician. Size 0 vegetarian capsules (Your Supplements) were filled using a capsule filling device (ALL-IN Capsule) and contained ~0.8 g SB (Health Leads Ltd.) or ~0.4 g corn flour (Sainsbury's). Capsule size influences acid–base balance pharmacokinetics after SB ingestion, with peak changes in HCO_3^- occurring ~2.5 hr postsupplementation for size 0 capsules (Middlebrook et al., 2021). Relative dose of PR Lotion (0.9036 g/kg BM) was calculated by accounting for the proportion of SB (33.2%) per gram of PR Lotion to match the 0.3 g/kg BM oral SB dose (Gurton, Greally et al., 2023; McKay et al., 2020). This meant the same amount of SB was given for oral and topical treatments, with absolute SB dosage ranging from 19.7 to 28.4 g. As such, there were no differences in the amount of HCO_3^- (range: 12.3–17.8 g; assuming the composition of SB is 62.6% HCO_3^- and 27.3% Na^+) delivered between SB-ORAL and SB-LOTION. PR Lotion was provided from Momentous. The placebo-matched lotion was supplied by the manufacturer with SB removed but still containing 0.5% menthol as per commercially available PR Lotion. Corn flour was used as the oral placebo, as it is an inert substance that effectively blinds SB (Gurton et al., 2022). Capsules were administered to the nearest whole number of capsules (31 ± 4) and consumed as three separate 0.1 g/kg BM doses with 7 ml/kg BM water (572 ± 73 ml) at 15 min intervals across a 30-min period. PR Lotion was weighed out to the nearest 0.1 g and given as three 0.3012 g/kg BM doses at these 15 min intervals. Participants were instructed to evenly spread out PR Lotion across their entire legs and lower back. In total, between 59.3 and 85.4 g (73.9 ± 9.5 g) PR Lotion was administered. Both lotions were provided in opaque plastic tubs.

Measurements and Questionnaires

Capillary blood samples (95 µl) were analyzed for pH, HCO_3^-, Na^+, K^+, and ionized calcium (iCa^{2+}) using an i-STAT Alinity (Abbott). This analyzer demonstrates excellent reliability and precision for

measuring blood pH and HCO_3^- after exercise (intraclass correlation coefficients, ICC's; $r = .88$, .86; Dascombe et al., 2007). Additional blood samples (20 µl) were analyzed for lactate using a Biosen C-Line (EKF Diagnostics; coefficient of variation < 1.5%, at a value of 12 mmol/L). Aggregate gastrointestinal discomfort was quantified from questionnaires consisting of 100 mm visual analog scales for side effects (nausea, flatulence, abdominal discomfort, gut fullness, bowel urgency, diarrhea, vomiting, and belching; Gurton et al., 2021). To examine the cooling effect of menthol in PR Lotion, questionnaires consisting of 7-point Likert scales were used to measure cooling sensation at the thighs and calves (ASHRAE, 2004). Blinding questionnaires were completed that asked participants to select which treatment they thought had been given ("oral SB," "topical SB," "placebo," and "unsure") and explain their reasons (Gurton et al., 2022).

Statistical Analysis

Grouped data and standardized residuals were assessed for normality using Shapiro–Wilk tests. Homogeneity of variance/sphericity was analyzed using Mauchly tests, and violations were corrected via Greenhouse–Geisser adjustments. To determine the reproducibility of soccer-specific exercise tests, typical error of measurement (% TEM) and ICC's were calculated between familiarization and PLA. Two-way mixed-model, absolute agreement ICC's were interpreted as poor ($r < .50$), moderate ($r = .50$–$.75$), good ($r = .75$–$.90$), or excellent ($r > .90$; Koo & Li, 2016). Repeated-measures two-way ANOVA were used to investigate Treatment × Time interactions for normally distributed data. When significant interactions were observed, post hoc tests were performed to assess treatment effects across individual time points and time effects within treatments. Otherwise, pairwise comparisons were used to examine main effects for treatment and time. Bonferroni correction factors were used to adjust p values for multiple comparisons. Existence of learning effects was examined via repeated-measures two-way ANOVA by comparing average sprint time, agility time, and CMJ height from the first, second, and third trials. Effect sizes for ANOVA main effects and interactions were reported as η_P^2. These were interpreted using the classifications of .01, .06, and .14 as small, medium, and large, respectively (Cohen, 1988). Between-treatment effect sizes were calculated by dividing mean difference by the pooled SD and applying Hedges' g (g) correction (Lakens, 2013). These were interpreted as trivial (<0.20), small (0.20–0.49), moderate (0.50–0.79), or large (≥0.80; Cohen, 1988). Normal distribution was violated for aggregate gastrointestinal discomfort and cooling sensations; therefore, multiple Friedman tests were used to explore differences between treatments across individual time points. When significant effects were found, post hoc pairwise comparisons were conducted to explore treatment differences further, with Z statistic and median values presented. Treatment assignment ratings ("correct," "incorrect") were analyzed using 2 × 2 chi-squared tests to assess blinding. Improvements in performance are reported as percentages. Data are presented as mean ± SD (unless stated; median [interquartile range]), and statistical significance was set at $p < .05$. Statistical analyses were performed using SPSS (version 26.0).

Results

Soccer-Specific Exercise Performance

Repeated sprint performance was highly reproducible, with fastest and average sprint times showing low TEM (2.3%, 2.8%) and good ICC's (r = .89, .82). Treatment × Time interactions existed for fastest ($F[4,36] = 3.733$, $p = .012$, $\eta_P^2 = .293$) and average ($F[4,36] = 2.888$, $p = .036$, $\eta_P^2 = .243$) sprint times. Repeated sprint times were similar between treatments pre-SAFT90 ($p > .05$; Figure 2A–2B). Fastest time was improved for SB-ORAL during half-time compared with PLA (3.2%, $p = .021$, $g = .51$) and post-SAFT90 compared with SB-LOTION (3.6%, $p = .025$, $g = .51$) and PLA (5.1%, $p = .012$, $g = .69$). SB-ORAL offset declines in fastest times, with no differences between time points ($F[3,12] = 3.034$, $p = .073$, $\eta_P^2 = .252$). Average times were improved for SB-ORAL during half-time compared with PLA (3.7%, $p = .049$, $g = .57$) and post-SAFT90 compared with SB-LOTION (3.8%, $p = .035$, $g = .52$) and PLA (4.9%, $p = .041$, $g = .66$). Neither SB-ORAL or SB-LOTION offset declines in average times, with performance

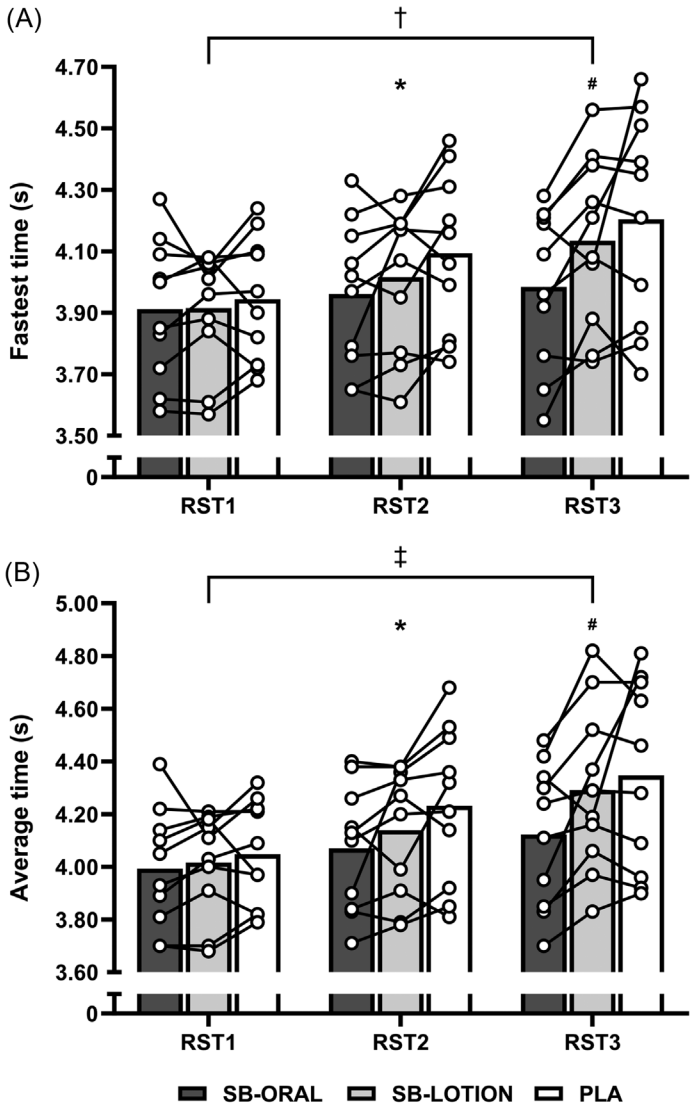

Figure 2 — (A) Fastest and (B) average times during the 8 × 25 m repeated sprint tests. Bars represent mean values; $n = 10$. Individual treatment differences depicted by symbol/line. Symbols denote significance ($p < .05$): *SB-ORAL versus PLA. #SB-ORAL versus SB-LOTION and PLA. †Decline in sprint times for SB-LOTION and PLA, but not SB-ORAL. ‡Decline in sprint times for all treatments. RST1/2/3 = Repeated Sprint Test 1 (pre-SAFT90), 2 (half-time), and 3 (post-SAFT90); SAFT90 = 90-min soccer-specific aerobic field test.

worse during half-time and post-SAFT90 than pre-SAFT90 ($p < .05$).

Agility performance was highly reproducible, with fastest and average sprint times showing low TEM (3.1%, 3.0%) and good ICC's ($r = .83, .85$). No Treatment × Time interactions existed for fastest ($p = .071$) or average ($p = .143$) times, but there were main effects for treatment and time ($p < .001$; Figure 3A–3B). Treatment main effects revealed quicker fastest times for SB-ORAL compared with SB-LOTION (3.1%, $p = .018$) and PLA (4.9%, $p = .004$), but not for SB-LOTION compared with PLA ($p = .206$). Treatment main effects revealed faster average times for SB-ORAL compared with SB-LOTION (3.1%, $p = .007$) and PLA (4.9%, $p = .002$) but not for SB-LOTION compared with PLA ($p = .123$).

Jump height was highly reproducible, with maximum and average CMJ height showing low TEM (3.4%, 2.8%) and excellent ICC's ($r = .98, .98$). No Treatment × Time interactions existed for maximum ($p = .207$) or average ($p = .105$) height. There were no treatment or time main effects for maximum ($p = .731$, $p = .201$) or average ($p = .794$, $p = .226$) height.

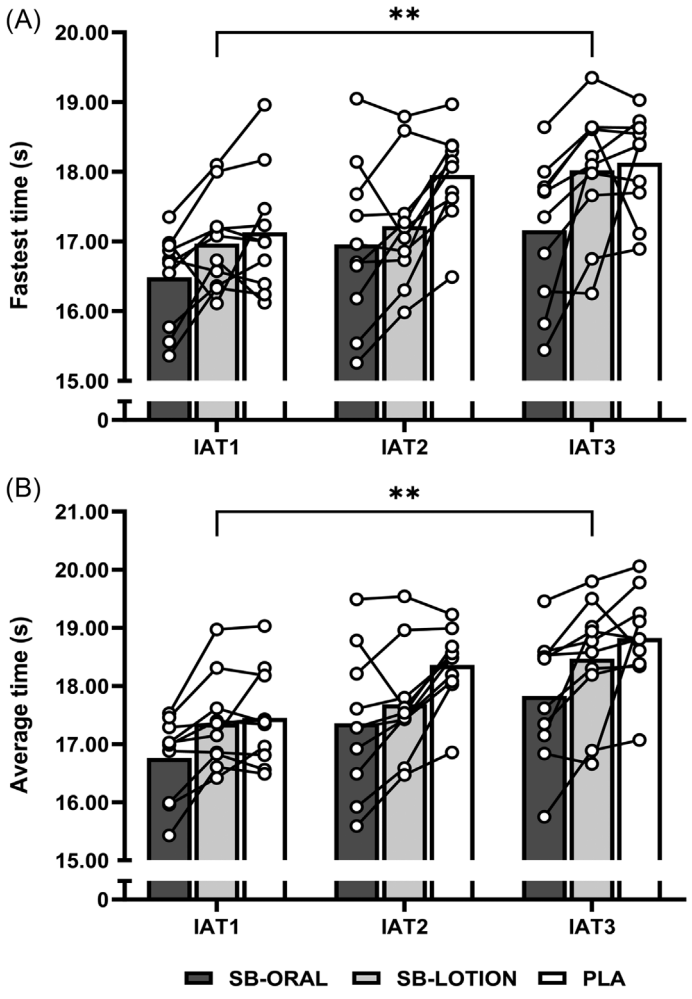

Figure 3 — (A) Fastest and (B) average times during the Illinois agility tests. Bars represent mean values; $n = 10$. Individual treatment differences depicted by symbol/line. Symbols denote significance ($p < .05$): **Main effect for treatment (SB-ORAL faster than SB-LOTION and PLA. IAT1/2/3 = Illinois Agility Test 1 (pre-SAFT90), 2 (half-time), and 3 (post-SAFT90); PLA = placebo; SAFT90 = 90-min soccer-specific aerobic field test.

No learning effects existed for soccer-specific performance. Irrespective of the order participants completed treatments, performance during the first, second, and third trials was similar, with no Order × Time interactions for the repeated sprint ($F[1.49,13.42] = 0.936$, $p = .390$), agility ($F[4,36] = 0.383$, $p = .819$), or CMJ ($F[2.29,20.62] = 0.651$, $p = .552$) tests.

Blood Metabolites

Treatment × Time interactions existed for blood pH ($F[6,54] = 3.802$, $p = .003$, $\eta_P^2 = .297$), HCO_3^- ($F[1.85,16.34] = 4.355$, $p = .033$, $\eta_P^2 = .326$), Na^+ ($F[6,54] = 2.982$, $p = .014$, $\eta_P^2 = .249$), K^+ ($F[3.06,27.54] = 5.844$, $p = .003$, $\eta_P^2 = .394$), and iCa^{2+} ($F[2.75, 24.77] = 3.138$, $p = .047$, $\eta_P^2 = .259$), but not lactate ($p = .207$) where only a main effect was shown for time ($p < .001$, $\eta_P^2 = .821$; Figure 4).

With respect to SB-ORAL, blood pH and HCO_3^- were elevated compared with PLA prewarm-up (both $p < .001$) and during half-time ($p = .015$, $p = .018$; Table 1). Blood pH and HCO_3^- were higher compared with SB-LOTION prewarm-up (both $p < .001$). Half-time HCO_3^- was greater than SB-LOTION ($p = .040$). Half-time K^+ and iCa^{2+} were lower than SB-LOTION ($p = .035$, $p = .011$), with iCa^{2+} less than PLA ($p = .017$; Table 2). Postexercise K^+ and iCa^{2+} were reduced compared with SB-LOTION ($p = .034$, $p = .003$), with iCa^{2+} lower than PLA ($p = .003$). All other comparisons for SB-ORAL were nonsignificant ($p > .05$).

With respect to SB-LOTION, blood pH was elevated compared with PLA during half-time ($p = .019$). Half-time K^+ was lower than PLA ($p = .012$). Postexercise Na^+ was higher compared with PLA ($p = .008$). All other comparisons for SB-LOTION were nonsignificant ($p > .05$).

Rating of Perceived Exertion

No Treatment × Time interactions existed for RPE during repeated sprints ($p > .05$) with only a main effect for time ($p < .001$). A Treatment × Time interaction existed for RPE during the SAFT90 ($F[3.34,30.02] = 3.220$, $p = .032$, $\eta_P^2 = .2630$). RPE was lower after the first block for SB-LOTION compared with SB-ORAL (−1.3 au, $p = .028$) and PLA (−1.5 au, $p = .036$) and after the second block for SB-LOTION compared with SB-ORAL (−1.8 au, $p = .020$) but was not different from Blocks 3 to 6 ($p < .05$; Figure 5).

Gastrointestinal Discomfort, Blinding, and Cooling Sensation

In general, gastrointestinal discomfort was mild for each treatment (Table 3); however, a treatment effect was shown postsupplementation ($\chi^2[2] = 7.824$, $p = .026$), with aggregate gastrointestinal higher after SB-LOTION compared with PLA ($Z = 1.100$, $p = .042$). Only a single participant identified SB-ORAL and PLA postsupplementation and prewarm-up; however, more correct ratings were recorded postexercise (SB-ORAL: 3/10; PLA: 4/10). Five participants identified SB-LOTION from the "stronger cooling effect" (3/5) and "thicker texture" (2/5), but the number of correct and incorrect ratings was similar between treatments ($p > .05$; Table 4). Treatment effects existed for cooling sensations postsupplementation for the thighs ($\chi^2[2] = 6.452$, $p = .040$) and prewarm-up for the calves ($\chi^2[2] = 12.069$, $p = .002$). Cooling for the thighs was greater postsupplementation for SB-LOTION (−2 [1] au) compared with SB-ORAL (−1 [1] au, $Z = 2.236$, $p = .025$) but not PLA (−1 [2] au, $p = .264$) and for the calves prewarm-up for

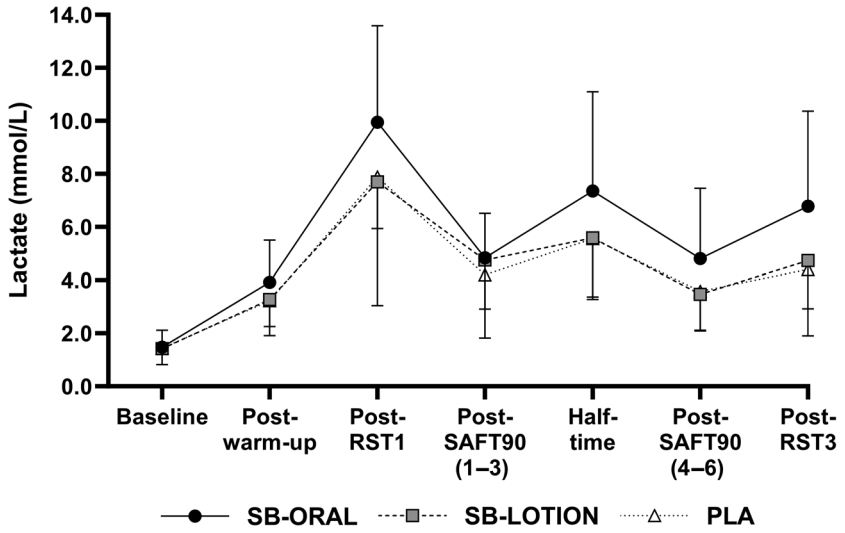

Figure 4 — Blood lactate response throughout the simulated soccer exercise. Values are presented as mean ± *SD*; $n = 10$. Some error bars removed for clarity. RST1/2/3 = Repeated Sprint Test 1 (pre-SAFT90), 2 (half-time), and 3 (post-SAFT90); PLA = placebo; SAFT90 = 90-min soccer-specific aerobic field test.

Table 1 Blood Acid–Base Balance From Baseline to Postexercise

	Baseline	Prewarm-up	Half-time	Postexercise
pH (au)				
SB-ORAL	7.42 ± 0.01	7.48 ± 0.04#	7.46 ± 0.04*	7.46 ± 0.05
SB-LOTION	7.41 ± 0.02	7.42 ± 0.03	7.41 ± 0.02^	7.43 ± 0.03
PLA	7.41 ± 0.02	7.41 ± 0.03	7.39 ± 0.03	7.42 ± 0.03
HCO_3^- (mmol/L)				
SB-ORAL	25.6 ± 1.3	30.6 ± 2.0#	26.9 ± 4.6#	26.9 ± 4.8
SB-LOTION	25.6 ± 1.6	25.9 ± 1.6	22.6 ± 2.2	23.9 ± 1.8
PLA	25.4 ± 1.3	25.5 ± 1.1	21.8 ± 1.2	22.4 ± 1.8

Note. Values are presented as mean ± *SD*; $n = 10$. SB = sodium bicarbonate; PLA = placebo.
*SB-ORAL versus PLA; ^SB-LOTION versus PLA; #SB-ORAL versus SB-LOTION and PLA ($p < .05$).

Table 2 Strong Ion Concentration From Baseline to Postexercise

	Baseline	Prewarm-up	Half-time	Postexercise
Na^+ (mmol/L)				
SB-ORAL	135 ± 2	137 ± 2	139 ± 2	138 ± 3
SB-LOTION	135 ± 3	137 ± 2	138 ± 4	141 ± 4^
PLA	135 ± 2	135 ± 2	138 ± 2	138 ± 2
K^+ (mmol/L)				
SB-ORAL	4.6 ± 0.4	4.3 ± 0.3	4.1 ± 0.5*	3.9 ± 0.4†
SB-LOTION	4.3 ± 0.3	4.2 ± 0.4	4.3 ± 0.4^	4.8 ± 0.7
PLA	4.4 ± 0.4	4.3 ± 0.3	4.9 ± 0.5	4.6 ± 0.6
iCa^{2+} (mmol/L)				
SB-ORAL	0.81 ± 0.08	0.73 ± 0.09	0.67 ± 0.06#	0.67 ± 0.06#
SB-LOTION	0.80 ± 0.12	0.78 ± 0.05	0.75 ± 0.08	0.78 ± 0.09
PLA	0.77 ± 0.09	0.80 ± 0.09	0.76 ± 0.06	0.77 ± 0.06

Note. Values are presented as mean ± *SD*; $n = 10$. SB = sodium bicarbonate; PLA = placebo.
Symbols denote significance: *SB-ORAL versus PLA; ^SB-LOTION versus PLA; †SB-ORAL versus SB-LOTION; #SB-ORAL versus SB-LOTION and PLA ($p < .05$).

SB-LOTION (−1 [1] au) compared with SB-ORAL (0 [0] au, $Z = 2.236$, $p = .025$) and PLA (0 [1] au, $Z = 2.795$, $p = .005$).

Discussion

The aim of this study was to investigate the effect of oral and topical SB during simulated soccer match play exercise. Our primary finding was that SB-ORAL improved repeated sprint performance during simulated soccer exercise, with sprint times ~4% faster during half-time and post-SAFT90 compared with PLA. Ergogenic benefits were less pronounced during IAT and CMJ, with only positive main effects for treatment in favor of SB-ORAL for agility performance. No significant improvements in performance were observed for SB-LOTION throughout. Blood buffering capacity was increased prewarm-up and during half-time for SB-ORAL, with small elevations in blood pH for SB-LOTION during half-time. Blood K^+ was reduced for SB-ORAL during half-time and postexercise, but only during half-time for SB-LOTION. Finally, RPE was lower during the first and second bouts of the SAFT90 for SB-LOTION, although positive effects wore off throughout exercise.

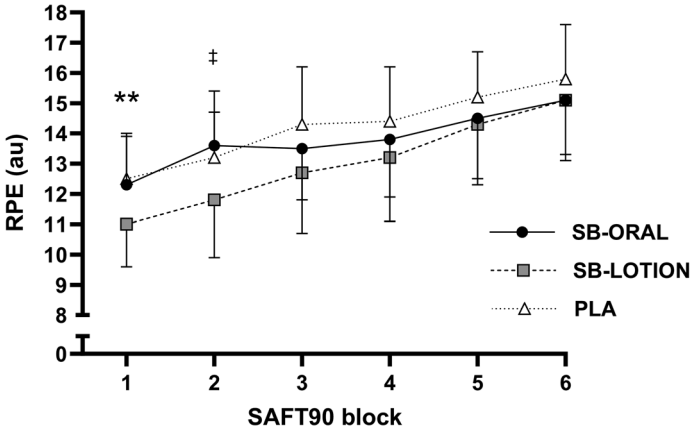

Figure 5 — Rating of perceived exertion throughout the SAFT90. Values are presented as mean ± *SD*; $n = 10$. Some error bars removed for clarity. Symbols denote significance ($p < .05$) at individual time points: **SB-LOTION lower than SB-ORAL and PLA; ‡SB-LOTION lower than SB-ORAL. RPE = rating of perceived exertion; PLA = placebo; SAFT90 = 90-min soccer-specific aerobic field test.

Blood buffering capacity was elevated for SB-ORAL, with prewarm-up changes in HCO_3^- (~5 mmol/L) consistent with studies showing ergogenic effects after SB (Gurton, Greally et al., 2023; Krustrup et al., 2015). In contrast, blood pH and HCO_3^- did not increase prewarm-up following SB-LOTION, supporting recent studies (Gurton, Greally et al., 2023; McKay et al., 2020). Transdermal drug delivery is only effective when small doses (in milligrams per day) of a treatment are required (Prausnitz & Langer, 2008). While we were unable to track diffusion rates across the skin, blood buffering capacity was lower for topical SB compared with oral SB, indicating that insufficient SB from PR Lotion reaches systemic circulation to elicit ergogenic effects. Interestingly, neither SB-ORAL nor SB-LOTION improved performance pre-SAFT90, contradicting previous work from our laboratory (Gurton, Greally, et al., 2023). Inconsistent results could relate to discrepancies in testing battery, as the "all-out" nature of IAT efforts may have utilized increased circulating HCO_3^- ahead of our 8 × 25 m repeated

Table 3 Aggregate Gastrointestinal Discomfort Score From Baseline to Postexercise

	Baseline	Postsupplementation	Prewarm-up	Half-time	Postexercise
SB-ORAL	15 [22]	24 [30]	26 [28]	20 [20]	23 [15]
SB-LOTION	22 [17]	22 [24]*	25 [20]	25 [35]	26 [24]
PLA	11 [27]	16 [24]	17 [36]	18 [37]	27 [28]

Note. Values presented as median [interquartile range]. Aggregate gastrointestinal discomfort score (out of 800 mm) calculated from sum of visual analog scales for eight symptoms. SB = sodium bicarbonate; PLA = placebo.
Symbols denote significance: *exacerbated compared with PLA ($p < .05$).

Table 4 Treatment Assignment Ratings for Each of the Three Interventions

	SB-ORAL	SB-LOTION	PLA
Postsupplementation			
Correct ratings	1 (10%)	**5 (50%)**	1 (10%)
Incorrect ratings	0 (0%)	0 (0%)	1 (10%)
Unsure ratings	9 (90%)	5 (50%)	8 (80%)
Prewarm-up			
Correct ratings	1 (10%)	**5 (50%)**	1 (10%)
Incorrect ratings	1 (10%)	0 (0%)	2 (20%)
Unsure ratings	8 (80%)	5 (50%)	7 (70%)
Postexercise			
Correct ratings	3 (30%)	**5 (50%)**	**4 (40%)**
Incorrect ratings	2 (20%)	1 (10%)	2 (20%)
Unsure ratings	5 (50%)	4 (40%)	4 (40%)

Note. Percentage of treatment assignment ratings displayed in parenthesis. Number of correct guesses recorded greater than expected by chance alone (>33%) are highlighted in bold.

sprints (Gurton et al., 2021). That being said, Marriott et al. (2015) found SB to increase distance covered during the Yo-Yo Intermittent Recovery Test Level 2 despite a prior exercise bout. Alternatively, equivocal results could relate to exercise duration, with SB eliciting greater benefits during exercise lasting longer than 4 min (Hadzic et al., 2019). This offers insight to why Marriott et al. (2015) showed larger improvements for SB during a Yo-Yo Intermittent Recovery Test Level 2 (~10 min) compared to our testing battery where exercise duration was ~1.5 min.

Of note, however, was that sprint times were ~3.5% faster during half-time for SB-ORAL compared with PLA. Positive effects were less clear for IAT performance, with only main effects for treatment in favor of SB-ORAL. Greater emphasis on cognitive and technical components (e.g., speed accuracy) during agility tests (Young et al., 2015) may minimize ergogenic benefits after SB, whereas repeated sprints are limited by the accumulation of metabolic by-products (McNaughton et al., 2016). Improved repeated sprint times for SB-ORAL were likely underpinned by greater blood buffering capacity and regulation of strong ions. First, elevated blood pH and HCO_3^- suggest oral SB protected against declining intramuscular pH during the simulated soccer exercise (Bishop et al., 2004). Second, lower blood K^+ and iCa^{2+} infer increased movement of strong ions from extra- to intracellular compartments. Despite not measuring changes occurring within the muscle, elevated intracellular Ca^{2+} would increase rate of troponin C binding for skeletal muscle contractions (Debold et al., 2008) and higher intramuscular K^+ levels are crucial for preserving muscle excitability (Cairns & Lindinger, 2008; Street et al., 2005).

No improvements in repeated sprint performance were reported during half-time for SB-LOTION, with small positive changes in blood pH and K^+ compared with PLA, which expands on previous findings (Gurton, Greally et al., 2023; McKay et al., 2020). Improved repeated sprint performance for oral but not topical SB could be explained by differences in blood buffering capacity and strong ion concentration, as these were consistently lower for SB-LOTION. Gibson et al. (2023) documented marked increases in blood pH (+0.04 au) after applying 80 g PR Lotion (~1.23 g/kg BM), suggesting that larger doses of PR Lotion might elicit a greater rise in pH and thus be more likely to improve performance, but dose–response investigations are warranted to elucidate this theory. Interestingly, SB-LOTION attenuated RPE during the first and second SAFT90 blocks. We previously hypothesized that reduced RPE for PR Lotion is due to an interaction between menthol and residual SB molecules that forms a protective layer over the skin to intensify localized cooling sensations (Gurton, Greally, et al., 2023). At present, this remains speculative, meaning future experimental research should examine whether an interaction exists, but it is based off theoretical knowledge that menthol induces cooling sensations by stimulating membrane-bound ion channel transient receptor potential melastatin 8 (Rosales et al., 2024). Importantly, despite the placebo lotion also containing menthol, greater cooling sensations were reported for SB-LOTION, inferring SB molecules somehow contributed to stronger cooling sensations. These may have resulted in analgesic effects that alleviated localized muscle discomfort (Pan et al., 2012) and caused participants' feelings of muscle pain to be lower than their actual degree of fatigue (Johar et al., 2012). This offers some insight to how SB-LOTION reduced RPE during the SAFT90. Nonetheless, as RPE was similar from Blocks 3 to 6, it appears effects wore off during exercise.

Sprint times were ~4.5% faster for SB-ORAL post-SAFT90 compared with SB-LOTION and PLA. Combined with SB-ORAL offsetting decline in fastest sprint times, it appears oral SB improves repeated sprint ability until the latter stages of soccer matches. In contrast, Macutkiewicz and Sunderland (2018) showed no effect of SB on hockey-specific skilled performance in female athletes following 60 min intermittent exercise. Inconsistent findings could relate to sex-specific differences (Durkalec-Michalsk et al., 2020). Our male soccer players likely had larger Type II muscle fibers that rely heavily on glycolysis for adenosine triphosphate production (Simoneau & Bouchard, 1989), meaning they had more to gain from SB. Unlike previous studies (Gurton, Greally, et al., 2023; Krustrup et al., 2015), nonsignificant increases in lactate were observed for SB-ORAL, suggesting performance benefits were not attributed to upregulated glycolytic flux. Instead, reduced blood K^+ post-SAFT90 for SB-ORAL reaffirms that preserved muscle excitability may have contributed to improved performance (Cairns & Lindinger, 2008). Once again, repeated sprint and IAT times were not improved for SB-LOTION post-SAFT90, likely as neither blood buffering nor strong ion regulation was improved compared to PLA. Therefore, it seems PR Lotion is not an effective ergogenic aid during soccer matches. One finding that remains difficult to explain was elevated postexercise Na^+ (~3 mmol/L) for SB-LOTION. Our study is the first to examine PR Lotion over ~4 hr, so it is possible transdermal delivery of Na^+ takes longer than initially thought.

Strengths, Limitations, and Practical Applications of the Study

One of this study's strengths was recruiting collegiate-level soccer players. Specifically, the high level of test reproducibility, combined with the absence of order effects, confirms participants were familiarized to soccer-specific exercise, meaning improvements for SB-ORAL were not attributed to learning effects. Second, oral SB was successfully blinded, allowing us to conclude ergogenic benefits were due to pharmacological properties of SB (Gurton, Matta, et al., 2023). This study's main limitation was that five participants identified SB-LOTION, which may have induced placebo effects that influenced study outcomes (Hurst et al., 2020). Depending on participants expectancy of positive benefits, identifying PR Lotion could have contributed to lower RPE during the SAFT90.

Practical implications of our results are that oral SB is the most effective supplementation approach for improving blood buffering capacity and repeated sprint performance during soccer match play exercise. Negligible, or less pronounced, effects were shown for IAT and CMJ. Considerably, fewer benefits were reported for topical SB, adding to equivocal findings for the efficacy of PR Lotion (Gurton, Greally et al., 2023; McKay et al., 2020). Interestingly, oral SB caused milder gastrointestinal discomfort compared with previous studies (Cameron et al., 2010; Gurton et al., 2020). Splitting SB supplementation across 30 min likely alleviates gastrointestinal side effects; however, SB must be trialed on an individual basis, as symptoms may still occur. It is recommended that practitioners take the results of this study into consideration when incorporating SB into nutritional regimes for soccer players.

Conclusions

Ingesting 0.3 g/kg BM SB improved repeated sprint ability throughout simulated soccer exercise. Elevated blood buffering capacity and greater regulation of strong ions likely underpinned ergogenic effects. PR Lotion did not improve soccer-specific performance, although

reductions in RPE and elevated blood pH suggest some benefits might exist. Consuming SB orally in capsules is a more effective strategy than topical SB for improving blood buffering capacity and repeated sprint performance throughout soccer matches.

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References

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). (2004). *Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bangsbo, J., Iaia, F.M., & Krustrup, P. (2007). Metabolic response and fatigue in soccer. *International Journal of Sports Physiology and Performance, 2*(2), 111–127. https://doi.org/10.1123/ijspp.2.2.111

Bishop, D., Edge, J., Davis, C., & Goodman, C. (2004). Induced metabolic alkalosis affects muscle metabolism and repeated-sprint ability. *Medicine & Science in Sports & Exercise, 36*(5), 807–813. https://doi.org/10.1249/01.MSS.0000126392.20025.17

Bradley, P.S., Di Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-intensity activity profiles of elite soccer players at different performance levels. *The Journal of Strength & Conditioning Research, 24*(9), 2343–2351. https://doi.org/10.1519/JSC.0b013e3181aeb1b3

Cairns, S.P., & Lindinger, M.I. (2008). Do multiple ionic interactions contribute to skeletal muscle fatigue? *The Journal of Physiology, 586*(17), 4039–4054. https://doi.org/10.1113/jphysiol.2008.155424

Cameron, S.L., McLay-Cooke, R.T., Brown, R.C., Gray, A.R., & Fairbairn, K.A. (2010). Increased blood pH but not performance with sodium bicarbonate supplementation in elite rugby union players. *International Journal of Sport Nutrition and Exercise Metabolism, 20*(4), 307–321. https://doi.org/10.1123/ijsnem.20.4.307

Carr, A.J., Hopkins, W.G., & Gore, C.J. (2011). Effects of acute alkalosis and acidosis on performance. *Sports Medicine, 41*(10), 801–814. https://doi.org/10.2165/11591440-000000000-00000

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Dalle, S., Koppo, K., & Hespel, P. (2021). Sodium bicarbonate improves sprint performance in endurance cycling. *Journal of Science and Medicine in Sport, 24*(3), 301–306. https://doi.org/10.1016/j.jsams.2020.09.011

Dascombe, B.J., Reaburn, P.R.J., Sirotic, A.C., & Coutts, A.J. (2007). The reliability of the i-STAT clinical portable analyser. *Journal of Science and Medicine in Sport, 10*(3), 135–140. https://doi.org/10.1016/j.jsams.2006.05.023

Debold, E.P., Beck, S.E., & Warshaw, D.M. (2008). Effect of low pH on single skeletal muscle myosin mechanics and kinetics. *American Journal of Physiology-Cell Physiology, 295*(1), C173–C179. https://doi.org/10.1152/ajpcell.00172.2008

Durkalec-Michalski, K., Zawieja, E. E., Zawieja, B. E., Michałowska, P., & Podgórski, T. (2020). The gender dependent influence of sodium bicarbonate supplementation on anaerobic power and specific performance in female and male wrestlers. *Scientific Reports, 10*(1), Article 1878. https://doi.org/10.1038/s41598-020-57590-x

Fitts, R. (2016). The role of acidosis in fatigue: Pro perspective. *Medicine & Science in Sports & Exercise, 48*(11), 2335–2338. https://doi.org/10.1249/MSS.0000000000001043

Gabbett, T.J., Wiig, H., & Spencer, M. (2013). Repeated high-intensity running and sprinting in elite women's soccer competition. *International Journal of Sports Physiology and Performance, 8*(2), 130–138. https://doi.org/10.1123/ijspp.8.2.130

Gibson, B.M., Needham, K.W., Kaiser, B.W., Wilkins, B.W., Minson, C.T., & Halliwill, J.R. (2023). Transcutaneous delivery of sodium bicarbonate increases intramuscular pH. *Frontiers in Physiology, 14* Article 1142567. https://www.frontiersin.org/articles/10.3389/fphys.2023.1142567

Guimarães, R.dos S., de Morais Junior, A.C., Schincaglia, R.M.S., Saunders, B., Pimentel, G.D., & Mota, J.F. (2020). Sodium bicarbonate supplementation does not improve running anaerobic sprint test performance in semiprofessional adolescent soccer players. *International Journal of Sport Nutrition & Exercise Metabolism, 30*(5), 330–337. https://doi.org/10.1123/ijsnem.2020-0031

Gurton, W.H., Faulkner, S.H., & James, R.M. (2021). Effect of warm-up and sodium bicarbonate ingestion on 4-km cycling time-trial performance. *International Journal of Sports Physiology and Performance, 16*(11), 1573–1579. https://doi.org/10.1123/ijspp.2020-0743

Gurton, W.H., Gough, L.A., Sparks, S.A., Faghy, M.A., & Reed, K.E. (2020). Sodium bicarbonate ingestion improves time-to-exhaustion cycling performance and alters estimated energy system contribution: A dose-response investigation. *Frontiers in Nutrition, 7*, Article 154. https://doi.org/10.3389/fnut.2020.00154

Gurton, W.H., Greally, J., Chudzikiewicz, K., Gough, L.A., Lynn, A., & Ranchordas, M.K. (2023). Beneficial effects of oral and topical sodium bicarbonate during a battery of team sport-specific exercise tests in recreationally trained male athletes. *Journal of the International Society of Sports Nutrition, 20*(1), Article 2216678. https://doi.org/10.1080/15502783.2023.2216678

Gurton, W.H., Matta, G.G., Gough, L.A., & Hurst, P. (2022). Efficacy of sodium bicarbonate ingestion strategies for protecting blinding. *European Journal of Applied Physiology, 122*(12), 2555–2563. https://doi.org/10.1007/s00421-022-05031-0

Gurton, W.H., Matta, G.G., Gough, L.A., Ranchordas, M.K., King, D.G., & Hurst, P. (2023). Sodium bicarbonate and time-to-exhaustion cycling performance: A retrospective analysis exploring the mediating role of expectation. *Sports Medicine-Open, 9*, Article 65. https://doi.org/10.1186/s40798-023-00612-5

Hadzic, M., Eckstein, M.L., & Schugardt, M. (2019). The impact of sodium bicarbonate on performance in response to exercise duration in athletes: A systematic review. *Journal of Sports Science & Medicine, 18*(2), 271–281.

Hurst, P., Schipof-Godart, L., Szabo, A., Raglin, J., Hettinga, F., Roelands, B., Lane, A., Foad, A., Coleman, D., & Beedie, C. (2020). The placebo and nocebo effect on sports performance: A systematic review. *European Journal of Sport Science, 20*(3), 279–292. https://doi.org/10.1080/17461391.2019.1655098

Johar, P., Grover, V., Topp, R., & Behm, D.G. (2012). A comparison of topical menthol to ice on pain, evoked tetanic and voluntary force during delayed onset muscle soreness. *International Journal of Sports Physical Therapy, 7*(3), 314–322.

Koo, T.K., & Li, M.Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Krustrup, P., Ermidis, G., & Mohr, M. (2015). Sodium bicarbonate intake improves high-intensity intermittent exercise performance in trained young men. *Journal of the International Society of Sports Nutrition, 12*(1), Article 25. https://doi.org/10.1186/s12970-015-0087-6

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: A practical primer for t-tests and ANOVAs. *Frontiers in Psychology, 4*, Article 863. https://www.frontiersin.org/articles/10.3389/fpsyg.2013.00863

Macutkiewicz, D., & Sunderland, C. (2018). Sodium bicarbonate supplementation does not improve elite women's team sport running or field hockey skill performance. *Physiological Reports, 6*(19), Article e13818. https://doi.org/10.14814/phy2.13818

Marriott, M., Krustrup, P., & Mohr, M. (2015). Ergogenic effects of caffeine and sodium bicarbonate supplementation on intermittent exercise performance preceded by intense arm cranking exercise. *Journal of the International Society of Sports Nutrition, 12*(13), 1–8. https://doi.org/10.1186/s12970-015-0075-x

Maughan, R.J., King, D.S., & Lea, T. (2004). Dietary supplements. *Journal of Sports Sciences, 22*(1), 95–113. https://doi.org/10.1080/0264041031000140581

McKay, A.K.A., Peeling, P., Binnie, M.J., Goods, P.S.R., Sim, M., Cross, R., & Siegler, J. (2020). Topical sodium bicarbonate: No improvement in blood buffering capacity or exercise performance. *International Journal of Sports Physiology and Performance, 15*(7), 1005–1011. https://doi.org/10.1123/ijspp.2019-0345

McNaughton, L.R., Gough, L., Deb, S., Bentley, D., & Sparks, S.A. (2016). Recent developments in the use of sodium bicarbonate as an ergogenic aid. *Current Sports Medicine Reports, 15*(4), 233–244. https://doi.org/10.1249/JSR.0000000000000283

Messonnier, L., Kristensen, M., Juel, C., & Denis, C. (2007). Importance of pH regulation and lactate/H+ transport capacity for work production during supramaximal exercise in humans. *Journal of Applied Physiology, 102*(5), 1936–1944. https://doi.org/10.1152/japplphysiol.00691.2006

Middlebrook, I., Peacock, J., Tinnion, D.J., Leach, N.K., Hilton, N.P., Saunders, B., Sparks, A., & Mc Naughton, L.R. (2021). Capsule size alters the timing of metabolic alkalosis following sodium bicarbonate supplementation. *Frontiers in Nutrition, 8*, Article 634465. https://doi.org/10.3389/fnut.2021.634465

Pan, R., Tian, Y., Gao, R., Li, H., Zhao, X., Barrett, J.E., & Hu, H. (2012). Central mechanisms of menthol-induced analgesia. *Journal of Pharmacology and Experimental Therapeutics, 343*(3), 661–672. https://doi.org/10.1124/jpet.112.196717

Prausnitz, M.R., & Langer, R. (2008). Transdermal drug delivery. *Nature Biotechnology, 26*, 1261–1268. https://doi.org/10.1038/nbt.1504

Reilly, T. (1990). Human circadian rhythms and exercise. *Critical Reviews in Biomedical Engineering, 18*(3), 165–180. https://europepmc.org/article/med/2286092

Remer, T. (2001). Influence of nutrition on acid-base balance–metabolic aspects. *European Journal of Nutrition, 40*, 214–220. https://doi.org/10.1007/s394-001-8348-1

Rosales, A.M., Walters, M.J., McGlynn, M.L., Collins, C.W., & Slivka, D.R. (2024). Influence of topical menthol gel on thermoregulation and perception while walking in the heat. *European Journal of Applied Physiology, 124*(1), 317–327. https://doi.org/10.1007/s00421-023-05279-0

Sahlin, K. (2014). Muscle energetics during explosive activities and potential effects of nutrition and training. *Sports Medicine, 44*(Suppl 2), 167–173. https://doi.org/10.1007/s40279-014-0256-9

Simoneau, J.A., & Bouchard, C. (1989). Human variation in skeletal muscle fiber-type proportion and enzyme activities. *American Journal of Physiology-Endocrinology and Metabolism, 257*(4), E567–E572. https://doi.org/10.1152/ajpendo.1989.257.4.E567

Small, K., McNaughton, L., Greig, M., & Lovell, R. (2010). The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *Journal of Science and Medicine in Sport, 13*(1), 120–125. https://doi.org/10.1016/j.jsams.2008.08.005

Sostaric, S.M., Skinner, S.L., Brown, M.J., Sangkabutra, T., Medved, I., Medley, T., Selig, S. E., Fairweather, I., Rutar, D., & McKenna, M.J. (2006). Alkalosis increases muscle K+ release, but lowers plasma [K+] and delays fatigue during dynamic forearm exercise. *The Journal of Physiology, 570*(1), 185–205. https://doi.org/10.1113/jphysiol.2005.094615

Spencer, M., Bishop, D., Dawson, B., & Goodman, C. (2005). Physiological and metabolic responses of repeated-sprint activities: Specific to field-based team sports. *Sports Medicine, 35*(12), 1025–1044. https://doi.org/10.2165/00007256-200535120-00003

Spriet, L.L., Lindinger, M.I., McKelvie, R.S., Heigenhauser, G.J., & Jones, N.L. (1989). Muscle glycogenolysis and H+ concentration during maximal intermittent cycling. *Journal of Applied Physiology, 66*(1), 8–13. https://doi.org/10.1152/jappl.1989.66.1.8

Street, D., Nielsen, J-J., Bangsbo, J., & Juel, C. (2005). Metabolic alkalosis reduces exercise induced acidosis and potassium accumulation in human skeletal muscle interstitium. *The Journal of Physiology, 566*(2), 481–489. https://doi.org/10.1113/jphysiol.2005.086801

World Medical Association (2013). World medical association declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Young, W.B., Dawson, B., & Henry, G.J. (2015). Agility and change-of-direction speed are independent skills: Implications for training for agility in invasion sports. *International Journal of Sports Science & Coaching, 10*(1), 159–169. https://doi.org/10.1260/1747-9541.10.1.159