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

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Running head: Sodium Bicarbonate and Soccer Exercise

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ABSTRACT

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, ten 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 x 25 m repeated sprints) throughout a 90 min soccer-specific aerobic field test (SAFT90) following 0.3 g/kg body mass (BM) SB in capsules (SB-ORAL), 0.9036 g/kg BM 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^- pre-warm-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^+ post-exercise 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, ergogenic aids, lotion, sprints, agility, soccer

Introduction

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 (ATP) 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 towards 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 (Macutkiewicz & Sunderland, 2018; Dalle et al. 2021), 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 et al. (2023a)

showed a 1.8% improvement (p = .023, d = .38) in 8 x 25 m repeated sprint times after SB. Krustrup et al. (2015) and Mariott et al. (2015) found SB to increase distance covered during the Yo-Yo Intermittent Recovery Test Level 2 (Yo-Yo IR2) by 14% (p = .04) and 23% (p < .05), respectively. In contrast, Guimarães et al. (2020) reported no improvements for 6 x 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, Utah), which is a topically applied muscle cream purported to deliver SB into systemic circulation via the transdermal route (Prausnitz & Langer, 2008). Gurton et al. (2023a) reported a 1.9% improvement (p = .036, d = .34) for 8 x 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 x 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.

Whilst 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 towards 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 x 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, placebo) were allocated to be received by four participants first, second and third during experimental trials using a 3 x 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 (v3.1.9.4) revealed that 10 participants were needed to achieve statistical power (β = .80; α = .05). This assumed that repeated measures analysis of variances (ANOVA; within-factors) would be used to analyze sprint times (primary outcome) with a medium effect size (partial eta squared, η_p^2 = .06) expected. Correlation between repeated measures (r = .85) was estimated using data for the repeated sprint protocol (Gurton et al., 2023a). Twelve participants were recruited, however two withdrew due to time commitments. Therefore, ten collegiate male soccer players (age: 24 ± 3 years, stature: 1.82 ± 0.03 m, body mass: 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.

Pre-Experimental 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 post-prandial state to minimise the influence of potential renal acid load on acid-base balance (Remer, 2001). Visual inspection of food diaries (consistency of food choice, patterns, portion sizes) by the principal investigator revealed that compliance to dietary controls was met. Experimental trials were separated by 5-7 d 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 et al., 2023a). Familiarization involved conducting performance tests and one block of the SAFT90. Three CMJ were performed on an optical measurement system (Optojump Next, Microgate, USA), with 1 min separating each jump. Next, participants carried out three IAT followed by 8 x 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, USA) 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 CD 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 analysed 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, cornflakes with milk) over 30 min. They were not permitted to consume any additional food. Water was consumed ad libitum (1115 ± 465 mL) during the first trial, with equal volumes provided during subsequent sessions. Gastrointestinal discomfort, cooling sensations and blinding questionnaires were completed post-supplementation and pre-warm-up. Capillary blood samples were repeated pre-warm-up. Participants started the warm-up 105 min post-supplementation, with the first bout of performance tests (pre-SAFT90) commencing 120 min post-supplementation. 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 post-exercise. Additional blood samples were analyzed for lactate post-warm-up, after performance tests and following both halves of the SAFT90. Gastrointestinal discomfort was measured during half-time and post-exercise.

Blinding questionnaires were repeated post-exercise.

Supplementation Protocol

During experimental trials, participants received either: i) 0.3 g/kg BM SB in capsules and 0.9036 g/kg BM placebo lotion (SB-ORAL), ii) placebo capsules and 0.9036 g/kg BM PR Lotion (SB-LOTION), iii) placebo capsules and 0.9036 g/kg BM placebo lotion (PLA). Supplements were prepared by a laboratory technician. Size 0 vegetarian capsules (Your Supplements, UK) were filled using a capsule filling device (ALL-IN Capsule, USA) and contained ~0.8 g SB (Health Leads Ltd, UK) or ~0.4 g cornflour (Sainsbury's, UK). Capsule size influences acid-base balance pharmacokinetics after SB ingestion, with peak changes in HCO_3^- occurring ~2.5 hr post-supplementation 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 g of PR Lotion to match the 0.3 g/kg BM oral SB dose (McKay et al., 2020; Gurton et al., 2023a). 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 to 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 (Utah, USA). The placebo-matched lotion was supplied by the manufacturer with SB removed but still containing 0.5% menthol as per commercially available PR Lotion. Cornflour 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 analysed for pH, HCO_3^-, Na^+, K^+ and ionized calcium (iCa^{2+}) using an i-STAT Alinity (Abbott, USA). This analyser 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, Germany; coefficient of variation <1.5%, at a value of 12 mmol/L). Aggregate gastrointestinal discomfort was quantified from questionnaires consisting of 100 mm visual analogue scales for side-effects (nausea, flatulence, abdominal discomfort, gut fullness, bowel urgency, diarrhoea, vomiting, 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", "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 were analysed 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 to .75), good (r = .75 to .90) or excellent (r >

.90) (Koo and 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 were 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 partial eta squared (η_p^2). These were interpreted using the classifications of 0.01, 0.06 and 0.14 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 (< .20), small (.20 to .49), moderate (.50 to .79) or large (≥ .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 pair-wise comparisons were conducted to explore treatment differences further, with Z statistic and median values presented. Treatment assignment ratings ("correct," "incorrect") were analysed 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 [IQR]) and statistical significance was set at $p < .05$. Statistical analyses were performed using SPSS v26.0 (IBM, Chicago, IL).

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, η_p^2 = .293) and average ($F_{4,36}$ = 2.888, p = .036, η_p^2 = .243) sprint times. Repeated sprint times were similar between treatments pre-SAFT90 (p > .05; **Figure 2 A-B**). 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 decline in fastest times, with no differences between time-points ($F_{3,12}$ = 3.034, p = .073, η_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 decline in average times, with performance 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 3 A-B**). 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.

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, η_p^2 = .297), HCO_3^- ($F_{1.85,16.34}$ = 4.355, p = .033, η_p^2 = .326), Na^+ ($F_{6,54}$ = 2.982, p = .014, η_p^2 = .249), K^+ ($F_{3.06,27.54}$ = 5.844, p = .003; η_p^2 = .394) and iCa^{2+} ($F_{2.75,24.77}$ = 3.138, p = .047, η_p^2 = .259) but not lactate (p = .207) where only a main effect was shown for time (p < .001, η_p^2 = .821; **Figure 4**).

With respects to SB-ORAL, blood pH and HCO_3^- were elevated compared with PLA pre-warm-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 pre-warm-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**). Post-exercise 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 non-significant (p > .05).

With respects to SB-LOTION, blood pH was elevated compared with PLA during half-time (p = .019). Half-time K^+ was lower than PLA (p = .012). Post-exercise Na^+ was higher compared with PLA (p = .008). All other comparisons for SB-LOTION were non-significant (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, η_p^2 = .263). 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 block 3 to 6 (p < .05; **Figure 5**).

Gastrointestinal Discomfort, Blinding & Cooling Sensation

In general, gastrointestinal discomfort was mild for each treatment (**Table 3**), however a treatment effect was shown post-supplementation ($\chi^2(2)$ = 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 post-supplementation and pre-warm-up, however more correct ratings were recorded post-exercise (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 were similar between treatments (p > .05; **Table 4**). Treatment effects existed for cooling sensations post-supplementation for the thighs ($\chi^2(2)$ = 6.452, p = .040) and pre-warm-up for the calves ($\chi^2(2)$ = 12.069, p = .002). Cooling for the thighs were greater post-supplementation 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 pre-warm-up for 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 favour of SB-ORAL for agility performance. No significant improvements in performance were observed for SB-LOTION

throughout. Blood buffering capacity was increased pre-warm-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 post-exercise, 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.

Blood buffering capacity was elevated for SB-ORAL, with pre-warm-up changes in HCO_3^- (~5 mmol/L) consistent with studies showing ergogenic effects after SB (Krustrup et al., 2015; Gurton et al., 2023a). In contrast, blood pH and HCO_3^- did not increase pre-warm-up following SB-LOTION, supporting recent studies (McKay et al., 2020; Gurton et al., 2023a). Transdermal drug delivery is only effective when small doses (mg per day) of a treatment are required (Prausnitz & Langer, 2008). Whilst 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 et al., 2023a). Inconsistent results could relate to discrepancies in testing battery, as the “all-out” nature of IAT efforts may have utilised increased circulating HCO_3^- ahead of our 8 x 25 m repeated sprints (Gurton et al., 2021). That being said, Marriott et al. (2015) found SB to increase distance covered during the Yo-Yo IR2 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 IR2 (~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 favour 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. Firstly, elevated blood pH and HCO_3^- suggest oral SB protected against declining intramuscular pH during the simulated soccer exercise (Bishop et al., 2004). Secondly, 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 (McKay et al., 2020; Gurton et al., 2023). 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 hypothesised 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 et al., 2023a). 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 3-6, 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 & 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 et al., 2020). Our male soccer players likely had larger type II muscle fibres that rely heavily on glycolysis for ATP production (Simoneau & Bouchard, 1989), meaning they had more to gain from SB. Unlike previous studies (Krustrup et al., 2015; Gurton et al., 2023a), non-significant 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 were 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 post-exercise

351 Na^+ (~3 mmol/L) for SB-LOTION. Our study is the first to examine PR Lotion over ~4 hr, so
352 it is possible transdermal delivery of Na^+ takes longer than initially thought.
353
354 **Strengths, Limitations, and Practical Applications of the Study**
355 One of this study's strengths was recruiting collegiate level soccer players. Specifically, the
356 high level of test reproducibility, combined with the absence of order effects, confirms
357 participants were familiarized to soccer-specific exercise, meaning improvements for SB-
358 ORAL were not attributed to learning effects. Secondly, oral SB was successfully blinded,
359 allowing us to conclude ergogenic benefits were due to pharmacological properties of SB
360 (Gurton et al., 2023b). This study's main limitation was that five participants identified SB-
361 LOTION, which may have induced placebo effects that influenced study outcomes (Hurst et
362 al., 2020). Depending on participants expectancy of positive benefits, identifying PR Lotion
363 could have contributed to lower RPE during the SAFT90.
364 Practical implications of our results are that oral SB is the most effective
365 supplementation approach for improving blood buffering capacity and repeated sprint
366 performance during soccer match play exercise. Negligible, or less pronounced effects, were
367 shown for IAT and CMJ. Considerably fewer benefits were reported for topical SB, adding to
368 equivocal findings for the efficacy of PR Lotion (McKay et al., 2020; Gurton et al., 2023a).
369 Interestingly, oral SB caused milder gastrointestinal discomfort compared with previous
370 studies (Cameron et al., 2010; Gurton et al., 2020). Splitting SB supplementation across 30 min
371 likely alleviates gastrointestinal side-effects, however SB must be trialled on an individual
372 basis, as symptoms may still occur. It is recommended that practitioners take the results of this
373 study into consideration when incorporating SB into nutritional regimes for soccer players.
374
375 ## 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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Tables

Table 1 Blood acid-base balance from baseline to post-exercise

	Baseline	Pre-warm-up	Half-time	Post-exercise
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-ORAL vs. PLA, ^ SB-LOTION vs. PLA, # SB-ORAL vs. SB-LOTION and PLA ($p < .05$).

Table 2 Strong ion concentration from baseline to post-exercise

	Baseline	Pre-warm-up	Half-time	Post-exercise
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; $n = 10$. Symbols denote significance: * SB-ORAL vs. PLA, ^ SB-LOTION vs. PLA, † SB-ORAL vs. SB-LOTION, # SB-ORAL vs. SB-LOTION and PLA ($p < .05$).

Table 3 Aggregate gastrointestinal discomfort score from baseline to post-exercise

	Baseline	Post-supplementation	Pre-warm-up	Half-time	Post-exercise
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 [IQR]. Aggregate gastrointestinal discomfort score (out of 800 mm) calculated from sum of visual analogue scales for eight symptoms; 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
Post-supplementation			
Correct ratings	1 (10%)	**5 (50%)**	1 (10%)
Incorrect ratings	0 (0%)	0 (0%)	1 (10%)
Unsure ratings	9 (90%)	5 (50%)	8 (80%)
Pre-warm-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%)
Post-exercise			
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.

Figure legends

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. *Abbreviations:* ABB = acid-base balance (blood pH, bicarbonate), strong ions (sodium, potassium, calcium), GI = gastrointestinal discomfort questionnaire (visual analogue scales for eight symptoms).

Figure 2 – (A) fastest and (B) average times during the 8 x 25 m repeated sprint tests. Bars represent mean values; *n* = 10. Individual treatment differences depicted by symbol/line. *Abbreviations:* RST1/2/3 = repeated sprint test 1 (pre-SAFT90), 2 (half-time) and 3 (post-SAFT90). Symbols denote significance ($p < .05$): * SB-ORAL vs. PLA, $^{\#}$ SB-ORAL vs. SB-LOTION and PLA, † decline in sprint times for SB-LOTION and PLA, but not SB-ORAL, ‡ decline in sprint times for all treatments.

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. *Abbreviations:* IAT1/2/3 = Illinois agility test 1 (pre-SAFT90), 2 (half-time) and 3 (post-SAFT90). Symbols denote significance ($p < .05$): ** main effect for treatment (SB-ORAL faster than SB-LOTION and PLA).

Figure 4 – blood lactate response throughout the simulated soccer exercise. Values are presented as Mean ± SD; *n* = 10. Some error bars removed for clarity. *Abbreviations:* RST1/2/3 = repeated sprint test 1 (pre-SAFT90), 2 (half-time) and 3 (post-SAFT90).

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.

Figures

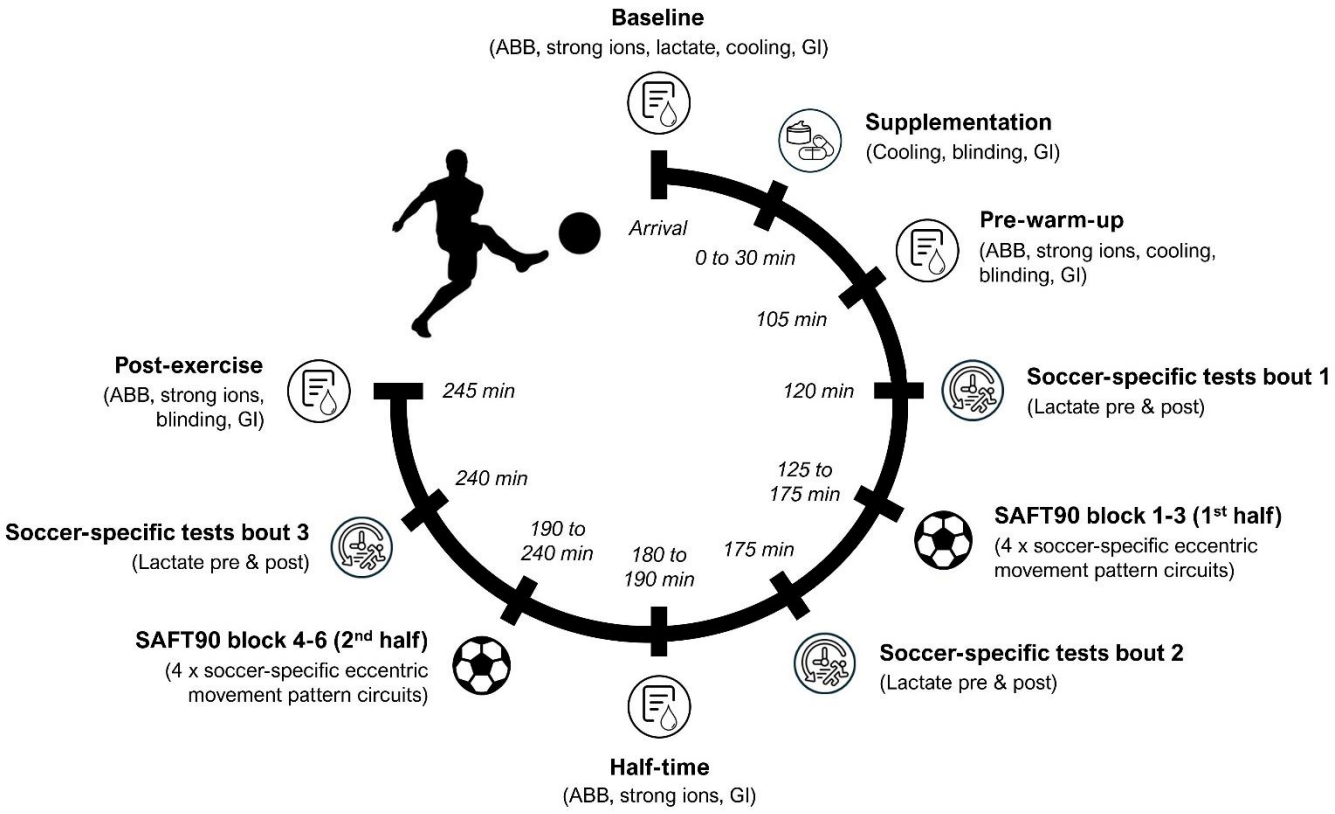

Figure 1

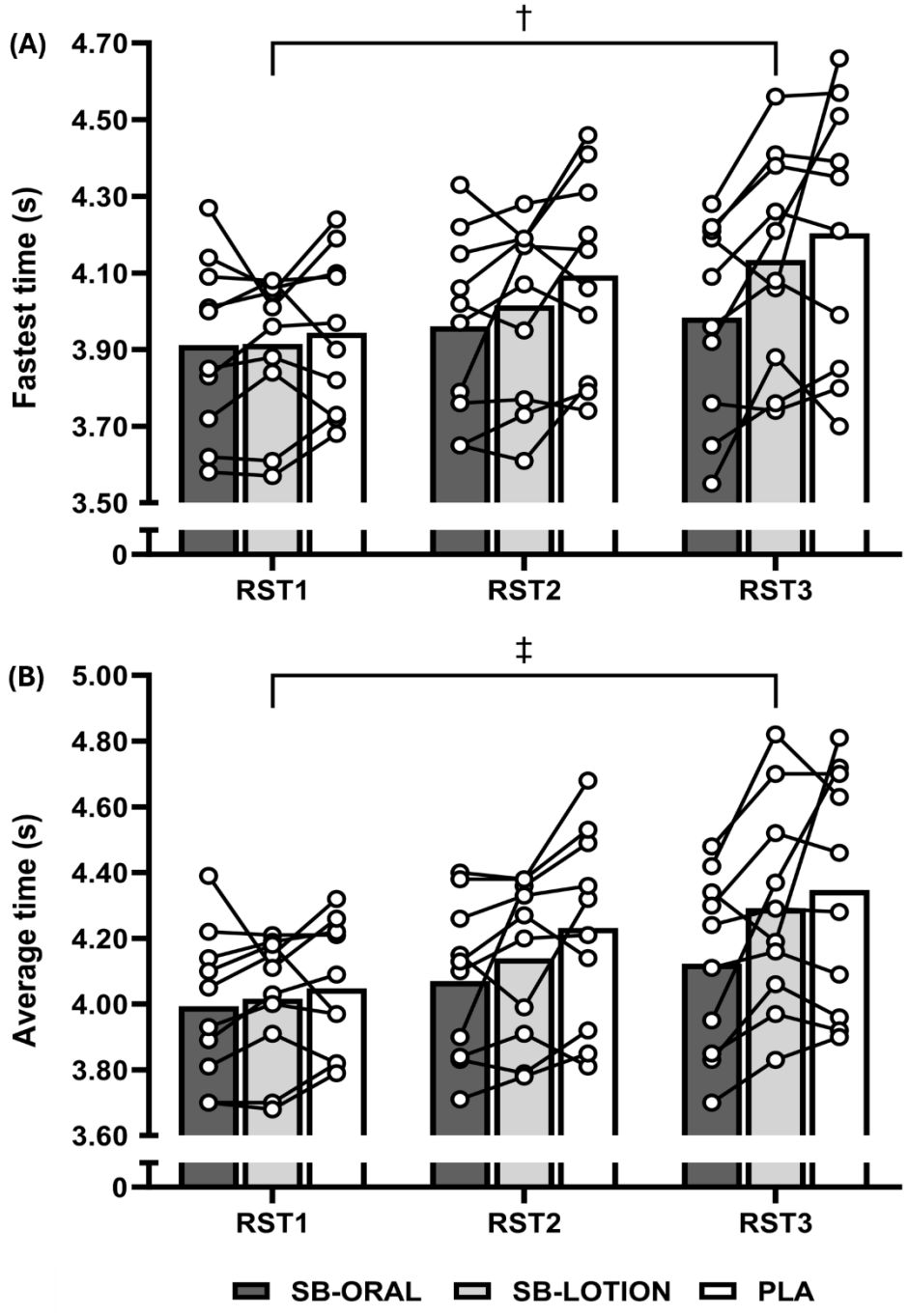
(A)
†
Fastest time (s)
4.70
4.50
4.30
4.10
3.90
3.70
3.50
0
RST1
RST2
RST3
(B)
‡
Average time (s)
5.00
4.80
4.60
4.40
4.20
4.00
3.80
3.60
0
RST1
RST2
RST3
SB-ORAL
SB-LOTION
PLA

Figure 2 A-B

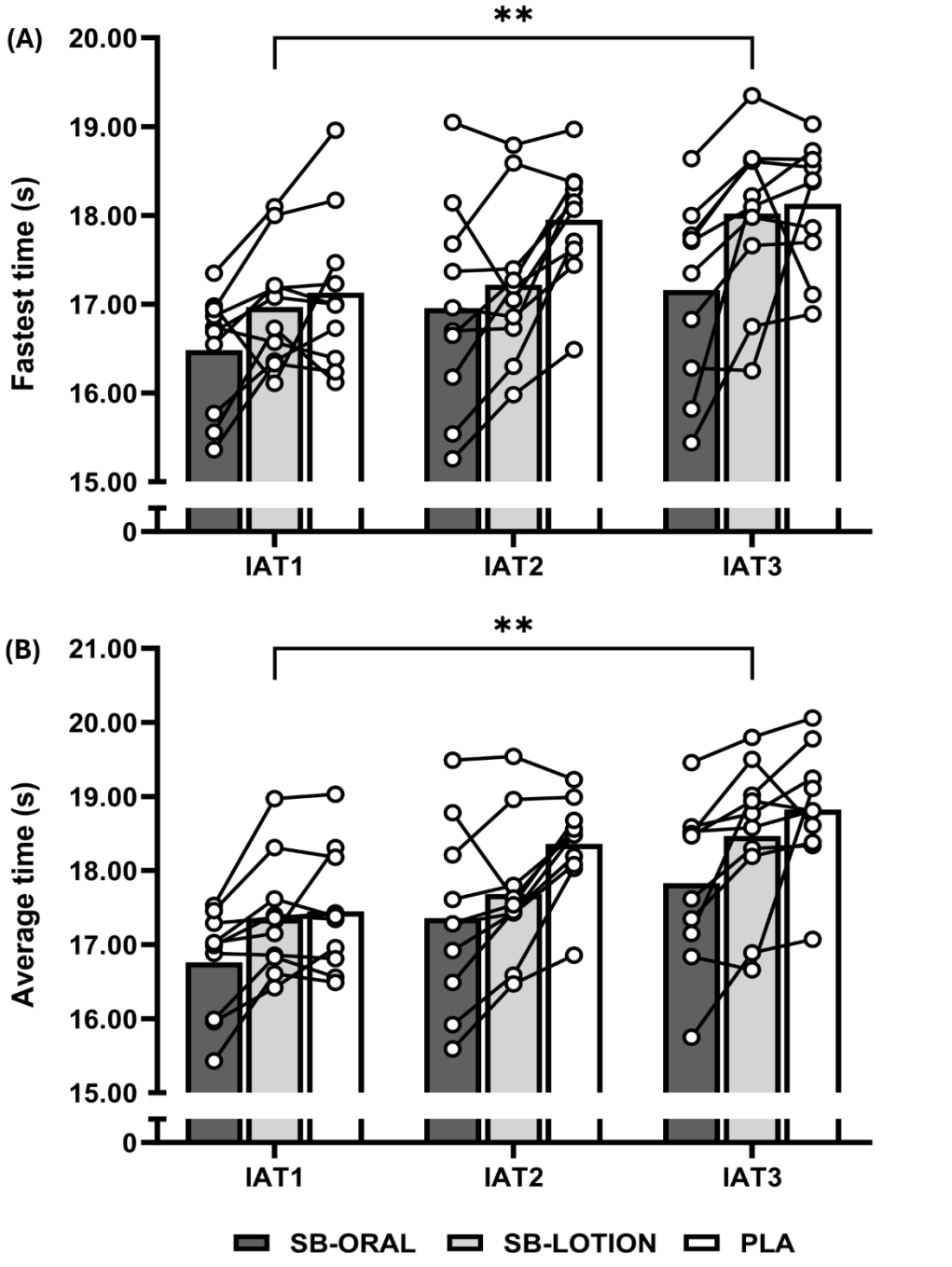
(A)
**
20.00
19.00
18.00
17.00
16.00
15.00
0
Fastest time (s)
IAT1
IAT2
IAT3
(B)
**
21.00
20.00
19.00
18.00
17.00
16.00
15.00
0
Average time (s)
IAT1
IAT2
IAT3
SB-ORAL
SB-LOTION
PLA

Figure 3 A-B

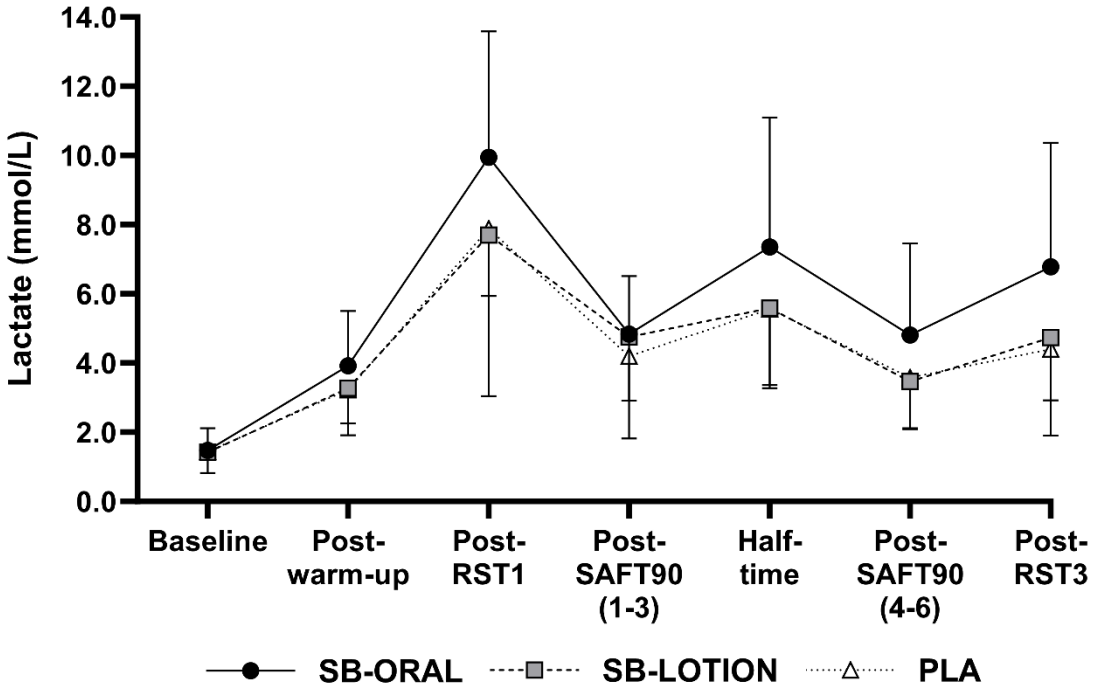

Figure 4

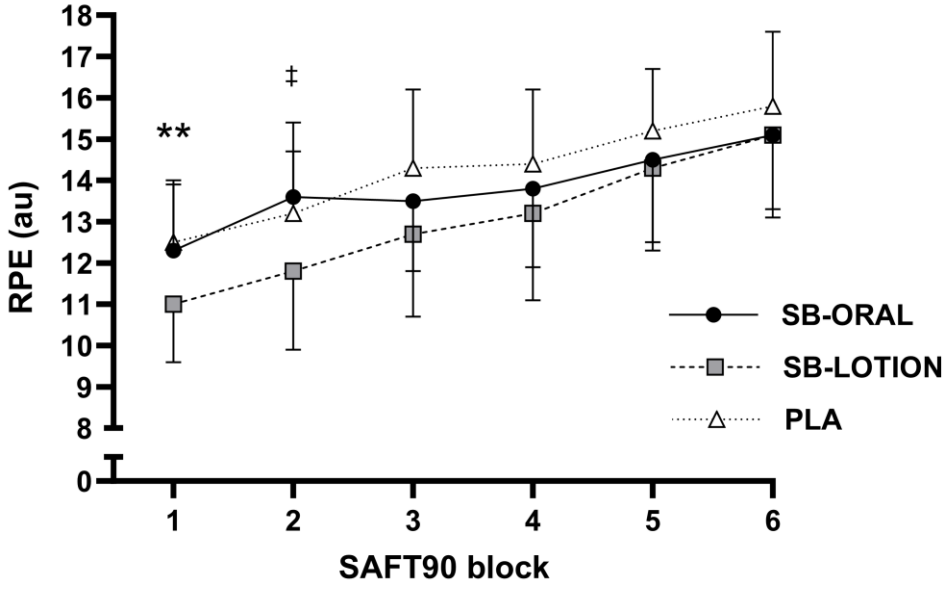

Figure 5