Manuscript Title Negligible effects of high fructose–glucose and moderate glucose-only carbohydrate intake on technical and neuromuscular performance during a prolonged soccer match simulation in semi-professional soccer players

Running Head Carbohydrates and soccer performance

Abstract

Higher carbohydrate availability, achieved through combined intake of glucose and fructose, has shown to enhance endurance performance. This study examined the effects of higher carbohydrate doses containing a fructose–glucose mixture (1:2 ratio) on performance during a 120-min simulated soccer match, compared to lower doses containing only glucose. Fifteen semi-professional soccer players (7 males, 8 females) completed two 120-min soccer-specific exercise sessions in a randomised and crossover design. Participants consumed either 60 $g \cdot h^{-1}$ glucose, or a combination of 0.5 $g \cdot min^{-1}$ fructose and 1.0 $g \cdot min^{-1}$ glucose (90 $g \cdot h^{-1}$) at pre-exercise, halftime, full-time, and midway through extra-time. Measures including gastrointestinal (GI) discomfort, mental fatigue, passing accuracy, neuromuscular performance (reactive strength index, countermovement jump height, peak power output), and sprint performance (15 and 30m sprints), were assessed at 0-min, 45-min, 90-min, and 120-min. Blood glucose and lactate concentrations were assessed every 15 min. Fructose–glucose co-ingestion elevated blood glucose concentration from 105 min (p=0.006, d=1.2), but did not maintain performance (p>0.05). GI symptoms of gastric reflux at 45-min (p=0.011, d=0.9), fullness at 90-min (p=0.013, d=0.9), and flatulence at 120-min worsened in glucose (p=0.003, d=1.1). Abdominal cramps were greater in fructose–glucose at 45-min (p<0.001, d=1.7) and 90-min (p<0.001, d=1.6). Although supplementation did not influence any other variables (p<0.05), countermovement jump height, peak power output and sprint performance was negatively influenced by exercise in both conditions (p<0.05). A higher carbohydrate dosage of fructose–glucose co-ingestion increases blood glucose concentrations but does not mitigate technical and neuromuscular performance impairments during a prolonged simulated soccer match.

Keywords Gastrointestinal discomfort, intermittent exercise, football

Introduction

During prolonged exercise lasting ≥ 2 h, dietary carbohydrate (CHO) ingestion may delay the onset of fatigue by reducing liver glycogen depletion (Fuchs et al., 2019), maintaining blood glucose concentration — an essential energy source for both muscle and brain (Cermak & van Loon, 2013) — and by influencing neurotransmitter activity, which could affect cognition and motor skill performance (Welsh et al., 2002). Despite these benefits, the optimal CHO dose for exercise exceeding 2 h remains unknown. Recent evidence indicates a dose-response relationship, provided that the ingested CHO are oxidised and do not induce gastrointestinal (GI) distress (Rollo & Williams, 2023). The oxidation rate of single-CHO formulations, such as glucose, are approximately 60 $g \cdot h^{-1}$ due to saturation of the sodium-dependent glucose transporter (SGLT1) at higher ingestion rates (Currell & Jeukendrup, 2008). However, oxidation efficiency is influenced by factors such as on body size (Ijaz et al., 2024) and the type of CHO consumed (Rowlands et al., 2015). Ingesting fructose–glucose blends at rates exceeding 70 $g \cdot h^{-1}$ enhances oxidation compared to isocaloric glucose-only beverages during prolonged exercise lasting ≥ 2 h (Currell & Jeukendrup, 2008; Jentjens et al., 2004; Jeukendrup, 2010; Jeukendrup et al., 2006). This is attributed to the utilisation of distinct intestinal transporters, allowing for greater CHO absorption and oxidation (Jeukendrup & Jentjens, 2000). Consequently, combining multiple monosaccharides when CHO intake surpasses 60 $g \cdot h^{-1}$ may optimise oxidation, improve gut comfort, and enhance endurance performance. (Jeukendrup, 2004; Macdermid et al., 2012).

Most evidence on the effectiveness of differing doses of CHO provision during prolonged endurance exercise is derived from investigations conducted with endurance cyclists. A study investigated the relationship between CHO ingestion rate and endurance performance in 51 cyclists and triathletes (Smith et al., 2013). Participants consumed varying CHO doses in increments of 10 $g \cdot h^{-1}$, ranging from 10 to 120 $g \cdot h^{-1}$, during a 2-h constant load ride, followed by a 20-km time trial to assess performance outcomes. The results revealed that performance improvements peaked at a CHO ingestion rate of 78 $g \cdot h^{-1}$ (1:1:1 glucose-fructose-maltodextrin), beyond which additional intake provided no further benefits. A separate investigation found that ingestion of 90 $g \cdot h^{-1}$ CHO, with a 1:2 ratio of fructose to glucose, was optimal for cycling time trial performance after prolonged sub-maximal exercise compared to 80 and 100 $g \cdot h^{-1}$ CHO (King et al., 2019). This study demonstrated that increased CHO availability enhances performance, with 90 $g \cdot h^{-1}$ of CHO in a 1:2 fructose-to-glucose ratio identified as optimal for endurance cycling athletes. However, it remains unclear whether these findings translate to intermittent exercise performance, such as team sports, particularly when the activity lasts around 2 h (e.g., soccer matches extending into extra time). Guidelines recommend ingesting 30–60 $g \cdot h^{-1}$ CHO during 90-min soccer matches (Collins et al., 2021); however, players competing over an extended duration might benefit from higher CHO ingestion rates, which might be optimally absorbed *via* combinations of fructose and glucose. Additionally, fructose–glucose combinations may help mitigate the adverse effects of consuming concentrated CHO, which is particularly important given the limited opportunities for CHO intake during real-world soccer match play (Rodriguez-Giustiniani et al., 2019).

Soccer matches usually last 90-min, however when matches are tied and an outright winner is required, for example during the knockout phase of major international tournaments (e.g., FIFA World Cup), an additional 30-min period, called extra-time, is required. Recently, 33% of knockout matches advanced to extra-time at the 2022 FIFA World Cup and 2024 UEFA Euro competitions, with >85% of finalists participating in a 120-min match since 1992 (Mohr et al., 2023). Compared to typical 90-min soccer matches, players cover 5–12% less total distance, approximately 18% less high-speed distance, and experience a 20% reduction in passing success during extra-time (Field et al., 2022). Players also perform less frequent activities of running at high speed or sprinting during extra-time versus 90-min (Mohr et al., 2023). CHO-electrolyte gels (0.7 ± 0.1 $g \cdot kg^{-1} BM^{-1}$), when ingested five min before commencing the extra-time period of simulated soccer matches, can restore technical performance, with enhanced dribbling performance compared with an energy-free placebo, although without an impact on physical performance (Harper et al., 2016). A separate study examined the effects of three different CHO intake conditions during a 90-min soccer-specific exercise protocol: glucose (1 $g \cdot min^{-1}$), a glucose (0.66 $g \cdot min^{-1}$) plus fructose (0.33 $g \cdot min^{-1}$) combination, and a placebo (<0.5 g CHO) (Clarke et al., 2012). The study found that although total CHO oxidation was higher with the glucose–fructose solution, there were no significant differences in muscle glycogen concentration or exercise capacity between treatments. However, since participants in the studies above consumed an acute dose of CHO (Harper et al., 2016), and exercised for 90 min rather than 120 min (Clarke et al., 2012), it remains uncertain whether higher doses of fructose–glucose can help preserve performance in simulated soccer tasks that replicate the demands of extra time.

This study aimed to evaluate the effects of a high-CHO fructose–glucose gel on performance during a 120-min simulated soccer match, compared to a lower-CHO glucose-only gel. It was hypothesised that consuming the fructose–glucose composite would attenuate declines in soccer-specific exercise performance more effectively than the glucose-only control condition.

Methods

Ethical approval

Institutional ethical approval was granted (ID: 59869). The study was registered on the Open Science Framework (link) and complied with the latest revision of the *Declaration of Helsinki*. All participants provided written informed consent prior to participation, after experimental procedures and risks were explained.

Research design

A cross-over design was applied with an independent technician assigning participants to fructose–glucose and glucose conditions in a counterbalanced order, using a random number generator. The study involved three visits to the laboratory. A screening/familiarisation visit preceded the two main trials, including a health screening questionnaire, anthropometric measures, and habituation with the experimental procedures, including the soccer-specific warm-up, Loughborough Soccer Passing Test (LSPT), 120-min simulated soccer-match simulation, physical measurement techniques, and interpretations of subjective data collection. All measurements exhibited a coefficient of variation (CV) below 5% between familiarisation and testing across all time points, indicating that learning effects were minimal. The subsequent two visits included completion of the 120-min simulation, where participants received gels containing either fructose–glucose or glucose only. GI discomfort (nausea, fullness, reflux, abdominal cramps, flatulence and urges to have a bowel movement), mental fatigue (visual analogue scale [VAS]), passing accuracy (LSPT), countermovement jump (CMJ, jump height, peak power output, negative displacement), drop jump (DJ, reactive-strength index) and sprint performance (15 and 30m) were assessed at 0-min, 45-min, 90-min and 120-min. Capillary blood samples (blood glucose (Blg) and lactate (BLa) concentrations; Biosen C-Line, Wales) were obtained each 15-min period during trials.

Participants

Fifteen semi-professional soccer players, including seven males (age: 21.4±2.1 years, stature: 1.78.0±0.03 m, mass: 77.0±4.7 kg) and eight females (age: 20.6±1.8 years, stature: 1.63.1±0.04 m, mass: 58.7±3.4 kg) voluntarily completed all study procedures between February and May 2024. The players were classified as semi-professional, as they were not participating on a full-time basis, but still received some payment from the soccer club. An *a priori* power calculation was undertaken (G*Power, Germany, version 3.1), with a sample size of 14 sufficient, based on 90% power (1–β), an alpha (α) of .05, a large effect size (Cohen's f=0.4), two groups and four measurement points. These effects were based on previous data evaluating the effects of CHO-electrolyte gels on skill measures during extra-time Participants were recruited from a range of local semi-professional soccer clubs, had 3 ±1 years of competitive soccer experience at the semi-professional level and engaged in soccer training and/or competition three days per week. Individuals with contraindications to exercise (e.g., not injury free at data collection) were deemed ineligible. The subsequent main trial was completed 8±1 days after the first experimental trial, with hormonal contraceptive users undertaking trials during the pill taking phase. Non-hormonal contraceptive users completed their second trial 29±2 days after the first, aiming to be in the same estimated phase of the menstrual cycle. Cycle phase was estimated using calendar-based counting, whereby the self-reported onset of menses was considered as day one, and the phase was identified by counting forward from this point (McNulty et al., 2020). Three participants dropped out of the study due being incapable of completing the soccer match simulation (n=2) and personal issues (n=1).

Dietary standardisation

Participants recorded dietary intake via weighed food diaries 24h preceding the first experimental trial, which was repeated for the subsequent trial with remote food photography used to monitor engagement (Stables et al., 2021). Additionally, water was consumed *ad libitum* at 45-min (511 ± 214 ml) and 90-min (278±119 ml) during the first experimental trial. Water volumes were measured and replicated in the second trial. Participants were advised to meet current CHO guidelines in the 24 h before the trial (6–8 g·kg^{-1}BM^{-1}) (Collins et al., 2021) and avoid alcohol, caffeine and strenuous exercise 48 h prior to testing. In the 24 h before the trial, participants consumed 3,192 ± 490 kcal with 352 ± 153 g CHO (5.19 ± 2.26 g·kg^{-1} BM^{-1}), 182 ± 38 g protein (2.68 ± 0.56 g·kg^{-1} BM^{-1}), and 118 ± 32 g fat (1.74 ± 0.47 g·kg^{-1} BM^{-1}) for the fructose–glucose condition, and 3,042 ± 510 kcal with 330 ± 165 g CHO (4.87 ± 2.43 g·kg^{-1} BM^{-1}), 160 ± 40 g protein (2.36 ± 0.59 g·kg^{-1} BM^{-1}), and 120 ± 28 g fat (1.77 ± 0.41 g·kg^{-1} BM^{-1}) for the glucose condition, with no significant differences between conditions (p>0.05). A standardised, pre-packaged breakfast meal comprising of milk, cereal, and orange juice (2-g·kg^{-1} BM^{-1} CHO) was consumed 3h before arrival for the experimental trials in line with recommendations (Collins et al., 2021).

Experimental approach

Upon arrival at the laboratory at ~10 am, baseline hydration status was measured from a mid-flow urine sample (Osmocheck, Vitech Scientific, UK), resting fingertip blood capillary samples were taken for BLa and Blg concentrations, and body mass recorded (Seca 875, Germany). Participants completed a standardised ~20-min warm-up comprising of dynamic activity (high-knees, butt-kicks, bodyweight squats), multi-directional running (straight-line running, lateral skipping/jumping, multidirectional tasks), technical actions (dribbling, passing) and progressive, maximal sprinting (Zois et al., 2011). Before the soccer match simulation, baseline assessments of GI discomfort, mental fatigue, LSPT, DJ, CMJ and 30m sprints were conducted. Testing was performed indoors, and environmental conditions were similar between conditions (temperature: 17.1 ± 1.8°C vs. 16.6 ± 1.9°C, pressure: 928 ± 11 mmHg vs. 939±10 mmHg, humidity: 48 ± 11% vs. 45 ± 10% for glucose and fructose–glucose, respectively; all $p>0.05$).

Soccer match simulation

Participants completed a validated 120-min soccer match simulation (Harper et al., 2016). Although the simulation was originally validated in male players (Russell et al., 2011), adjustments were made such that females completed shorter distances within each given timeframe. Male players covered ~14.1 km, including, 5.45 km in the first and second half each and 3.2 km during extra-time (Harper et al., 2016). Females covered ~12.3 km, including, 4.3 km in the first and second half each, and 3.7 km during extra-time. Table 1 summarises the soccer match simulation in alignment with female match data (Datson et al., 2014). Audio signals controlled the simulation, which involved completion of varying speeds, forwards, backwards and sideways activity across set distances (20 or 18m), sprints (15 or 13m), and ball dribbling (18 or 16m) for males and females. Participants completed the soccer match simulation in two 45-min halves separated by 15-min recovery, plus a subsequent extra-time period, comprising of two 15-min bouts separated by a two-min break. Participants were informed after 90-min only that the simulated soccer-match would proceed to extra-time to avoid pacing.

*******INSERT TABLE 1*******

Heart rate was continuously recorded (Polar H10, Polar Electro Oy, Finland), and Blg and BLa concentrations (CV=1.5%), and ratings of perceived exertion (RPE: CR-100 scale) were determined every 15 min throughout exercise. Assessments of GI discomfort, mental fatigue, LPST, DJ, CMJ, 15m and 30m sprint performance were conducted at 45-min, 90-min, and 120-min. Body mass and hydration status were obtained after trial completion and sweat loss (corrected for fluid intake and urine loss) was calculated as change in body mass.

Sex-specific characteristics

The study involved four hormonal contraceptive users (three combined pill, one implant user) and four non-hormonal contraceptive users, possessing a regular cycle (21 and 35 days for ≥ nine cycles/calendar year). Non-hormonal contraceptive user participants performed both trials in the same estimated phase of the menstrual cycle (two early luteal [days 16–19], one mid-luteal [days 20–23], one late luteal [days 24-28]). This approach was taken as menstrual cycle phase has shown to influence the effect of CHO supplementation on hormonal responses to exercise (McAnulty et al., 2007).

Measurements

Gastrointestinal discomfort

Participants were asked to rate their GI symptoms of nausea, fullness, reflux, abdominal cramps, flatulence and urges to have a bowel movement on a 100mm visual analogue scale (Gaskell et al., 2019).

Mental fatigue

Subjective sensations of mental fatigue were recorded at 0-min, 45-min, 90-min and 120-min (Smith et al., 2016). Participants marked their response on a 100mm line anchored by 0 (no mental fatigue at all) and 100 (maximal mental fatigue). Participant responses were measured from the left anchor and expressed in mm.

Technical performance

The LSPT was completed to assess passing performance, with completion of 16 passes against a target area required as quickly as possible, while minimising errors. The first examiner timed the test, whilst also recording errors, which resulted in the accrual of added penalty time. A coloured piece of card (0.6x0.3m) served as target area and was affixed to each of four standard gymnasium benches placed at distances of ~3.5m (short pass) and ~4m (long pass), forming a rectangle around the participant. A second examiner randomly called out the colour of the next target before the participant completed the current pass. Participants were instructed that passes should be executed from within the designated passing area. The outcomes included original time (time to complete all 16 passes), penalty time (additional time for errors, inaccurate passes, slow performance), and performance time (original time plus penalty time). Detailed procedures can be found elsewhere, including the penalty time afforded to a given error (Ali et al., 2003).

Neuromuscular performance

Ground reaction force and time history of CMJs and DJs were measured using portable dual force platforms (HD Gen 4, Hawkin Dynamics, Maine, USA) with a sampling rate of 1000 Hz. Jump height (CV=6.6%) and power (CV=4.1%) were calculated for the CMJ, while the reactive strength index defined as jump height divided by contact time (CV=6.9%), was calculated for the DJ using proprietary HD software. The mean value from all jumps was used in subsequent analyses. After two sub-maximal practice jumps, participants performed three maximal drop jumps followed by CMJs, with 60s between each jump. Participants were instructed to jump as high and fast as possible during CMJs, and to perform the drop jump from a 0.4m platform, aiming to minimise contact time and maximise jump height.

Sprints

Linear sprints were performed with timing gates placed at approximately hip-height (0.8m) and perpendicular along a 2m wide sprint track at 15m and 30m to record sprint times (Witty Photocells, Microgate, USA). Participants commenced in a two-point staggered stance 0.5m behind the first timing gates. Two sprints were completed per timepoint, separated by 2 min active recovery. The mean of two sprints was presented for analyses. No sprint-specific coaching or verbal encouragement was provided; however, participants received standardised instructions before each sprint to complete the distance as quickly as possible to ensure maximal effort. The CVs for test-retest measurements in our laboratory are <3.8% for 15 and 30m sprint times.

Nutritional intervention

For the fructose–glucose condition, participants consumed commercially available energy gels, containing fructose and maltodextrin in a 1:2 ratio (orange flavour Dual-Fuel Energy Gel, Lucozade Sport, UK). Maltodextrin and glucose are largely interchangeable in terms of exogenous CHO oxidation rates during exercise, as their hydrolysis and oxidation rates are similarly efficient for both CHO monomers and polymers (Moodley et al., 1992). Each 45 ml gel provided 1132 kJ (273 kcal) of energy per 100 g and 67 g CHO. A total of 180 g CHO was consumed, equating to ~90 $g \cdot h^{-1}$ (1.5 $g \cdot min^{-1}$). CHO intake was distributed as follows: 60g at warmup and 45-min, followed by 30g at 90-min, and mid-way through extra-time (105-min), which totalled 270 ml of gel. This corresponded to 2.3 $g \cdot kg^{-1}BM^{-1}$ CHO for males, and 3.1 $g \cdot kg^{-1}BM^{-1}$ CHO for females.

In the glucose control condition, participants ingested maltodextrin (orange flavour Go Gel, SIS Ltd, UK). Each 60 ml gel provided 613 kJ (144 kcal) per 100 g, with 36 g CHO. A total of 120 g of CHO was consumed (~60 $g \cdot h^{-1}$, 1.0 $g \cdot min^{-1}$), with 40g ingested at warmup and 45-min, followed by 20g at 90-min, and mid-way through extra-time, which totalled 360 ml of gel. This equated to 1.6 $g \cdot kg^{-1}BM^{-1}$ CHO for males, and 2.0 $g \cdot kg^{-1}BM^{-1}$ CHO for females. The glucose intake of 60 $g \cdot h^{-1}$ was selected as a control to compare against the addition of 30 $g \cdot h^{-1}$ of fructose. This decision was based on peak oxidation rates of ingested glucose during exercise (~1.0 $g \cdot min^{-1}$) (Rowlands et al., 2015), and aligns with current recommendations and practices (Collins et al., 2021).

While the gels differed slightly in taste and volume, participants were unaware of the study's objectives or which trial they were undertaking. The study’s aims were disclosed after completion, and follow-up inquiries revealing that six out of fifteen participants (~40%) accurately identified the different conditions.

Statistical analysis

Statistical analyses were carried out using SPSS software (version 29, SPSS Inc., USA). Normality of data was assessed using the Shapiro Wilk test. Normally distributed data were analysed using a repeated measures analysis of variance. Mauchly's test was conducted and a Greenhouse–Geisser correction applied if sphericity assumptions were violated. Where significant interaction effects (fuel type x time) occurred, simple main effect analyses were completed to isolate the effects. Significant time effects were investigated using pairwise comparisons with Bonferroni confidence-interval adjustment. Non-parametric data (fullness, Blg) were analysed with the Friedman test. A Wilcoxon signed-rank post-hoc test with Bonferroni-corrected alpha values was performed where a significant fuel type x time effect occurred. Effect sizes for selected pairwise comparisons were determined using Cohen’s *d*. Data are expressed as mean ± SD. Significance was assumed at <0.05.

Results

Interaction effects (time x treatment)

Fructose–glucose increased abdominal cramps versus glucose (time × treatment interaction: $F(2.286, 64.006)=3.357$, $p=0.035$). At 45 min, abdominal cramps were 9.3% higher with fructose–glucose ($t(14)=7.715$, $p<0.001$, $d=1.7$), and at 90 min, values were 9% higher ($t(14)=4.827$, $p<0.001$, $d=1.6$). Fructose–glucose resulted in 0.41 mmol·L^{-1} higher Blg versus glucose alone (time × treatment interaction: $\chi^2(3)=49.229$, $p<0.001$) at 120-min ($Z=-2.756$, $p=0.006$, $d=1.2$).

Fullness was 9.9% higher for glucose versus fructose–glucose (time × treatment interaction: $\chi^2(3)=50.373$, $p<0.001$), with values elevated at 90 min ($Z=-2.474$, $p=0.013$, $d=0.9$). Reflux was more pronounced following glucose ingestion (time × treatment interaction: $F(3, 72.38)=3.337$, $p=0.023$), with 7.8% greater values observed at 45 min ($t(14)=-2.559$, $p=0.011$, $d=0.9$). Flatulence was 3.1% higher for glucose (time × treatment interaction: $F(2.314, 64.788)=3.55$, $p=0.029$) at 120 min ($t(14)=-3.254$, $p=0.003$, $d=1.1$). Blg was 0.16 mmol·L^{-1} higher after glucose ingestion (time × treatment interaction: $\chi^2(3)=49.229$, $p<0.001$) at 15-min ($Z=-2.405$, $p=0.016$, $d=0.9$). No time × treatment interaction effects were observed for any other variables ($p>0.05$, Table 2 and 3).

*******INSERT FIGURE 1*******

*******INSERT FIGURE 2*******

Time effects (time of sample)

Exercise (time of sample) reduced jump height, jump depth, PPO, 15m and 30m sprints performance ($p<0.05$). The remaining variables were unaffected by exercise ($p>0.05$, Table 2 and 3).

*******INSERT TABLE 2*******

*******INSERT TABLE 3*******

Discussion

Higher CHO dosages through fructose–glucose co-ingestion attenuated the decline in Blg levels during the latter stages of extra time (105–120 min) but did not influence performance during simulated soccer match performance compared with lower CHO intake glucose-only ingestion. GI disturbances were observed at various time points following both 90 g·h^{-1} fructose–glucose and 60 g·h^{-1} glucose-only intake, highlighting that individual tolerance is evident. These findings emphasise the importance of tailored fuelling strategies rather than a universal approach during prolonged soccer-specific scenarios.

In this study, the continued decline in Blg during the extra-time period within the glucose-only condition likely reflects the increased reliance on blood-borne glucose when muscle glycogen becomes heavily depleted (Coyle et al., 1986). Indeed, muscle glycogen is reported to decrease by 50% from pre-exercise values following 120 min of soccer match-play (Mohr et al., 2023). Furthermore, whilst changes in Blg are not evident following 90 min, Blg concentrations are reported to fall by the end of extra-time (Mohr et al., 2023). As such, it appears that the ingestion of 60 $g \cdot h^{-1}$ glucose in the present study may be insufficient to support the increased reliance on blood-borne during the extra-time period resulting in a progressive decline in Blg concentrations whereas the ingestion of 90 $g \cdot h^{-1}$ appears to be sufficient to prevent such declines.

Performance decrements were observed over 120-min in CMJ height and depth, PPO and 15m and 30m sprint performance, with no differences observed between conditions. This suggests that consuming CHO amounts of 60 and 90 $g \cdot h^{-1}$ is not effective in reducing neuromuscular fatigue across 120 min of simulated soccer matches. A previous study examined how different CHO doses and compositions (60 $g \cdot h^{-1}$ glucose, 75 $g \cdot h^{-1}$ glucose, 90 $g \cdot h^{-1}$ fructose–glucose, and 112.5 $g \cdot h^{-1}$ fructose–glucose (1:2)) affects 30-min time trial performance after cycling at 77% *V*O2max for 2 h (King et al., 2018). Although fructose–glucose was optimal for time-trial performance compared to the glucose conditions and the 112.5 $g \cdot h^{-1}$ fructose–glucose condition, the current study found no differences in the preservation of performance. This discrepancy could be partly explained by differences in how performance was assessed. For instance, King et al. (2018) used a 30-min maximal time trial, whereas the present study evaluated neuromuscular function through brief, high-intensity efforts. Continuous or repeated high-power outputs, which require maximal glycogen breakdown and cause significant disruptions in cellular metabolite and ion balance, consistently lead to impaired performance when glycogen levels are low (Vigh-Larsen et al., 2021). In contrast, maximal force can be produced for short periods, such as during a single or limited series of maximal contractions, even when muscle glycogen is depleted (Vigh-Larsen et al., 2021). This suggests that fatigue-induced performance decrements may not have been detectable with the measures used in the present study, irrespective of differences in muscle glycogen content between conditions. Although no performance differences were observed, maintaining Blg levels may be crucial, especially in prolonged 145-min matches like the 2024 FIFA World Cup final, which could further deplete glycogen stores. Ingesting exogenous CHO, particularly fructose and glucose, before and during exercise may help sustain performance, delay hypoglycaemia, and spare glycogen, especially during high-intensity efforts in the later stages of prolonged match-play (Field et al., 2022). This could also enhance post-exercise glycogen repletion (Fuchs et al., 2019), though further research is needed.

GI symptoms of reflux at 45-min, fullness at 90-min, and flatulence at 120-min were higher in the glucose trial compared to fructose–glucose. However, abdominal cramps were greater in the fructose–glucose trial at 45-min and 90-min. High CHO intake, exceeding 60 g·h^{-1}, is needed before the SGLT1 transporter becomes saturated (Jentjens et al., 2004), with gut absorption acting as the rate-limiting factor, potentially causing GI discomfort (Rowlands et al., 2015). For instance, consuming 1.8 g·min^{-1} glucose alone, compared to the co-ingestion of 0.6 g·min^{-1} fructose and 1.2 g·min^{-1} glucose during 120-min of low-moderate intensity cycling, led to higher GI symptoms (bloating, nausea) and increased non-oxidised exogenous CHO concentrations (Jentjens et al., 2004). This suggests that less CHO was absorbed in the GI tract and instead accumulated in the gut, which may explain the advantages of fructose–glucose combinations when CHO intake exceeds 1.2 g·min^{-1}. Interestingly, despite a lower CHO intake (60 g·h^{-1}), glucose ingestion led to greater GI symptoms—such as fullness, reflux, and flatulence—at various time points. However, when considering overall GI distress, both nutritional strategies caused discomfort. Given the variability in GI responses, along with individual tolerance and preferences, these findings emphasise the importance of personalised fuelling strategies over a one-size-fits-all approach.

Mental fatigue experienced across prolonged simulated soccer match-play was not influenced by type of CHO ingestion. Glucose is the brain´s primary fuel source and homeostasis must be maintained for optimum brain functioning to occur (Rollo & Williams, 2023). Depletion of Blg availability may impact mental fatigue, with ingestion of CHO reportedly minimising the negative effects of prolonged exercise on cognitive function (Meeusen, Watson, & Dvorak, 2006). This emphasises the importance of Blg regulating central neurotransmission and alterations in extracellular glucose concentrations, which are known to influence serotonin release and reuptake during exercise (Meeusen, Watson, Hasegawa, et al., 2006). Skill performance was not influenced by condition throughout the 120-min simulated soccer match; however, both CHO strategies effectively preserved the accuracy and speed of technical performance. Academy soccer players who consumed CHO-electrolyte gels (0.7 ± 0.1 g·kg^{-1} BM^{-1}) five min before extra-time showed a 29±20% improvement in dribbling accuracy compared versus an energy-free placebo condition (Harper et al., 2016). In another study, while passing performance showed no improvement after consuming 30 g·h^{-1} of CHO, participants scored significantly more points in a post-exercise shooting assessment (Ali et al., 2007). A similar investigation showed that ~60 g·h-1 CHO attenuated the decline in shot speed, but supplementation did not affect passing or dribbling (Russell et al., 2012). The present work extends on these findings by demonstrating that CHO ingested at rates of 90 g·h^{-1} and 60 g·h^{-1} across 120-min of simulated soccer results in skill performance preservation. However, research using alternative measures to criterion-based outcomes of technical proficiency under conditions of soccer-specific fatigue might be required in future studies.

The main limitation of the present study is the lack a 60 g·h^{-1} multiple transportable CHO control. A decision was made to include a glucose gel control that reflects common practices to evaluate whether a higher CHO dosage, supplemented with fructose, offers additional performance benefits. The soccer match simulation was validated only in male soccer players (Harper et al., 2016). After modifying the simulation for females, however, the data show that it effectively represents the demands of female soccer match play (Andersson et al., 2010; Krustrup et al., 2005; Mohr et al., 2008). The physiological responses are also consistent with those observed in female soccer players during simulated match play (Bendiksen et al., 2013). Another limitation is the lack of muscle and liver glycogen measurements.

Conclusion

Increased CHO availability from fructose and glucose co-ingestion helped preserve Blg during prolonged soccer-specific exercise but did not improve physical or technical performance during the extended simulated soccer match compared with glucose-only ingestion. This suggests that a higher CHO intake through fructose–glucose mixtures may not be necessary, with the optimal CHO quantity and composition depending on individual tolerance, which varies and can be improved through training. Additional experiments remain warranted to approximate how fructose and glucose strategies (e.g. 60 g·h^{-1}) influence player performance, GI symptoms, mental fatigue and recovery, particularly in preparation for extra-time scenarios.

Figure captions:

Figure 1: Gastrointestinal discomfort measures across timepoints (pre-exercise, half-time, full-time and post-extra-time). Fructose–glucose is depicted in white. Glucose is depicted in grey. *Significant condition and time interaction (p<0.05). Data are presented as Mean ± SD. Fullness data represented as Median (IQR).

Figure 2: Blood glucose concentration across participants at the end of each 15 min period of exercise (epochs; E*n*): 0–15 min (E1), 16–30 min (E2), 31–45 min (E3), 46–60 min (E4), 61–75 min (E5), 76–90 min (E6), 91–105 min (E7) and 106–120 min (E8). Fructose–glucose is depicted in white. Glucose is depicted in grey. *Significant condition and time interaction (p<0.05). Data are presented as Mean ± SD.

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Authorship

AF, LDH, LB, MH, PM and NH contributed to the conceptualisation of the study. AF and AFis contributed to data curation. AFis contributed to formal analyses, investigation, project administration and visualisation. AFis and AF contributed to the writing of the original draft of the manuscript. All authors LC, PK, CS, MR, DM, JF, MM reviewed and edited the manuscript. AF contributed to validation and supervision.

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Conflicts of interest

The authors report there are no competing interests to declare.

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Figure 1:

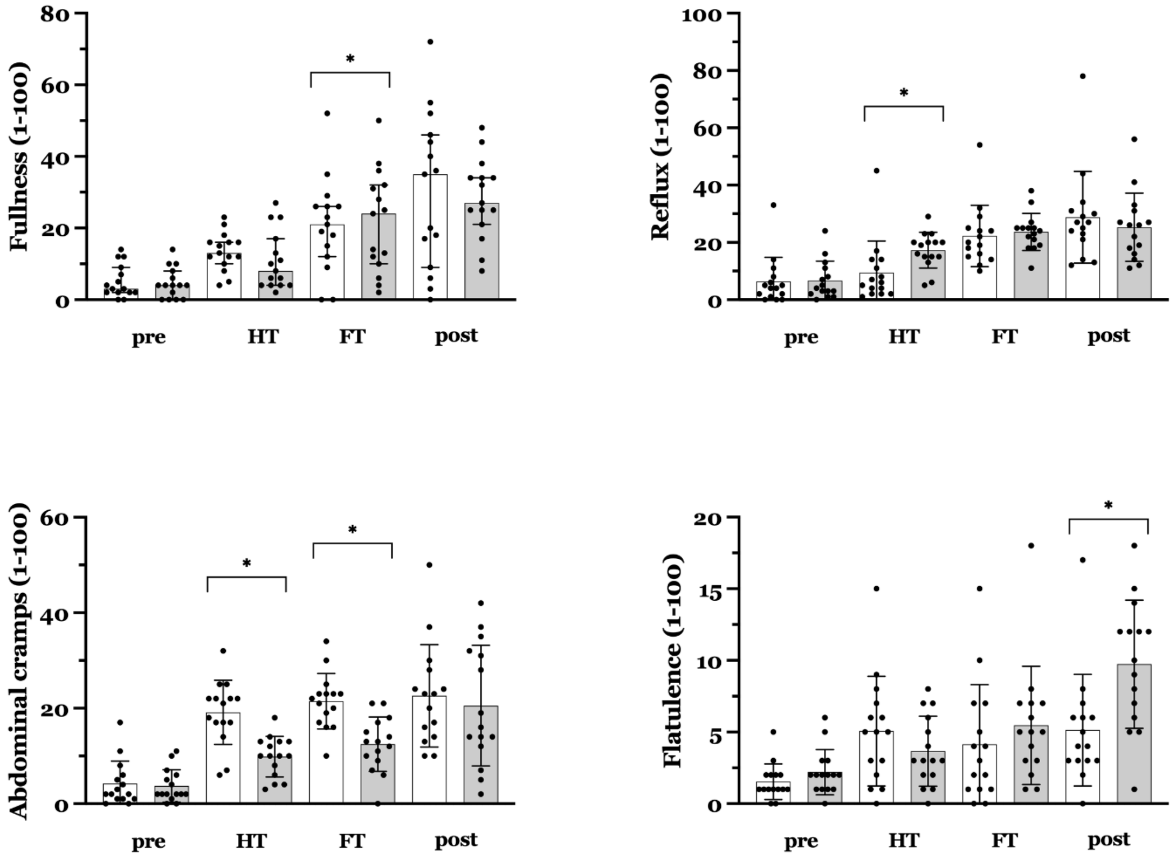
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Figure 2:

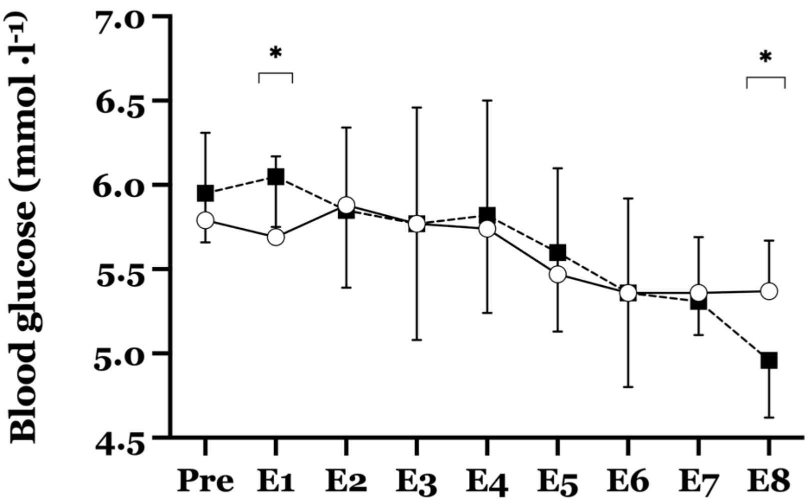

Table 1. Physical demands across numerous professional 90-min female soccer matches [22], and 90 min and 120 min of the soccer match simulation.

Physical variables	Matches [22]	90 min	120 min
Distance covered (km)	9.1 – 10.4	9.1	12.3
High-intensity running (km)	1.2 – 2.5	1.5	2.1
High-intensity distance (%)	4.4 – 6.0	5.0	5.0
Sprint distance (m)	160 – 460	500	650
Number of sprints (*n*)	26 – 280	28	36

Data in the 'Matches' column are reported as the range across several 90-min matches according to a review of female soccer match demands [22].

Table 2: Technical, neuromuscular, gastrointestinal, cognitive and hydration responses across the 120-min soccer match simulation and conditions

	Pre-match	Half-time (45-min)	Fulltime (90-min)	Post extra-time
LSPT (s)				
Glucose	59.8 ± 7.6 (95% CI 55.8 to 63.9)	59.5 ± 6.8 (95% CI 56.0 to 63.0)	60.6 ± 7.0 (95% CI 56.6 to 64.5)	62.5 ± 8.5 (95% CI 58.8 to 66.1)
Fructose:Glucose	59.6 ± 7.3 (95% CI 55.5 to 63.7)	60.5 ± 5.8 (95% CI 57.0 to 64.0)	59.4 ± 7.4 (95% CI 55.5 to 63.4)	60.7 ± 4.2 (95% CI 57.0 to 64.3)
DJ RSI				
Glucose	2.0 ± 0.68 (95% CI 1.63 to 2.37)	1.99 ± 0.65 (95% CI 1.63 to 2.35)	1.97 ± 0.67 (95%CI 1.60 to 2.34)	1.95 ± 0.70 (95% CI 1.58 to 2.33)
Fructose:Glucose	2.04 ± 0.69 (95% CI 1.67 to 2.41)	1.99 ± 0.65 (95% CI 1.63 to 2.35)	1.98 ± 0.68 (95% CI 1.61 to 2.35)	1.98 ± 0.66 (95 % CI 1.60 to 2.35)
CMJ height (cm)				
Glucose	34.9 ± 6.2 (95% CI 31.2 to 38.5)	34.2 ± 6.0 (95% CI 30.9 to 37.5)	33.5 ± 6.1 [a, b] (95% CI 30.1 to 36.8)	33.1 ± 6.3 [a, b] (95% CI 29.7 to 36.5)
Fructose:Glucose	33.9 ± 7.0 (95% CI 30.2 to 37.5)	33.6 ± 6.2 (95% CI 30.3 to 37.0)	32.7 ± 6.2 [a, b] (95% CI 29.4 to 36.1)	32.7 ± 6.3 [a, b] (95% CI 29.3 to 36.1)
CMJ peak propulsive power (W)				
Glucose	3629.5 ± 629.7 (95% CI 3287.0 to 3971.9)	3631.4 ± 622.7 (95% CI 3290.4 to 3972.3)	3629.0 ± 625.1 (95% CI 3286.8 to 3971.2)	3626.9 ± 628.3 [b] (95% CI 3283.0 to 3970.8)
Fructose:Glucose	3627.1 ± 621.3 (95% CI 3284.7 to 3969.6)	3629.0 ± 622.7 (95% CI 3288.0 to 3969.9)	3626.6 ± 625.1 (95% CI 3284.4 to 3968.8)	3625.2 ± 628.0 [b] (95% CI 3281.3 to 3969.0)
CMJ depth (m)				
Glucose	-0.25 ± 0.08 (95% CI -0.29 to -0.21)	-0.26 ± 0.07 (95% CI -0.30 to -0.23)	-0.26 ± 0.06 (95% CI -0.29 to -0.23)	-0.20 ± 0.08 [a, b, c] (95% CI -0.33 to -0.25)
Fructose:Glucose	-0.27 ± 0.07 (95% CI -0.31 to -0.23)	-0.26 ± 0.06 (95% CI -0.30 to -0.22)	-0.25 ± 0.06 (95% CI -0.29 to -0.22)	-0.30 ± 0.06 [a, b, c] (95% CI -0.34 to -0.26)
15m sprints (s)				
Glucose	2.47 ± 0.34 (95% CI 2.28 to 2.66)	2.48 ± 0.34 (95% CI 2.29 to 2.67)	2.51 ± 0.35 [a] (95% CI 2.32 to 2.70)	2.55 ± 0.35 [a, b, c] (95% 2.37 to 2.73)
Fructose:Glucose	2.45 ± 0.36 (95% CI 2.26 to 2.64)	2.48 ± 0.35 (95% CI 2.29 to 2.67)	2.49 ± 0.34 [a] (95% CI 2.30 to 2.67)	2.51 ± 0.33 [a, b, c] (95% CI 2.33 to 2.70)
30m sprints (s)				
Glucose	4.94 ± 0.67 (95% CI 4.56 to 5.32)	4.96 ± 0.68 (95% CI 4.58 to 5.34)	5.01 ± 0.70 (95% CI 4.63 to 5.39)	5.03 ± 0.72 [a] (95% CI 4.66 to 5.40)
Fructose:Glucose	4.89 ± 0.71 (95 % CI 4.52 to 5.27)	4.95 ± 0.70 (95% CI 4.57 to 5.33)	4.96 ± 0.70 (95% CI 4.57 to 5.34)	4.98 ± 0.64 [a] (95% CI 4.60 to 5.35)
Nausea (VAS)				

Glucose	5.3 ± 4.2	10.4 ± 5.8 ^{a}	14.5 ± 5.8 $^{a, b}$	19.9 ± 17.7 ^{b}
	(95% CI 2.9 to 7.8)	(95% CI 7.3 to 13.5)	(95% CI 8.7 to 20.3)	(95% CI 12.0 to 27.9)
Fructose:Glucose	5.7 ± 4.9	8.1 ± 5.6 ^{a}	15.9 ± 10.4 $^{a, b}$	18.0 ± 10.5 ^{b}
	(95% CI 3.2 to 8.1)	(95% CI 5.0 to 11.3)	(95% CI 10.1 to 21.7)	(95% CI 10.0 to 26)
Reflux (VAS)				
Glucose	6.7 ± 6.5	17.3 ± 6.0 *	23.7 ± 6.2	25.3 ± 11.5
	(95% CI 2.7 to 10.8)	(95% CI 12.5 to 22.0)	(95% CI 19.0 to 28.4)	(95% CI 17.8 to 32.7)
Fructose:Glucose	6.3 ± 8.2	9.5 ± 10.6 *	22.3 ± 10.3	28.8 ± 15.4
	(95% CI 2.3 to 10.4)	(95% CI 4.7 to 14.2)	(95% CI 17.6 to 27.0)	(95% CI 21.3 to 36.3)
Abdominal cramps (VAS)				
Glucose	3.7 ± 3.3	9.9 ± 4.1 ^{a}*	12.5 ± 5.5 ^{a}*	20.5 ± 12.2 $^{a, b, c}$
	(95% CI 1.6 to 5.9)	(95% CI 6.9 to 12.8)	(95% CI 9.4 to 15.5)	(95% CI 14.3 to 26.7)
Fructose:Glucose	4.2 ± 4.5	19.1 ± 6.6 ^{a}*	21.5 ± 5.6 ^{a}*	22.6 ± 10.4 $^{a, b, c}$
	(95% CI 2.0 to 6.4)	(95% CI 16.2 to 22.1)	(95% CI 18.4 to 24.5)	(95% CI 16.4 to 28.8)
Flatulence (VAS)				
Glucose	2.3 ± 1.6	3.7 ± 2.4 ^{a}	5.5 ± 4.0 ^{a}	9.7 ± 4.3 $^{a, b, c}$*
	(95% CI 1.9 to 5.2)	(95% CI 1.9 to 4.4)	(95% CI 2.0 to 5.5)	(95% CI 3.8 to 6.6)
Fructose:Glucose	1.5 ± 1.3	5.1 ± 3.7 ^{a}	4.1 ± 4.1 ^{a}	5.1 ± 3.7 $^{a, b, c}$*
	(95% CI 0.2 to 3.4)	(95% CI 2.0 to 4.5)	(95% CI 1.8 to 5.4)	(95% CI 0.7 to 3.5)
Urges to have a bowel movement (VAS)				
Glucose	3.5 ± 3.7	3.1 ± 2.2	3.7 ± 2.9	5.2 ± 2.9
	(95% CI 1.9 to 5.2)	(95% CI 1.9 to 4.4)	(95% CI 2.0 to 5.5)	(95% CI 3.8 to 6.6)
Fructose:Glucose	1.8 ± 1.9	3.3 ± 2.3	3.6 ± 3.5	2.1 ± 2.2
	(95% CI 0.2 to 3.4)	(95% CI 2.0 to 4.5)	(95% CI 1.8 to 5.4)	(95% CI 0.7 to 3.5)
Fullness (VAS)				
Glucose	4 (0, 8)	8 (4, 17) $^{a, b}$*	24 (10, 32) ^{a}	27 (21, 34) $^{a, b, c}$
Fructose:Glucose	3 (2, 9)	13 (10, 16) ^{a}	21 (12, 26) $^{a, b}$*	35 (9, 46) $^{a, b, c}$
Cognitive RPE				
Glucose	0.5 ± 0.8	3.8 ± 0.6 ^{a}	5.0 ± 0.9 $^{a, b}$	7.4 ± 0.9 $^{a, b, c}$
	(95% CI 0.2 to 0.8)	(95% CI 1.4 to 6.1)	(95% CI 4.5 to 5.5)	(95% CI 6.9 to 7.9)
Fructose:Glucose	0.7 ± 0.7	4.9 ± 0.6 ^{a}	4.7 ± 1.0 $^{a, b}$	7.6 ± 1.1 $^{a, b, c}$
	(95% CI 0.4 to 1.0)	(95% CI 2.6 to 7.2)	(95% CI 4.2 to 5.2)	(95% CI 7.1 to 8.2)
Mental fatigue (VAS)				
Glucose	3.4 ± 3.2	26.8 ± 4.2 ^{a}	35.5 ± 6.3 $^{a, b}$	66.1 ± 11.6 $^{a, b, c}$
	(95% CI 1.6 to 5.2)	(95% CI 24.3 to 29.3)	(95% CI 31.5 to 39.5)	(95% CI 59.7 to 72.4)
Fructose:Glucose	3.6 ± 3.2	25.4 ± 5.0 ^{a}	35.3 ± 8.3 $^{a, b}$	63.1 ± 11.7 $^{a, b, c}$
	(95% CI 1.8 to 5.4)	(95% CI 22.9 to 27.9)	(95% CI 31.1 to 39.3)	(95% CI 56.8 to 69.5)

	Pre-match	Post extra-time
Urine osmolality (mOsm/kg)		
Glucose	563.3 ± 118.4 (95% CI 498.2 to 628.5)	684.7 ± 128.0 [a] (95% CI 621.7 to 747.6)
Fructose:Glucose	618 ± 127.7 (95% CI 553.5 to 683.8)	700.7 to 109.3 [a] (95% CI 637.7 to 763.6)
Urine corrected body mass (kg)		
Glucose	67.2 ± 10.2 (95% CI 61.8 to 72.6)	66.2 ± 10.2 [a] (95% CI 60.8 to 71.6)
Fructose:Glucose	67.3 ± 10.2 (95% CI 61.9 to 72.7)	66.1 ± 10.2 [a] (95% CI 60.7 to 71.5)

Presented as Mean ± SD (95% CI); Median (IQR) for fullness.

[a, b, c] Indicate a significant difference from pre-match, half-time and full-time, retrospectively.

* Indicates significant interaction effects.

Table 3: Physiological and perceptual responses across the 120-min soccer match simulation across conditions

	Pre	E1 (0–15 min)	E2 (15–30 min)	E3 (30–45 min)	E4 (45–60 min)	E 5 (60–75 min)	E6 (75–90 min)	E7 (90–105 min)	E8 (105–120 min)
Bla (mmol/L)									
Glucose	1.25 ± 0.29 (95% CI 1.06 to 1.45)	5.81 ± 2.16 (95% CI 4.55 to 7.07)	6.15 ± 1.71 [b] (95% CI 5.20 to 7.10)	6.53 ± 2.20 [b] (95% CI 5.25 to 7.81)	5.45 ± 1.76 [b] (95% CI 4.50 to 6.40)	6.47 ± 1.85 [b, d, e] (95% CI 5.39 to 7.54)	4.69 ± 1.17 [b, e] (95% CI 4.02 to 5.37)	4.77 ± 1.10 [b-e] (95% CI 4.25 to 5.30)	4.71 ± 1.27 [b-g] (95% CI 4.04 to 5.38)
Fructose:Glucose	1.29 ± 0.40 (95% CI 1.10 to 1.48)	5.88 ± 2.44 (95% CI 4.62 to 7.14)	6.37 ± 1.77 [b] (95% CI 5.42 to 7.32)	6.71 ± 2.46 [b] (95% CI 5.42 to 7.99)	5.55 ± 1.68 [b] (95% CI 4.60 to 6.50)	6.91 ± 2.06 [b, d, e] (95% CI 5.84 to 7.99)	4.91 ± 1.30 [b, e] (95% CI 4.23 to 5.59)	5.01 ± 0.80 [b-e] (95% CI 4.48 to 5.54)	4.99 ± 1.17 [b-g] (95% CI 4.32 to 5.66)
Blg (mmol/L)									
Glucose	6.0 (5.9, 6.2)	6.0 (5.9, 6.4) *	5.9 (5.3, 6.3)	5.9 (5.2, 6.2)	5.9 (5.3, 6.3)	5.4 (5.3, 5.9) [a-e]	5.4 (5.2, 5.8) [a-e]	5.3 (5.2, 5.4) [a-f]	5.1 (4.8, 5.2) [a-f, h] *
Fructose:Glucose	5.9 (5.2, 6.2)	5.8 (5.2, 6.1) *	6.0 (5.3, 6.2)	5.9 (5.2, 6.2)	5.9 (5.3, 6.3)	5.3 (5.1, 6.0) [a-e]	5.4 (5.2, 5.8) [a-e]	5.4 (5.2, 5.5) [a-f]	5.4 (5.2, 5.5) [a-f, h] *

	E1 (0–15 min)	E2 (15–30 min)	E3 (30–45 min)	E4 (45–60 min)	E5 (60–75 min)	E6 (75–90 min)	E7 (90–105 min)	E8 (105–120 min)
HR mean (bpm)								
Glucose	169 ± 8 (95% CI 165 to 173)	168 ± 8 [b] (95% CI 164 to 172)	168 ± 8 (95% CI 164 to 171)	166 ± 7 [b, d] (95% CI 162 to 170)	166 ± 7 [b-d] (95% CI 162 to 169)	165 ± 7 [b-d] (95% CI 162 to 169)	165 ± 7 [b-e] (95% CI 161 to 168)	164 ± 7 [b-g] (95% CI 161 to 168)
Fructose:Glucose	170 ± 8 (95% CI 166 to 174)	168 ± 7 [b] (95% CI 163 to 172)	169 ± 7 (95% CI 165 to 173)	167 ± 8 [b, d] (95% CI 163 to 171)	166 ± 6 [b-d] (95% CI 163 to 169)	166 ± 6 [b-d] (95% CI 163 to 170)	165 ± 6 [b-e] (95% CI 162 to 169)	164 ± 6 [b-g] (95% CI 160 to 167)
RPE								
Glucose	41.9 ± 13.1 (95% CI 34.3 to 49.6)	51.1 ± 17.4 [b] (95% CI 41.4 to 60.9)	54.1 ± 12.7 [b, c] (95% CI 45.1 to 63.0)	55.9 ± 11.8 [b, c] (95% CI 48.1 to 63.6)	62.5 ± 13.8 [b-e] (95% CI 54.0 to 70.9)	70.4 ± 15.0 [b-f] (95% CI 61.3 to 79.5)	80.3 ± 13.6 (95% CI 72.2 to 88.4)	88.3 ± 13.8 [b-h] (95% CI 79.2 to 97.5)
Fructose:Glucose	41.4 ± 14.7 (95% CI 33.8 to 49.0)	49.5 ± 18.1 [b] (95% CI 39.7 to 59.2)	56.5 ± 19.4 [b, c] (95% CI 47.5 to 65.4)	55.5 ± 16.2 [b, c] (95% CI 47.7 to 63.2)	63.3 ± 16.8 [b-e] (95% CI 54.8 to 71.7)	70.8 ± 18.2 [b-f] (95% CI 61.7 to 79.9)	78.9 ± 15.9 (95% CI 70.8 to 87.0)	88.8 ± 19.3 [b-h] (95% CI 79.6 to 98.0)

Presented as Mean ± SD (95% CI); Mean ± SD Median (IQR) for Blg.

[a–h] Indicates significant time effects from Pre–E8 ($p \leq 0.05$), respectively.

* Indicates significant interaction effect