This paper is a preprint submitted to SportRxiv

Cite as: Dean, E., Osborne, A., Subar, D., Hendrickse, P., and Gaffney, C.J. (2025) *Comparative effects of a glucose-fructose bar, glucose-fructose hydrogel, and a maltodextrin gel on carbohydrate oxidation and sprint performance in tier two athletes*.

Title

Comparative Effects of a Glucose-Fructose bar, Glucose-Fructose hydrogel, and a Maltodextrin gel on Carbohydrate Oxidation and Sprint Performance in Tier two Athletes

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Abstract

Carbohydrate supplementation plays a key role in optimising athletic performance. We compared the efficacy of three commercial carbohydrate supplements: a glucose-fructose bar (VOOM), a fructose-glucose hydrogel (MAU), and a maltodextrin-based gel (SIS). Antegrade venous blood samples for glucose and insulin were measured alongside substrate utilisation in healthy Tier 2 athletes after ingesting 45 g of carbohydrates from VOOM, MAU, and SIS during a modified 1-hour Oral Glucose Tolerance Test (OGTT). Additionally, the effect of supplementation on high-intensity interval exercise was evaluated during repeat maximal sprint performance. During the OGTT, VOOM elicited greater total carbohydrate oxidation than SIS (24.6 ± 7.4 g vs 17.8 ± 8.6 g, $p = 0.03$) but not MAU (20.1 ± 6.4 g, $p > 0.05$). Carbohydrate oxidation per minute varied over time ($p < 0.0001$) and between products ($p = 0.04$), with VOOM (0.27 ± 0.05 $g \cdot min^{-1}$) showing higher oxidation than MAU (0.21 ± 0.05 $g \cdot min^{-1}$) and SIS (0.19 ± 0.06 $g \cdot min^{-1}$). No significant differences were observed in glucose peak, time to peak glucose, or total insulin concentration ($p > 0.05$). In the exercise trial, peak power ($p < 0.01$), mean power ($p < 0.0001$), and total work varied across subsequent sprints ($p < 0.0001$) but were not influenced by product ($p > 0.05$). Perceived exertion and gastrointestinal discomfort were similar between products ($p > 0.05$). Despite differences in carbohydrate oxidation during the OGTT, VOOM, MAU, and SIS displayed similar metabolic and sprint performance outcomes, suggesting that, within this study, carbohydrate formulation did not impact short-duration maximal exercise.

Keywords

Carbohydrates ; Supplements ; Exercise ; Oxidation ; Glucose

Introduction

Carbohydrate supplementation during exercise has well-documented effects including enhancing performance, oxidation, and delaying fatigue (Podlogar & Wallis, 2022). This is achieved by providing rapid energy availability in the form of convenient supplements, like gels, drinks, and bars, typically composed of easily digestible monosaccharides (e.g., glucose and fructose), disaccharides (e.g., sucrose), and specific high glycaemic index polysaccharides (e.g., maltodextrin) (Gromova et al., 2021; Rollo et al., 2020).

Different carbohydrate supplements utilise a variety of compositions, such as glucose-fructose mixtures. This variety can be overwhelming for consumers, particularly as carbohydrate intake should be tailored to exercise duration, intensity, and individual preference (Jeukendrup, 2014; Podlogar & Wallis, 2022). Gels offer fast, easily digestible carbohydrates and, although previously linked to gastrointestinal discomfort (Saunders et al., 2007; Pfeiffer et al., 2010), recent formulations of glucose-fructose mixtures are now shown to be well tolerated even at high carbohydrate intake levels of 120 $g \cdot h^{-1}$ (Hearris et al., 2022). Drinks provide hydration alongside carbohydrates and electrolytes and are again shown to be well tolerated at up to 120 $g \cdot h^{-1}$ (Hearris et al., 2022; Podlogar et al., 2022). Bars, while nutritionally comparable, may be less convenient due to their solid form and potential to cause gastrointestinal discomfort during exercise (Guillochon & Rowlands., 2017). Despite these subtle differences, research indicates similar performance outcomes across all three. Pfeiffer et al. (2010) demonstrated the consumption of a solid glucose-fructose bar elicited similar peak carbohydrate oxidation rates to a glucose-

fructose drink during 180 minutes of cycling (Bar 1.25 ± 0.15 g·min^{-1} and Drink 1.34 ± 0.27 g·min^{-1}). Similarly, Hearris et al. (2022) demonstrated comparable high rates of carbohydrate oxidation from solid (jelly chew), semisolid (gel), fluid (drink), and a combination of the forms (mix) during 180 minutes of cycling and an exercise capacity test. Peak carbohydrate oxidation was similar across all three forms (Chew 1.59 ± 0.08 g·min^{-1}, Gel 1.58 ± 0.13 g·min^{-1}, Drink 1.56 ± 0.16 g·min^{-1}, Mix 1.66 ± 0.02 g·min^{-1}).

The carbohydrate composition of energy products is typically formulated to maximise the absorption of sugars into the bloodstream, where they can be utilised as an immediate source of energy. Historically, carbohydrate oxidation during exercise was thought to be limited to approximately 60 g·h^{-1}, based on the assumption that the intestinal glucose transporters became saturated beyond this threshold (Jeukendrup & Jentjens, 2000). However, subsequent research has shown that combining different carbohydrate types – such as glucose and fructose – can enhance absorption via distinct intestinal transporters: sodium-glucose transporter 1 (SGLT1) for glucose and glucose transporter 5 (GLUT5) for fructose (Jentjens et al., 2004; Jeukendrup, 2010). This strategy, including combinations like maltodextrin and fructose, has been shown to significantly increase carbohydrate oxidation rates. For example, Wallis et al. (2005) demonstrated that ingestion of maltodextrin and fructose at 1.8 g·min^{-1} (~108 g·h^{-1}) resulted in a higher peak exogenous carbohydrate oxidation rate compared to maltodextrin alone (1.50 ± 0.07 vs. 1.06 ± 0.08 g·min^{-1}). Similarly, Podlogar et al. (2022) reported greater oxidation rates when carbohydrates were consumed at 120 g·h^{-1} in a 0.8:1 fructose-to-glucose ratio compared to 90 g·h^{-1} in a 1:2 ratio (1.51 ± 0.22 vs. 1.29 ± 0.60 g·min^{-1}).

Furthermore, Hearris et al. (2022) found that ingesting glucose-fructose at 120 $g \cdot h^{-1}$ improved exercise capacity across four different feeding formats; drink (446 ± 350 s), gel (529 ± 396 s), chew (596 ± 416 s), and mixed format (470 ± 395 s) compared to water (231 ± 244 s), during 180 minutes cycling at 95% lactate threshold followed by an exercise capacity test at 150% lactate threshold.

While mainly associated with endurance performance, carbohydrate supplementation may also support high-intensity exercise. Vigh-Larsen et al. (2024) demonstrated carbohydrate ingestion during repeated high-intensity exercise-maintained blood glucose (5.3 ± 0.2 vs 4.1 ± 0.2 mmol/L) and reported a fivefold greater increase in plasma insulin with carbohydrate ingestion compared to a placebo. The authors suggest carbohydrate ingestion during high-intensity exercise may create a greater reliance on carbohydrate oxidation and possibly preserve liver glycogen. This may help to prevent hypoglycaemia and delay fatigue. Rodriguez-Giustiniani et al. (2019) observed a 13% improvement in high-intensity running capacity in football players, with higher glucose levels at halftime (5.8 ± 0.5 vs. 4.1 ± 0.4 mmol/L) and post-exercise (4.9 ± 0.4 vs. 4.3 ± 0.4 mmol/L). Krings et al. (2017) similarly demonstrated performance benefits during repeated maximal cycling sprints, with higher mean power output (659.3 ± 103.0 vs. 645.8 ± 99.7 watts), total work (9849.8 ± 1598.8 vs. 9447.5 ± 1684.9 joules), and a lower fatigue index (15.3 ± 8.6 vs. 17.7 ± 10.4 watts/s) following carbohydrate ingestion.

While research on carbohydrate supplementation has established important nutritional strategies, such as carbohydrate loading (Baker et al., 2015; Ismardi et al., 2024; Kazemi et al., 2023), there remains limited evidence evaluating the efficacy of

different commercially available carbohydrate supplements. This research can help athletes make informed decisions of the effectiveness of their nutritional supplements. The present study aimed to compare the postprandial glucose responses between three commercially available carbohydrate supplements at rest and during high-intensity exercise, in addition to their effects on high-intensity exercise performance. The commercially available carbohydrate supplements compared in this study were the glucose-fructose Voom Pocket Rocket Electro Energy bar (VOOM), the fructose-glucose hydrogel Maurten Gel 160 (MAU), and the maltodextrin-based Science in Sport Go Isotonic Energy gel (SIS).

Materials and methods

Subjects

All subjects were classified as Tier 2 athletes, as defined by McKay et al. (2022), indicating they trained regularly (~3 times per week) with the purpose of competing in their respective sports, including running, cycling, or triathlon.

The modified oral glucose tolerance trial (OGTT) aimed to assess metabolic responses (glucose, insulin, substrate oxidation), which are known to vary by sex due to hormonal fluctuations, particularly in females during different phases of the menstrual cycle (Ciarambino et al., 2023; Tucker et al., 2025). To reduce heterogeneity and improve internal validity, only males were recruited.

In contrast, the exercise trial focussed on exercise performance in a mixed-sex athletic population. Given the applied nature of this protocol and the emphasis on ecological validity, both male and female athletes were included to better reflect real-

world sporting contexts. Appropriate standardisation procedures (time of day, pre-trial nutrition, and self-reported menstrual cycle phase) were implemented to minimise heterogeneity (Elliot-Sale et al., 2020; Smeith et al., 2024).

Table 1. Anthropometric characteristics

Subjects	OGTT (16 males)	Exercise (5 males)	Exercise (5 females)	Exercise (total)
Age (y)	23 ± 4.2	27.8 ± 5.7	23.2 ± 1.8	25.5 ± 4.7
Height (cm)	182.0 ± 6.5	181.9 ± 3.4	170.7 ± 6.2	176.3 ± 7.6
Weight (kg)	79.5 ± 8.3	80.4 ± 7.8	68.1 ± 8.9	74.3 ± 10.3
BMI (kg/m^2)	23.81 ± 1.2	23.8 ± 1.3	22.7 ± 2.1	23.2 ± 10.3
Lean mass (kg)	65.8 ± 5.4	65.6 ± 3.9	48.3 ± 3.1	56.9 ± 9.7
Body fat (%)	14.5 ± 5.0	13.7 ± 3.5	24.6 ± 5.7	19.2 ± 7.3

Values are means ± SD. OGTT = Oral glucose tolerance test. BMI = Body mass index

Oral glucose tolerance test (OGTT)

For the OGTT trial, sixteen healthy male Tier 2 athletes (mean ± standard deviation, SD) (aged 23 ± 4.2 years; height 182.0 ± 6.5 cm; weight 79.5 ± 8.3 kg; BMI 23.8 ± 1.2 kg/m²) were recruited. For the exercise trial, ten healthy male and female Tier 2 athletes (aged 25 ± 4.7 years; height 176.3 ± 7.6 cm; weight 74.3 ± 10.3 kg; BMI 23.2 ± 10.3 kg/m²) were recruited. In both studies, participants were fully informed of all procedures and potential risks before providing written informed consent. All protocols were approved by the Lancaster University Ethics Committee and conducted in accordance with the *Declaration of Helsinki* (*8th Revision*, World

Medical Association, 2025) and Good Clinical Practice. Both studies used a randomised crossover design and were preregistered on clinicaltrials.gov: OGTT trial (NCT06375577) and Exercise trial (NCT06768333).

Medical screening

All subjects completed a medical screening form aligned with the American College of Sports Medicine (ACSM) safety-to-exercise guidelines (Liguori, 2020) to confirm no contraindications to exercise or allergies to the carbohydrate products, as previously described in our lab (Gaffney et al., 2022). Subjects were excluded if they had any diagnosed medical condition, took prescribed medication, or adhered to diets (such as high carbohydrate-low fat, or low carbohydrate-high fat) affecting gut microbiome glucose responses (Rauch et al., 2022). Height and body mass were measured using an ultrasonic stadiometer and scales (217 ultrasonic stadiometer and scales, Seca, Hamburg, Germany), while body composition was assessed with bioimpedance scales (DC-430P, Tanita, Tokyo, Japan). Blood pressure was measured using an automatic blood pressure monitor (M3 Comfort, Omron, Kyoto, Japan) to ensure subjects were safe to exercise.

Experimental protocols

Both the OGTT and exercise study were conducted following a double-blind randomised crossover design and required three experimental visits each, separated by a minimum of 48 hours to replicate the frequency of Tier 2 athletes' training.

OGTT trial

Subjects attended the Human Performance Laboratory at Lancaster University following a two-hour fast and were asked to record and replicate their breakfast meal for each subsequent visit. Upon arrival, an antegrade venous cannula (Vasofix Safety IV Catheter 18G, BBraun, Sheffield, UK) was inserted into the antecubital fossa of the forearm, and a resting blood sample of 1 ml was drawn for blood glucose, lactate, and electrolytes (sodium, potassium, chloride), and a 3 ml sample was taken for insulin using a gold-top serum separator vacutainer (CAT Serum Sep Clot Activator, VACUETTE, Greiner Bio-One, Gloucestershire, UK). Subjects were then seated in a semi-supine position on a medical bed (Plinth 2000, Plinth Medical, Suffolk, UK) and asked to rest quietly for fifteen minutes to allow them to reach a relaxed state, as previously described in research measuring resting metabolic rate (Blannin & Wallis, 2024). To prevent clotting, the cannula was flushed with ~1ml 0.9% saline every 15 minutes during each study visit. A flush log was maintained, and on average, 4.6 ± 0.7 ml of saline was used per visit. A small sample was discarded after each flush to ensure the cannula was fully primed with blood before a sample was taken.

After the 15-minute rest period, subjects consumed 45 g of carbohydrates from either VOOM, MAU or SIS. During the 1-hour OGTT, blood was sampled via an antegrade venous cannula at regular intervals. One ml was collected every five minutes for blood glucose, lactate, and electrolytes. Additionally, three ml of blood was collected every ten minutes for insulin measurement. Substrate utilisation was measured via indirect calorimetry, recording the Respiratory Quotient (RQ). Carbohydrate and fat oxidation were calculated using the Frayn (1983) equations, which are appropriate for resting conditions where steady state assumptions apply:

$$\text{Carbohydrate oxidation } (g \cdot min^{-1}) = 4.55 \times \dot{V}CO_2 \text{ (L/min)} - 3.21 \times \dot{V}O_2 \text{ (L/min)}$$

$$\text{Fat oxidation } (g \cdot min^{-1}) = 1.67 \times \dot{V}O_2 \text{ (L/min)} - 1.67 \times \dot{V}CO_2 \text{ (L/min)}$$

Carbohydrate oxidation efficiency was calculated as the percentage of the ingested carbohydrate (45 g) that was oxidised, by dividing the total carbohydrate oxidised by 45 and multiplying it by 100, as previously described by Hulston et al. (2009).

Exercise visits

Subjects consumed a high-carbohydrate control snack bar of 196 kcal, consisting of 64% carbohydrate (27.0 g, of which sugars 11.3 g), 18% fat (7.6 g), and 8% protein (3.6 g), with 2.7 g fibre and 0.36 g salt two hours before attending the Human Performance Lab to mimic pre-training or competition nutrition conditions (Thomas et al., 2016). As with the OGTT, an antegrade venous cannula was inserted into the antecubital fossa of the forearm. Subjects consumed 45 g of carbohydrates from VOOM, MAU or SIS 35 minutes before the start of exercise as the mean time of peak glucose availability identified in the OGTT trial.

Repeated sprint protocol

Following a three-minute warm-up cycling at 70 rpm, subjects completed five 15-second maximal sprints against 0.075 kg · kg^{-1} body mass interspersed with three minutes of active recovery at 70 rpm against no resistance. In accordance with the ACSM guidelines (Liguori, 2020), the exercise was followed by a supervised active cool-down period, during which subjects continued low intensity cycling. Heart rate

was continuously monitored, and subjects remained under observation until their heart rate had returned to within 20% of pre-exercise resting values or until they self-reported readiness to stop. To record gastrointestinal (GI) discomfort before and after exercise, subjects completed a modified version of the Gastrointestinal Symptom Rating Scale (GSRS), shown to have good test-retest reliability in athletes (Wardenaar et al., 2024). Subjects also reported their ratings of perceived exertion (RPE) after the warm-up and after the final sprint using Borg's 6-20 RPE scale (Borg, 1982).

One ml of blood was sampled via an antegrade venous cannula for blood glucose, lactate and electrolytes (sodium, potassium, chloride, and calcium) at baseline, after the warm-up, and then at the end of each sprint and 3-minute recovery period. Substrate utilisation was measured via indirect calorimetry, recording the respiratory exchange ratio (RER), and heart rate was recorded throughout using a chest-worn heart rate monitor (Polar H10, Polar, Kempele, Finland). Carbohydrate oxidation was calculated using the Jeukendrup & Wallis (2005) equations, which are more appropriate for high-intensity exercise, accounting for increased ventilation, lactate production and changes in bicarbonate buffering, while considering protein oxidation negligible:

$$\text{Carbohydrate oxidation } (g \cdot min^{-1}) = 4.210 \times \dot{V}CO_2 \text{ (L/min)} - 2.962 \times \dot{V}O_2 \text{ (L/min)}$$

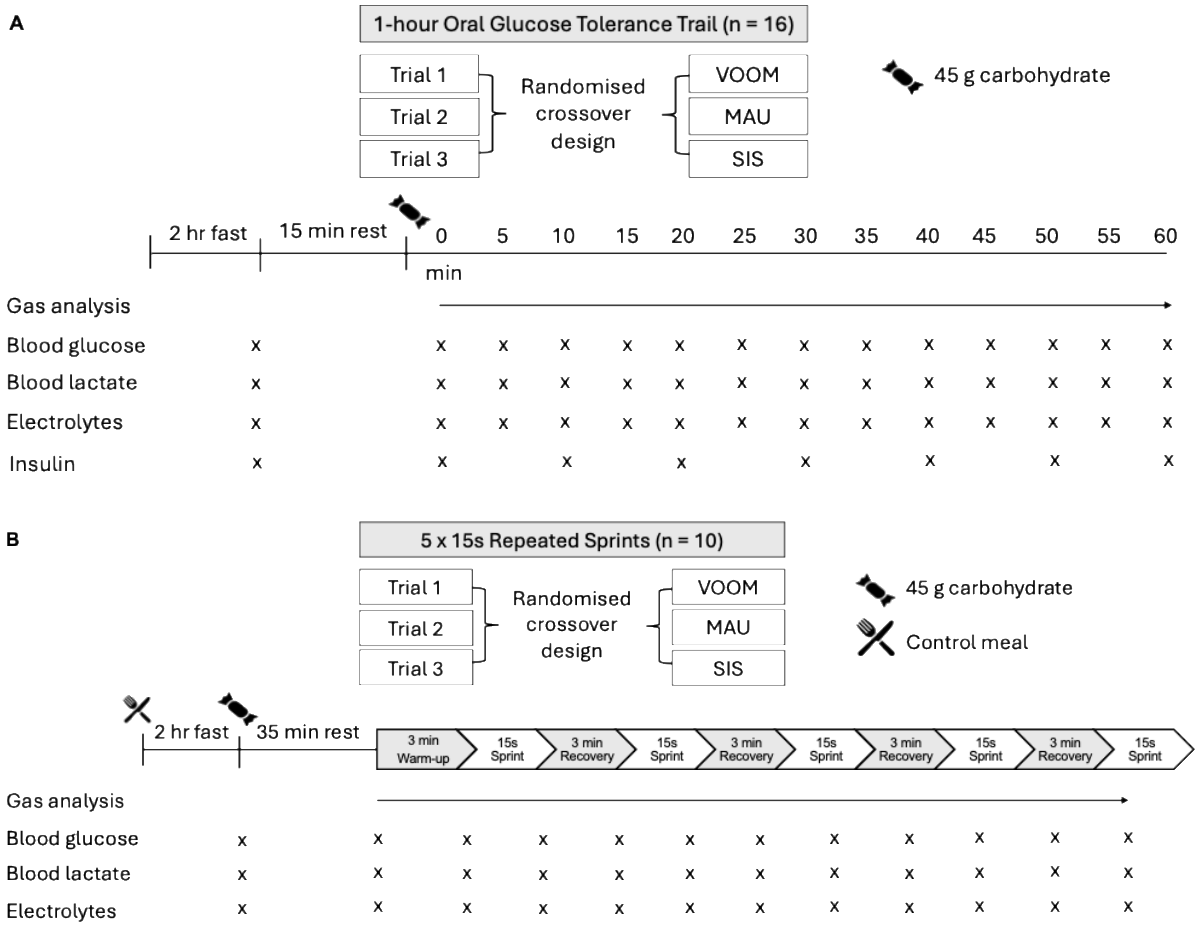


Figure 1. Flowchart study design and schematic of the (A) 1-hour Oral Glucose Tolerance Trial (OGTT), and (B) Repeated intermittent sprint intervals.

Supplement administration

All supplements were prepared by a laboratory technician in accordance with UK food hygiene standards and randomised by the laboratory technician using an online randomisation tool (Research Randomiser: https://www.randomizer.org). The carbohydrate products were labelled A, B and C, with a sealed envelope containing product details kept securely in a locked cabinet. This envelope was only to be opened if a subject experienced an adverse reaction, to identify the product involved. There were no adverse events, so blinding was preserved until analysis was complete. Following this, the products would be re-randomised and re-blinded to

both the subjects and investigators. The study utilised a randomised double-blind crossover design where neither the subjects nor the researchers involved in data collection and analysis knew which supplements were being consumed. The laboratory technician was not involved in analysing the data, maintaining blinding throughout the study. Nutritional information is shown in Table 2.

304 Table 2. Nutritional information of study supplements

Supplement	Ingredients	Nutritional information (matched for 45 g carbohydrate)
VOOM	Raw Cane Sugar, Glucose Syrup, Water, Dried Fruit (1%), Electrolytes (Tri-sodium Citrate, Pink Himalayan Salt, Potassium Chloride, Magnesium Oxide, Calcium Lactate) (0.3%), Natural Flavouring, B-Vitamins. No artificial sweeteners, thickeners or preservatives	176 kcal, 45 g carbohydrates, 41 g of which sugar, 0 g fat, 0 g protein, trace salt, 1 mg B-Vitamins, 120 mg electrolytes
MAU	Water, glucose, fructose, gelling agent: calcium carbonate, gelling agent: gluconic acid, gelling agent: sodium alginate	180 kcal, 45 g carbohydrates, 45 g of which sugars, 0 g fat, 0 g protein, 90 mg salt
SIS	Water, Maltodextrin (from Maize) (33%), Gelling Agents (Gellan Gum, Xanthan Gum), Natural Flavouring, Acidity Regulators (Citric Acid, Sodium Citrate), Preservatives (Sodium Benzoate, Potassium Sorbate), Sweetener (Acesulfame K), Sodium Chloride, Antioxidant (Ascorbic Acid)	178 kcal, 45 g carbohydrates, 1.23 g of which sugars, 0 g fat, 0 g protein, 20 mg salt

305

306 **Blood analysis**

307 Blood glucose and lactate were analysed immediately using a bench-top blood
308 analyser (Biosen C-Line GP+, EKF, Barleben, Germany). For insulin, the 3 ml
309 vacutainer was inverted several times and left to clot at room temperature for 15
310 minutes before being centrifuged at 4°C, 1800 RCF, for 10 minutes. The supernatant

was then transferred to a microfuge tube and stored at -20°C during the study day before moving to -80°C after the study visit for analysis at a future date.

Insulin analysis

Insulin was measured using an enzyme-linked immunosorbent assay (ELISA) (Human Insulin ELISA Kit, CrystalChem, Illinois, USA). Samples were prepared and analysed, and absorbance was read at both 450 nanometres (nm) and 630 nm before subtracting the 630 nm absorbance readings from the 450 nm absorbance readings, following the manufacturer's protocol. Insulin concentrations are presented as micro-units per millilitre (μU/mL).

Missing insulin values (VOOM = 7.8%, MAU = 8.6%, SIS = 6.3%) were imputed using a Monte Carlo methodology to minimise bias from incomplete observations (Schafer, 1997; Dong et al., 2013; Austin & van Buuren, 2022).

To enable temporal comparisons between glucose and insulin, values were normalised to a 0 -100% scale based on the range of each data set (where 0% represented the lowest value and 100% the highest value), previously described by Atherton et al. (2010). Normalisation reflected each subject's percentage change from baseline at 10-minute intervals during the OGTT, using the following equation:

$$([\text{Current Value} - \text{Baseline Value}]/[\text{Maximum Value} - \text{Minimum Value}]) \times 100$$

Following normalisation, the relative changes in glucose and insulin over time were compared to examine the temporal dynamics of both variables across the 1-hour OGTT.

Electrolyte analysis

The supernatant was analysed for electrolyte content using an electrolyte analyser (i-smart 30 PRO, Woodley Laboratory Diagnostics, Bolton, United Kingdom). Ten microlitres were inserted into the tip of the electrolyte reader and analysed for sodium, potassium, chloride, and calcium.

Statistical analysis

Data normality were assessed using Shapiro-Wilk tests. Results are reported as mean ± SD unless stated otherwise. Normally distributed time-series data were analysed using two-way repeated measures ANOVA with product and time as within-subject factors. Significant main or interaction effects were followed up with a Tukey multiple comparison test. Non-parametric data were analysed using a Friedman test, with Dunn's post-hoc tests for significant effects. Data analysis and figure preparation were conducted using GraphPad Prism 10.4.1 (GraphPad Software, San Diego, CA, USA). Statistical significance was set at $p < 0.05$.

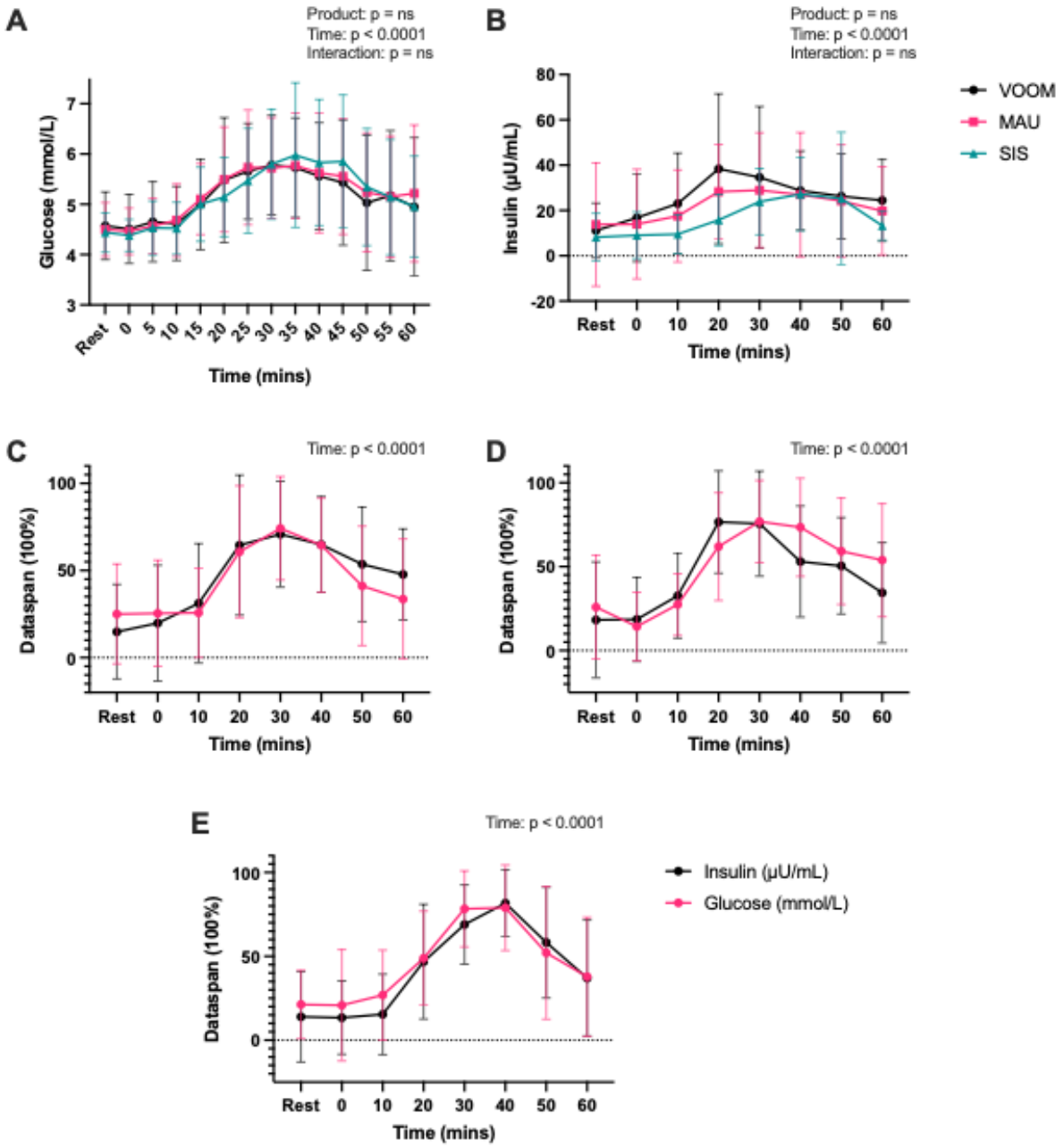
Results

Resting OGTT

Blood glucose and insulin responses to OGTT

A significant main effect of time was found for both glucose and insulin ($p < 0.001$), with no significant differences between products or interaction between time and product ($p > 0.05$). The area under the curve for glucose was similar between products (total area ± standard error) (VOOM 314.3 ± 12.45, MAU 317.2 ± 12.10, SIS 316.50 ± 12.04). Mean peak glucose concentration (VOOM 6.59 ± 1.18, MAU 6.20 ± 1.14 mmol/L, SIS 6.42 ± 1.15 mmol/L) and time to glucose peak (VOOM 31.25 ± 13.96 min, MAU 39.06 ± 12.28 min, SIS 33.13 ± 11.09 min) showed no statistical significance between products, nor any interaction effect ($p > 0.05$), reflecting comparable glucose metabolism across the OGTT.

VOOM elicited a greater area under the curve for insulin (total area ± standard error) (185.8 ± 43.77) than MAU (156.7 ± 44.76) and SIS (121.4 ± 29.35), indicating a greater or more prolonged insulin response when consuming VOOM.



372

373 Figure 2. (A) Blood glucose and (B) insulin concentrations were similar between

374 VOOM, MAU and SIS in a modified 1-hour OGTT ($p > 0.05$). Normalised (data span

375 = 100%) mean ± SD comparisons between insulin and glucose in response to 45 g

376 carbohydrate showed no differences between insulin and glucose for (C) VOOM, (D)

377 MAU, and (E) SIS, ($p > 0.05$).

378

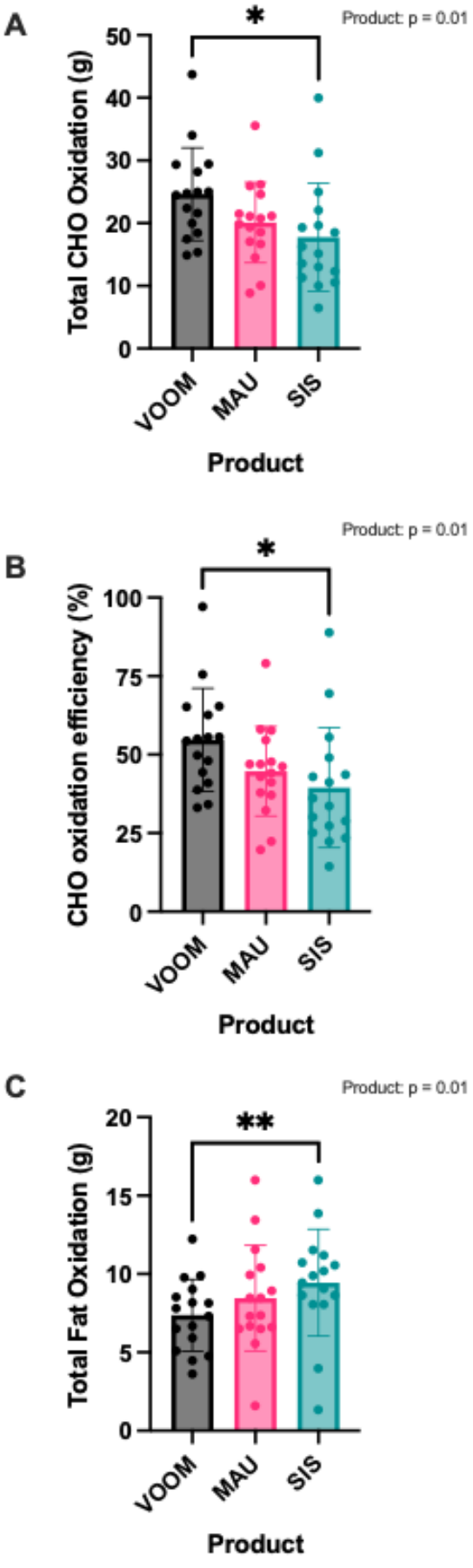
Following normalisation, the relative changes in glucose and insulin over time were compared to examine the temporal pattern of glucose and insulin throughout the study period. Both variables were presented as percentage changes from baseline (0%) and plotted for each participant every 10 minutes across the 1-hour OGTT. This normalisation approach enabled direct comparison of glucose and insulin dynamics independent of individual baseline values. A two-way repeated measures ANOVA revealed a main effect of time ($p < 0.0001$) but no significant product or interaction effect between glucose and insulin concentrations ($p > 0.05$).

VOOM enhances carbohydrate oxidation

A one-way repeated measures ANOVA revealed total carbohydrate oxidation significantly differed between products ($p = 0.01$). Tukey multiple comparisons revealed that VOOM had significantly greater total carbohydrate oxidation across the 1h OGTT than SIS (VOOM 24.63 ± 7.38 g, SIS 17.77 ± 8.61 g, $p = 0.03$, Figure 3A), despite matched carbohydrate provision. No differences were observed between MAU and VOOM, or MAU and SIS (MAU 20.11 ± 6.41 g, $p > 0.05$).

A one-way repeated measures ANOVA revealed carbohydrate oxidation efficiency significantly differed between products ($p = 0.01$). Tukey multiple comparisons test showed that VOOM had a significantly greater carbohydrate oxidation efficiency than SIS (VOOM 54.73 ± 16.4 %, SIS 39.5 ± 19.15%, $p = 0.03$, Figure 3B). No differences were seen between MAU and VOOM or MAU and SIS (MAU 44.68 ± 14.25%, $p > 0.05$).

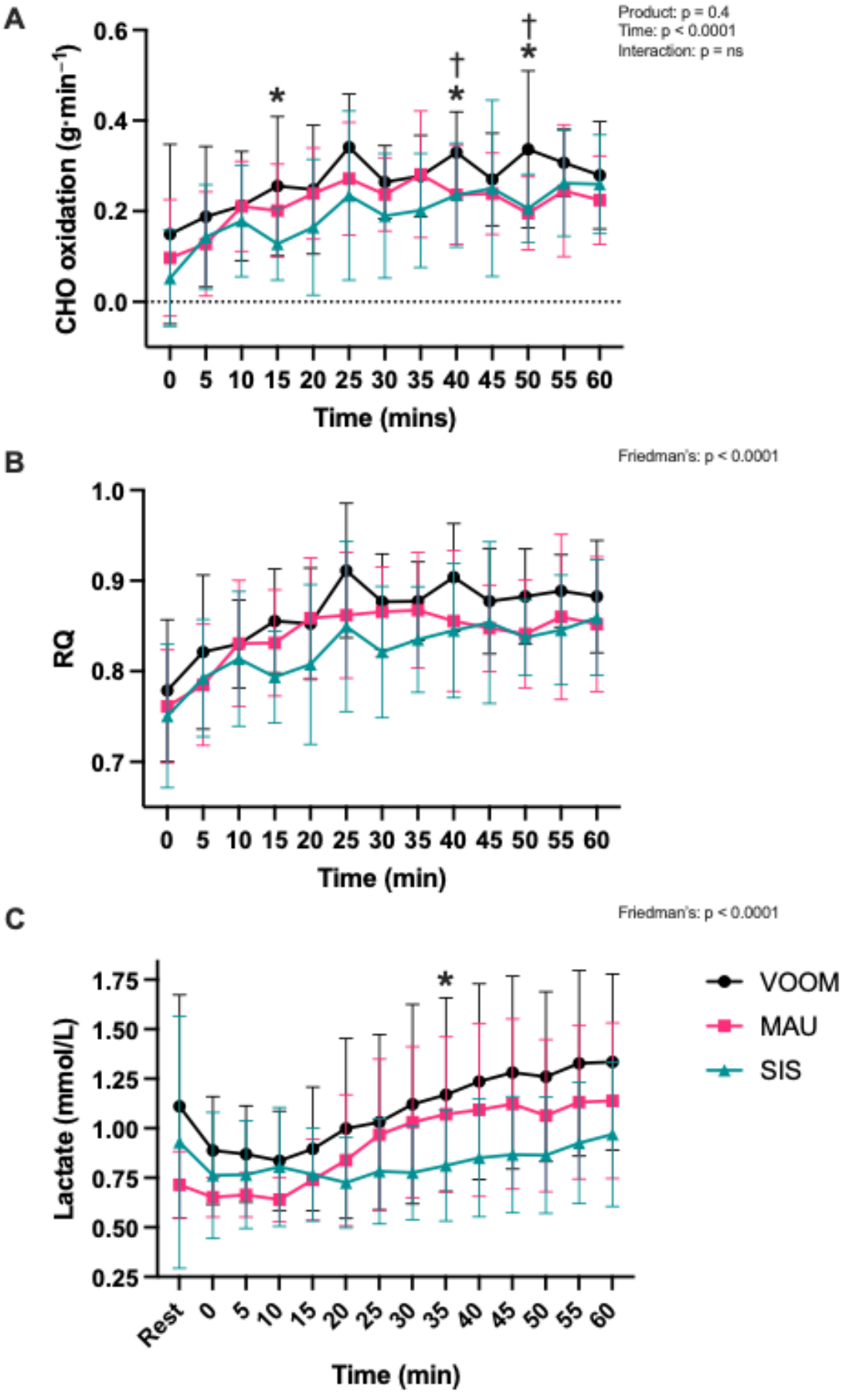
In keeping with the carbohydrate oxidation data, a one-way repeated measures ANOVA showed total fat oxidation significantly differed between products ($p = 0.01$). Indeed, total fat oxidation was suppressed to a greater extent in VOOM than SIS (SIS 9.45 ± 3.41 g, VOOM 7.37 ± 2.29 g, $p = 0.006$, Figure 3C). No differences were observed between MAU and VOOM or MAU and SIS (MAU 8.46 ± 3.41 g, $p > 0.05$).


A
Product: p = 0.01
*
Total CHO Oxidation (g)
50
40
30
20
10
0
VOOM
MAU
SIS
Product
B
Product: p = 0.01
*
CHO oxidation efficiency (%)
100
75
50
25
0
VOOM
MAU
SIS
Product
C
Product: p = 0.01
**
Total Fat Oxidation (g)
20
15
10
5
0
VOOM
MAU
SIS
Product

409

Figure 3. (A) Consuming VOOM resulted in a significant increase in total carbohydrate oxidation compared to SIS in a modified 1-hour OGTT ($p = 0.03$). (B) Carbohydrate oxidation efficiency was significantly greater in VOOM than SIS ($p = 0.03$). (C) Total fat oxidation was suppressed to a greater extent for VOOM than SIS ($p = 0.006$) during the 1-hour modified OGTT. *$p < 0.05$; **$p < 0.01$.

A two-way repeated measures ANOVA revealed a significant main effect for both time ($p < 0.0001$) and product ($p = 0.04$) on carbohydrate oxidation per minute, but no interaction effect was present ($p > 0.05$), Figure. 4A. VOOM elicited a greater mean carbohydrate oxidation rate (0.27 ± 0.05 g·min^{-1}) than MAU (0.21 ± 0.05 g·min^{-1}) and SIS (0.19 ± 0.06 g·min^{-1}). Tukey multiple comparisons showed that at 15 minutes, VOOM had a significantly greater carbohydrate oxidation rate per minute than SIS (VOOM 0.25 ± 0.15 g·min^{-1}; SIS 0.12 ± 0.07 g·min^{-1}, $p = 0.019$). At 40 minutes, VOOM had a significantly greater carbohydrate oxidation rate per minute than both MAU (VOOM 0.32 ± 0.09 g·min^{-1}; MAU 0.23 ± 0.10 g·min^{-1}, $p = 0.03$) and SIS (VOOM 0.32 ± 0.09 g·min^{-1}; 0.23 ± 0.11 g·min^{-1}, $p = 0.04$). Similarly, at 50 minutes, VOOM's carbohydrate oxidation rate per minute was significantly greater than MAU (VOOM 0.33 ± 0.17 g·min^{-1}; MAU 0.19 ± 0.08 g·min^{-1}, $p = 0.019$) and SIS (VOOM 0.33 ± 0.17 g·min^{-1}; SIS 0.20 ± 0.07 g·min^{-1}, $p = 0.03$).


A
Product: p = 0.4
Time: p < 0.0001
Interaction: p = ns
CHO oxidation (g·min⁻¹)
0.6
0.4
0.2
0.0
0 5 10 15 20 25 30 35 40 45 50 55 60
Time (mins)
B
Friedman's: p < 0.0001
RQ
1.0
0.9
0.8
0.7
0 5 10 15 20 25 30 35 40 45 50 55 60
Time (min)
C
Friedman's: p < 0.0001
Lactate (mmol/L)
1.75
1.50
1.25
1.00
0.75
0.50
0.25
Rest 0 5 10 15 20 25 30 35 40 45 50 55 60
Time (min)
VOOM
MAU
SIS

430

Figure 4. (A) VOOM elicited significantly greater CHO (carbohydrate) oxidation than SIS at 15 mins ($p = 0.019$) and greater than MAU ($p = 0.03$) and SIS ($p = 0.04$) at 40 mins and greater than MAU ($p = 0.019$) and SIS ($p = 0.03$) at 50 mins. (B) A higher RQ for VOOM than MAU and SIS, indicating increased carbohydrate use. * $p < 0.05$ for VOOM vs SIS. † $p < 0.05$ for VOOM vs MAU. (C) Blood lactate was significantly greater for VOOM than SIS at 35 minutes ($p = 0.01$). * $p < 0.05$.

A Friedman test was conducted on the non-parametric RQ data, revealing significant differences among products, X^2 (38) = 187.8, $p < 0.0001$, as shown in Figure 4B. above. Dunn's multiple comparisons revealed no significant differences between products. Mean ranks were as follows: VOOM (24), MAU (18), and SIS (16). Raw data means; VOOM (0.86 ± 0.06), MAU (0.84 ± 0.07), and SIS (0.83 ± 0.07).

A Friedman test revealed a significant difference in lactate concentration between the products (X^2 (41) = 253, $p < 0.001$). VOOM had a greater mean rank for lactate concentration (26) than MAU (20) and SIS (17). This was consistent with the raw mean data (VOOM 1.08 ± 0.42 mmol/L, MAU 0.91 ± 0.30 mmol/L, SIS 0.81 ± 0.31 mmol/L). Dunn’s multiple comparisons revealed a significantly greater lactate concentration in VOOM than in SIS at 35 minutes (VOOM mean rank = 29, raw data mean = 1.17 ± 0.49 mmol/L, SIS mean rank = 14, raw data mean = 0.77 ± 0.28 mmol/L, $p = 0.01$, Figure 4C).

No differences between electrolytes

There were no significant differences in the electrolyte content measured (sodium, potassium and chloride), with levels remaining similar throughout ($p > 0.05$).

Exercise study

Sex differences in performance metrics – warrant further investigation

A two-way repeated measures ANOVA revealed a significant effect of sex on mean peak power ($p < 0.0001$). Tukey multiple comparisons showed significant differences between males and females for VOOM (males 861.4 ± 97.45 watts; females 612 ± 94.47 watts, $p = 0.01$), MAU (males 826.8 ± 93.79 watts; females 601.9 ± 94.30 watts $p = 0.02$) and SIS (males 856.7 ± 101.3 watts; females 599.5 ± 104.9 watts, $p = 0.01$), Figure 4A. A similar effect was found for mean power ($p < 0.0001$), with significant differences for VOOM (males 684.7 ± 65.96 watts; females 501.4 ± 53.97 watts, $p = 0.01$), MAU (males 668.4 ± 66.83 watts; females 518.9 ± 51.28 watts $p = 0.04$) and SIS (males 691.5 ± 67.97 watts; females 487.3 ± 63.58 watts, $p = 0.006$), Figure 4B. A significant effect of sex was also observed for total work ($p < 0.0001$), with males performing significantly more work for VOOM (males 10131 ± 982.4 kJ; females 7365 ± 838.4 kJ, $p = 0.01$), MAU (males 10047 ± 1096 kJ; females 7559 ± 708.2 kJ, $p = 0.02$), and SIS (males 10231 ± 1096 kJ; females (7208 ± 927.2 kJ, $p = 0.007$), Figure 4C. No significant sex effect was found for the fatigue index ($p = 0.20$).

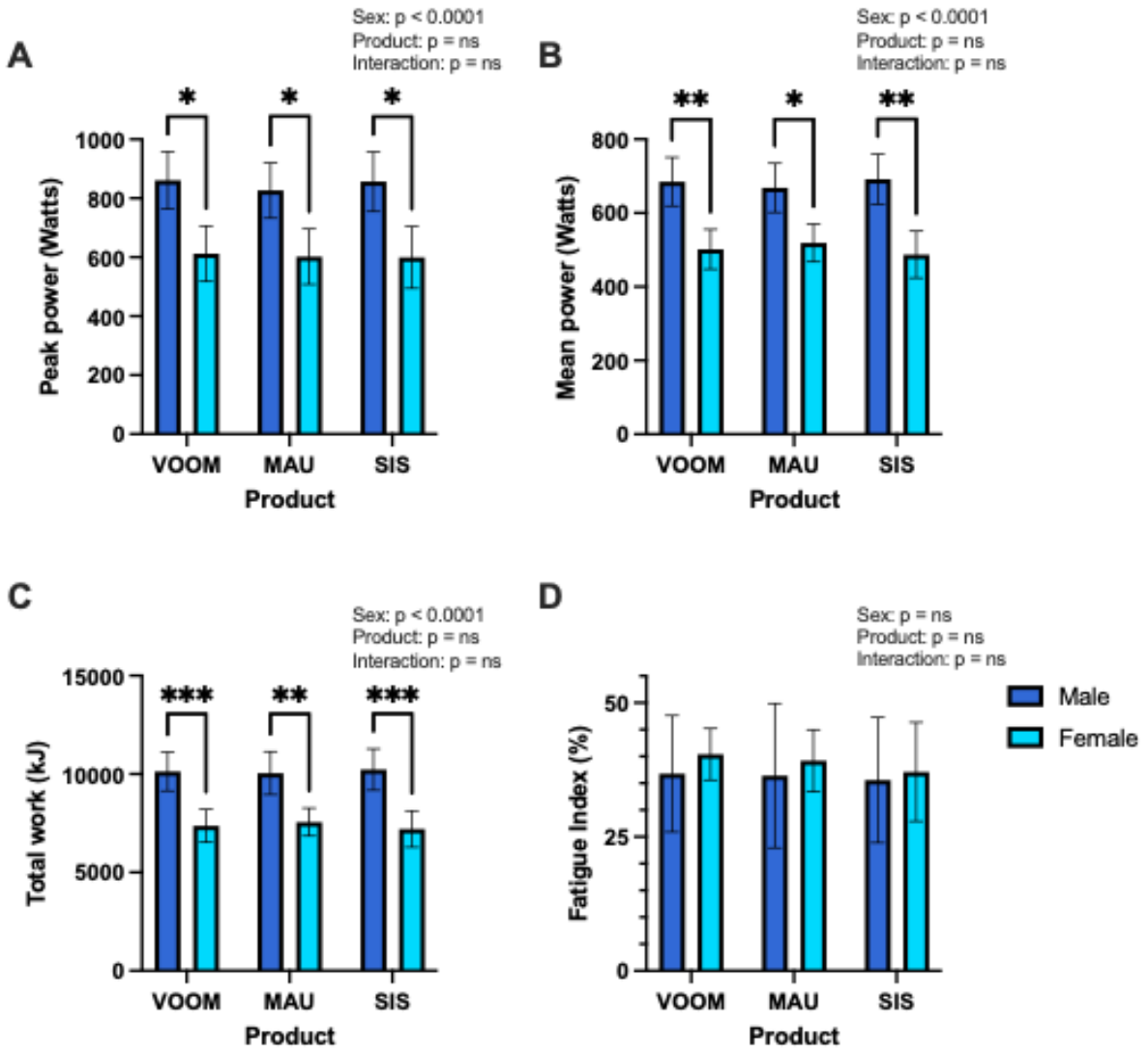
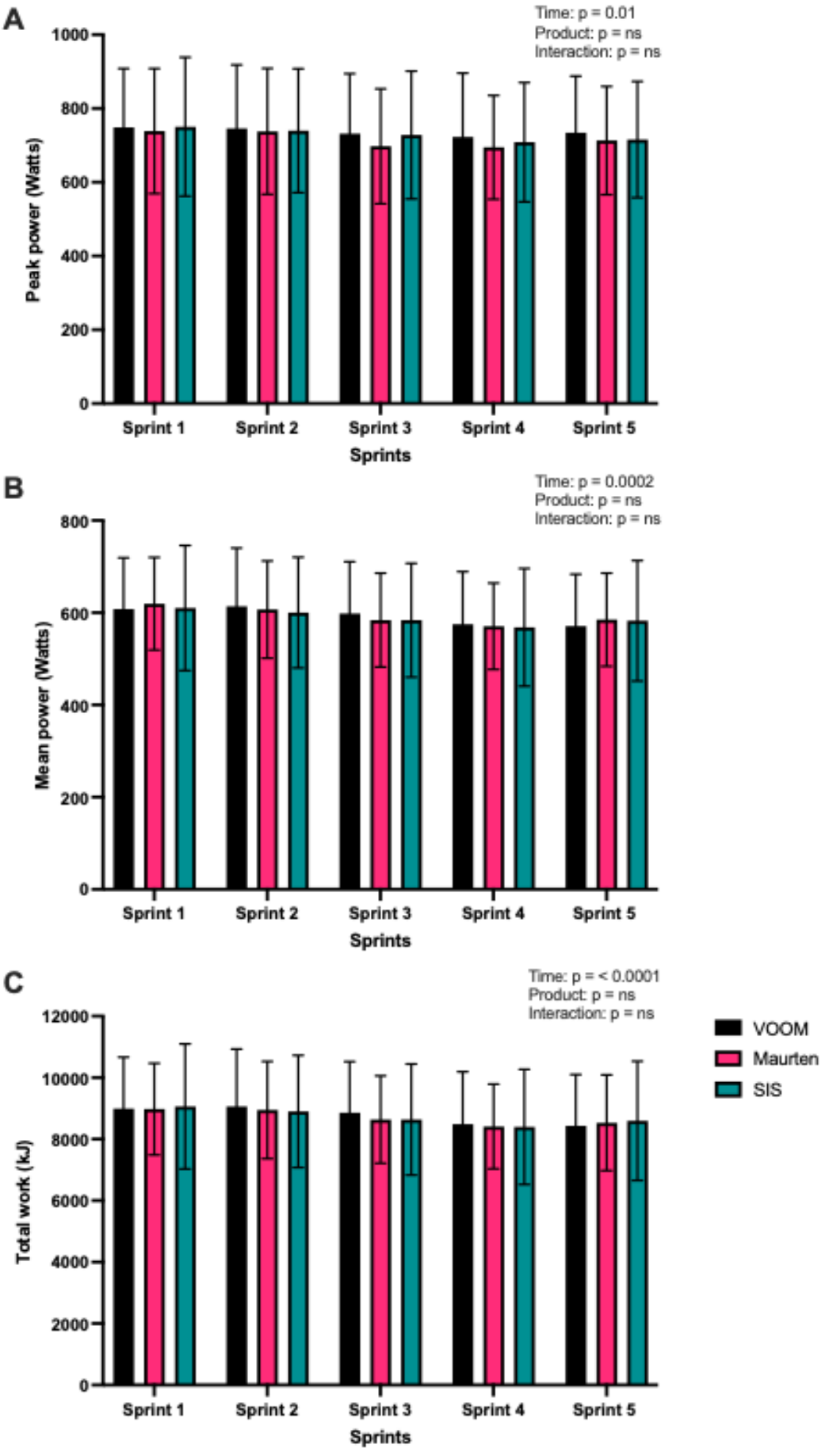


Figure 5. During the repeated sprints, males produced significantly greater readings than females for (A) Peak power, (B) Mean power, and (C) Total work when averaged across all five repeated sprints. (D) No significant effect of sex was shown for the Fatigue index ($p > 0.05$). *$p < 0.05$; **$p < 0.01$. kJ = kilojoules.

Performance metrics were comparable between products

A two-way repeated measures ANOVA for peak power per sprint revealed a significant effect of time ($p = 0.01$) but no product effect (VOOM 736.7 ± 10.51 watts; MAU 716.4 ± 21.2 watts; SIS 728.5 ± 17.08 watts, $p = 0.90$) or time x product interaction were found ($p = 0.90$). A similar trend was observed for mean power per

sprint, where a significant effect for time was found ($p = 0.0002$), but no difference was detected between products (VOOM 593.1 ± 19.17 watts; MAU 593.1 ± 19.63 watts; SIS 589 ± 16.41 watts, $p = 0.9$) or for the interaction effect ($p = 0.80$). Total work per sprint was also influenced by time ($p < 0.0001$) but not product (VOOM 8766 ± 290 kJ; MAU 8701 ± 251 kJ; SIS 8720 ± 263 kJ, $p = 0.90$) or time x product interaction ($p = 0.90$), as depicted in Figure 6. No significant effect was found for the fatigue index (VOOM 38.6 ± 8.1%; MAU 38.3 ± 10.0%; SIS 36.3 ± 9.6%, $p = 0.20$).


A
Time: p = 0.01
Product: p = ns
Interaction: p = ns
Peak power (Watts)
1000
800
600
400
200
0
Sprint 1
Sprint 2
Sprint 3
Sprint 4
Sprint 5
Sprints
B
Time: p = 0.0002
Product: p = ns
Interaction: p = ns
Mean power (Watts)
800
600
400
200
0
Sprint 1
Sprint 2
Sprint 3
Sprint 4
Sprint 5
Sprints
C
Time: p = < 0.0001
Product: p = ns
Interaction: p = ns
Total work (kJ)
12000
10000
8000
6000
4000
2000
0
Sprint 1
Sprint 2
Sprint 3
Sprint 4
Sprint 5
Sprints
VOOM
Maurten
SIS

494

Figure 6. Comparable results in (A) Peak power, (B) Mean power, and (C) Total work per sprint between VOOM, MAU and SIS. kJ = kilojoules

Similar substrate utilisation and electrolyte responses across carbohydrate products

A significant main effect of time was shown for glucose ($p < 0.0001$) and lactate ($p < 0.0001$), but no effect of product or time x product interaction were present ($p > 0.05$). No significant main or interaction effects were shown for carbohydrate oxidation nor carbohydrate oxidation efficiency ($p > 0.05$), indicating similar exogenous carbohydrate utilisation across products. RER had a significant main effect of time ($p < 0.0001$), but not product or time x product interaction ($p > 0.05$), further supporting comparable substrate utilisation during repeated sprints (see Table S1). A main effect of time was seen for potassium ($p = 0.001$) and chloride ($p = 0.02$), but no main effect of product or time x product interaction was shown. No main or interaction effects were shown for sodium or calcium ($p > 0.05$).

Minimal gastrointestinal discomfort and comparable perceptual responses across carbohydrate products

There were no significant main or interaction effects ($p > 0.05$) in GI discomfort, with subjects reporting minimal GI discomfort throughout, demonstrating comparable tolerability with both the volume and compositions of each carbohydrate product (see Table S1). No significant main or interaction effects were seen for heart rate or RPE ($p > 0.05$).

Discussion

This research found that the VOOM glucose-fructose energy bar resulted in a higher carbohydrate oxidation rate in a resting state compared to the MAU hydrogel (fructose-glucose) and SIS gel (maltodextrin-based). Higher carbohydrate oxidation is beneficial as it supports adenosine triphosphate (ATP) production, helping to fuel muscle contractions and delay fatigue (González-Marenco et al., 2024). This increased carbohydrate oxidation is likely what led to the significantly greater lactate concentration in VOOM compared to SIS, as the greater breakdown of carbohydrates through aerobic glycolysis may have led to more pyruvate being fully oxidised, resulting in excess pyruvate being converted to lactate (Hargreaves & Spreit, 2020). However, the significant differences in substrate oxidation between products seen in the OGTT did not translate into significant differences in exercise performance nor changes in glycaemia during repeated sprint intervals.

Differences in the carbohydrate formulations and compositions likely influenced these findings. The glucose-fructose mix used in likely increased carbohydrate oxidation due to its immediate availability of free glucose combined with fructose, utilising both SGLT1 and GLUT5 transporters (Jentjens et al., 2004; Jeukendrup, 2010), allowing for rapid oxidation and energy availability. In contrast, SIS relies on maltodextrin, which must be broken down to glucose before absorption (Hofman et al., 2016), potentially causing a slight delay in oxidation. MAU utilises a hydrogel formula comprised of three-dimensional hydrophilic polymers containing sodium alginate and pectin, which aid the absorption of multiple transportable carbohydrates by delivering them gradually at a pH level that is biocompatible to the stomach and intestine (King et al., 2020; Rowe et al., 2022). This may slow the release of sugars into the bloodstream and result in reduced carbohydrate oxidation compared with

VOOM. These differences highlight how formulation and carbohydrate type influence oxidation rate and energy availability.

Although there were metabolic differences during the OGTT, including increased carbohydrate oxidation with VOOM, these did not translate to improved performance during repeated sprint cycling. This may reflect the nature of energy provision during short, high-intensity efforts, which relies predominantly on phosphocreatine and intramuscular glycogen, rather than circulating glucose, with previous research demonstrating carbohydrate supplementation has little effect on glycogen depletion during short-duration, high-intensity intermittent exercise, even when blood glucose is elevated (Vigh-Larsen et al., 2024).

During the recovery periods between sprints, fat oxidation likely contributed more to energy provision; however, carbohydrate supplementation may have helped to maintain glycaemia, potentially delaying the onset of fatigue associated with hypoglycaemia (Cao et al., 2025; Prins et al., 2025). In this aspect, the present study showed similar reductions in performance over the five sprints with all three supplements and no differences in RPE, suggesting that no one product was superior in maintaining performance or reducing the perception of fatigue. Thus, the exogenous effects of carbohydrate supplementation may be more relevant to prolonged or glycogen-depleting exercise, where maintaining glycaemia or delaying glycogen depletion plays a more critical role (Kuipers et al. 1987; and Podlogar et al. 2023; Wallis et al. 2008).

None of the subjects reported significant GI discomfort during repeated sprints after consuming any of the three carbohydrate supplements (VOOM, MAU, SIS), each providing 45 g of carbohydrate – a valuable finding given concerns around exercise-induced GI symptoms (Gaskell et al., 2023; Ribichini et al., 2023). While minimal discomfort has been reported with hydrogel or gel-based formulations (Hearris et al., 2022; Rowe et al., 2022), the absence of symptoms with the solid VOOM bar is notable, as earlier research linked solid forms to greater GI discomfort (Guillochon & Rowlands, 2017; Pfeiffer et al., 2010). However, more recent evidence suggests improved GI tolerance with solid supplements (Hearris et al., 2022). Our findings support this, indicating that well-formulated solid carbohydrates can be comfortable consumed even during high-intensity exercise, reassuring athletes who may prefer solid options for practical or palatability reasons.

Limitations

Full blinding of subjects was not possible due to the differing physical forms of the supplements, with VOOM provided as a bar, MAU as a hydrogel, and SIS as a gel, making them distinguishable upon consumption. However, subjects were unaware of product names physical forms prior to consumption, limiting the risk of bias. The study also used antegrade rather than retrograde venous cannulation. Antegrade cannulation is a less invasive method with minimal impact on metabolite measurement accuracy (Wrench et al., 2024).

A further limitation is the lack of direct measurement of muscle glycogen, which would have provided a clearer understanding of glycogen utilisation and recovery in response to carbohydrate supplementation. Future studies incorporating muscle

biopsies could enhance the confidence and precision of interpretations relating to substrate utilisation.

Conclusion

The findings of this study show that the VOOM glucose-fructose bar elicits greater carbohydrate oxidation at rest compared to MAU and SIS, providing athletes with an effective alternative for carbohydrate supplementation. However, these metabolic differences did not enhance repeated sprint cycling performance – an exercise intensity less dependent on sustained carbohydrate availability – suggesting such benefits may be more applicable to conditions where blood glucose has a greater effect on performance, such as during prolonged or glycogen-depleting exercise.

Competing interests

ED was supported by Omega EFA Ltd, trading as Team Nutrition, to complete a Masters by Research.

Funding statement

This research was funded by Omega EFA Ltd, trading as Team Nutrition. The funder had no role in the study design, trial execution, data analyses, interpretation of the data, or decision to submit results.

Data availability statement

Data generated or analysed during this study are provided in full within the published article.

Supplementary table

Table S1. Physiological and metabolic responses under VOOM, MAU and SIS

	VOOM	MAU	SIS
Glucose (mmol/L)	4.50 ± 0.53	4.77 ± 0.42	5.08 ± 0.52
Lactate (mmol/L)	5.16 ± 3.09	5.09 ± 2.88	4.95 ± 2.92
Potassium (mmol/L)	4.52 ± 0.25	4.69 ± 0.32	4.51 ± 0.28
Chloride (mmol/L)	106.6 ± 0.87	106.3 ± 0.46	106 ± 0.66
Sodium (mmol/L)	139.9 ± 1.77	139.7 ± 1.09	140.2 ± 1.6
Calcium (mmol/L)	1.18 ± 0.03	1.21 ± 0.01	1.19 ± 0.02
RER	1.08 ± 0.08	1.04 ± 0.06	1.05 ± 0.07
Heart rate (bpm)	126 ± 21	129 ± 20	131 ± 21
CHO oxidation ($g \cdot min^{-1}$)	2.4 ± 0.7	2.1 ± 0.5	2.3 ± 0.7
CHO oxidation efficiency (%)	47.3 ± 12.0	51.5 ± 15.5	53.2 ± 12.9
Δ GI	0.7 ± 1.06	0.6 ± 1.08	0.3 ± 0.66
Δ RPE	9.1 ± 1.8	8.2 ± 2.5	9.5 ± 1.4

CHO = Carbohydrate. Δ RPE = Change in the rating of perceived exertion. Δ GI Discomfort = Change in gastrointestinal discomfort score.

References

Atherton P.J., Etheridge T., Watt P.W., Wilkinson D., Selby A., Rankin D., Smith K. and Rennie M.J. 2010. Muscle full effect after oral protein: time-dependent concordance and discordance between human muscle protein synthesis and mTORC1 signaling. Am.J.Clin.Nutr. 92(5): 1080–1088.

Austin P.C. and van Buuren S. 2022. The effect of high prevalence of missing data on estimation of the coefficients of a logistic regression model when using multiple imputation. 22(1): 196.

Baker L.B., Rollo I., Stein K.W. and Jeukendrup A.E. 2015. Acute effects of carbohydrate supplementation on intermittent sports performance. 7(7): 5733–5763.

Blannin A.K. and Wallis G.A. 2024. Effects of overnight-fasted versus fed-state exercise on the components of energy balance and interstitial glucose across four days in healthy adults. 203107716.

Borg G.A. 1982. Psychophysical bases of perceived exertion. Med.Sci.Sports Exerc. 14(5): 377–381.

Cao W., He Y., Fu R., Chen Y., Yu J. and He Z. 2025. A Review of Carbohydrate Supplementation Approaches and Strategies for Optimizing Performance in Elite Long-Distance Endurance. 17(5): 918.

Ciarambino T., Crispino P., Guarisco G. and Giordano M. 2023. Gender differences in insulin resistance: new knowledge and perspectives. Curr.Issues Mol.Biol. 45(10): 7845–7861.

Dong Y. and Peng C.J. 2013. Principled missing data methods for researchers. 2 1–17.

Frayn K.N. 1983. Calculation of substrate oxidation rates in vivo from gaseous exchange. J.Appl.Physiol. 55(2): 628–634.

Gaffney C.J., Cunnington J., Rattley K., Wrench E., Dyche C. and Bampouras T.M. 2022. Weighted vests in CrossFit increase physiological stress during walking and running without changes in spatiotemporal gait parameters. 65(1): 147–158.

Gaskell S.K., Burgell R., Wiklendt L., Dinning P.G. and Costa R.J. 2023. Impact of exercise duration on gastrointestinal function and symptoms. J.Appl.Physiol. 134(1): 160–171.

González-Marenco R., Estrada-Sánchez I.A., Medina-Escobedo M., Chim-Aké R. and Lugo R. 2024. The effect of Oral adenosine triphosphate (ATP) supplementation on anaerobic exercise in healthy resistance-trained individuals: a systematic review and Meta-analysis. 12(3): 82.

Gromova L.V., Fetissov S.O. and Gruzdkov A.A. 2021. Mechanisms of glucose absorption in the small intestine in health and metabolic diseases and their role in appetite regulation. 13(7): 2474.

Guillochon M. and Rowlands D.S. 2017. Solid, gel, and liquid carbohydrate format effects on gut comfort and performance. Int.J.Sport Nutr.Exerc.Metab. 27(3): 247–254.

Hargreaves M. and Spriet L.L. 2020. Skeletal muscle energy metabolism during exercise. 2(9): 817–828.

Hearris M.A., Pugh J.N., Langan-Evans C., Mann S.J., Burke L., Stellingwerff T., Gonzalez J.T. and Morton J.P. 2022. 13C-glucose-fructose labeling reveals comparable exogenous CHO oxidation during exercise when consuming 120 g/h in fluid, gel, jelly chew, or coingestion. J.Appl.Physiol. 132(6): 1394–1406.

Hofman D.L., Van Buul V.J. and Brouns F.J. 2016. Nutrition, health, and regulatory aspects of digestible maltodextrins. Crit.Rev.Food Sci.Nutr. 56(12): 2091–2100.

Hulston C.J., Wallis G.A. and Jeukendrup A.E. 2009. Exogenous CHO oxidation with glucose plus fructose intake during exercise. Med.Sci.Sports Exerc. 41(2): 357–363.

Ismardi I., Rahman D., Rifki M.S., Welis W., Okilanda A. and Ockta Y. 2024. The Importance of Carbohydrate Intake for Maintaining Glycogen Stores and Physical Performance during Prolonged Exercise: A Literature Review. 10(SpecialIssue): 83–89.

Jentjens R.L., Moseley L., Waring R.H., Harding L.K. and Jeukendrup A.E. 2004. Oxidation of combined ingestion of glucose and fructose during exercise. J.Appl.Physiol.

Jeukendrup A.E. and Wallis G.A. 2005. Measurement of substrate oxidation during exercise by means of gas exchange measurements. Int.J.Sports Med. 26(S 1): S28–S37.

Jeukendrup A. 2014. A step towards personalized sports nutrition: carbohydrate intake during exercise. 44(Suppl 1): 25–33.

Jeukendrup A.E. 2010. Carbohydrate and exercise performance: the role of multiple transportable carbohydrates. 13(4): 452–457.

Jeukendrup A.E. and Jentjens R. 2000. Oxidation of carbohydrate feedings during prolonged exercise: current thoughts, guidelines and directions for future research. 29 407–424.

Kazemi A., Racil G., Ahmadi Hekmatikar A.H., Behnam Moghadam M., Karami P. and Henselmans M. 2023. Improved physical performance of elite soccer players based on GPS results after 4 days of carbohydrate loading followed by 3 days of low carbohydrate diet. 20(1): 2258837.

King A.J., Rowe J.T. and Burke L.M. 2020. Carbohydrate hydrogel products do not improve performance or gastrointestinal distress during moderate-intensity endurance exercise. Int.J.Sport Nutr.Exerc.Metab. 30(5): 305–314.

Krings B.M., Peterson T.J., Shepherd B.D., McAllister M.J. and Smith J.W. 2017. Effects of carbohydrate ingestion and carbohydrate mouth rinse on repeat sprint performance. Int.J.Sport Nutr.Exerc.Metab. 27(3): 204–212.

Kuipers H., Keizer H.A., Brouns F. and Saris W. 1987. Carbohydrate feeding and glycogen synthesis during exercise in man. 410 652–656.

McKay A.K., Stellingwerff T., Smith E.S., Martin D.T., Mujika I., Goosey-Tolfrey V.L., Sheppard J. and Burke L.M. 2021. Defining training and performance caliber: a participant classification framework. 17(2): 317–331.

Pfeiffer B., Stellingwerff T., Zaltas E. and Jeukendrup A.E. 2010. Oxidation of solid versus liquid CHO sources during exercise. Med.Sci.Sports Exerc. 42(11): 2030–2037.

Podlogar T., Bokal Š, Cirnski S. and Wallis G.A. 2022. Increased exogenous but unaltered endogenous carbohydrate oxidation with combined fructose-maltodextrin ingested at 120 g h− 1 versus 90 g h− 1 at different ratios. Eur.J.Appl.Physiol. 122(11): 2393–2401.

Podlogar T., Shad B.J., Seabright A.P., Odell O.J., Lord S.O., Civil R., Salgueiro R.B., Shepherd E.L., Lalor P.F. and Elhassan Y.S. 2023. Postexercise muscle glycogen synthesis with glucose, galactose, and combined galactose-glucose ingestion.

Podlogar T. and Wallis G.A. 2022. New horizons in carbohydrate research and application for endurance athletes. 52(Suppl 1): 5–23.

Prins P.J., Noakes T.D., Buga A., Gerhart H.D., Cobb B.M., D'Agostino D.P., Volek J.S., Buxton J.D., Heckman K. and Plank E. 2025. Carbohydrate Ingestion Eliminates Hypoglycemia & Improves Endurance Exercise Performance in Triathletes Adapted to Very Low & High Carbohydrate Isocaloric Diets.

Rauch C.E., McCubbin A.J., Gaskell S.K. and Costa R.J. 2022. Feeding tolerance, glucose availability, and whole-body total carbohydrate and fat oxidation in male endurance and ultra-endurance runners in response to prolonged exercise, consuming a habitual mixed macronutrient diet and carbohydrate feeding during exercise. 12 773054.

Ribichini E., Scalese G., Cesarini A., Mocci C., Pallotta N., Severi C. and Corazziari E.S. 2023. Exercise-induced gastrointestinal symptoms in endurance sports: A review of pathophysiology, symptoms, and nutritional management. 2(3): 289–307.

Rodriguez-Giustiniani P., Rollo I., Witard O.C. and Galloway S.D. 2019. Ingesting a 12% carbohydrate-electrolyte beverage before each half of a soccer match simulation facilitates retention of passing performance and improves high-intensity running capacity in academy players. Int.J.Sport Nutr.Exerc.Metab. 29(4): 397–405.

Rollo I., Gonzalez J.T., Fuchs C.J., van Loon L.J. and Williams C. 2020. Primary, secondary, and tertiary effects of carbohydrate ingestion during exercise. 50 1863–1871.

Rosset R., Egli L. and Lecoultre V. 2017. Glucose–fructose ingestion and exercise performance: The gastrointestinal tract and beyond. 17(7): 874–884.

Rowe J.T., King R.F., King A.J., Morrison D.J., Preston T., Wilson O.J. and O'hara J.P. 2022. Glucose and fructose hydrogel enhances running performance, exogenous carbohydrate oxidation, and gastrointestinal tolerance. Med.Sci.Sports Exerc. 54(1): 129–140.

Saunders M.J., Luden N.D. and Herrick J.E. 2007. Consumption of an oral carbohydrate-protein gel improves cycling endurance and prevents postexercise muscle damage. 21(3): 678–684.

Schafer J.L. 1997. Analysis of incomplete multivariate data. CRC press.

Smith E.S., Weakley J., McKay A.K., McCormick R., Tee N., Kuikman M.A., Harris R., Minahan C., Buxton S. and Skinner J. 2024. Minimal influence of the menstrual cycle or hormonal contraceptives on performance in female rugby league athletes. 24(8): 1067–1078.

Thomas D.T., Erdman K.A. and Burke L.M. 2016. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. 116(3): 501–528.

Tucker J.A., McCarthy S.F., Bornath D.P., Khoja J.S. and Hazell T.J. 2025. The effect of the menstrual cycle on energy intake: A systematic review and meta-analysis. Nutr.Rev. 83(3): e866–e876.

Vigh-Larsen J.F., Kruse D.Z., Moseholt M.B., Hansen L.G., Christensen A.L., Bæk A., Andersen O.E., Mohr M. and Overgaard K. 2024. No Effects of Carbohydrate Ingestion on Muscle Metabolism or Performance During Short-Duration High-Intensity Intermittent Exercise. Scand.J.Med.Sci.Sports . 34(9): e14731.

Wallis G.A., Hulston C.J., Mann C.H., Roper H.P., Tipton K.D. and Jeukendrup A.E. 2008. Postexercise muscle glycogen synthesis with combined glucose and fructose ingestion. 40(10): 1789–1794.

Wallis G.A., Rowlands D.S., Shaw C., Jentjens R.L. and Jeukendrup A.E. 2005. Oxidation of combined ingestion of maltodextrins and fructose during exercise. Med.Sci.Sports Exerc. 37(3): 426–432.

Wardenaar F.C., Chan Y., Clear A.M., Schott K., Mohr A.E., Ortega-Santos C.P., Seltzer R.G. and Pugh J. 2024. The Gastrointestinal Symptom Rating Scale has

a Good Test–Retest Reliability in Well-Trained Athletes With and Without Previously Self-Identified Gastrointestinal Complaints 1–12.

World Medical Association. 2025. World Medical Association Declaration of Helsinki: Ethical Principles for Medical Research Involving Human Participants. 331(1): 71–74.

Wrench E., Subar D.A., Bampouras T.M., Lauder R.M. and Gaffney C.J. 2024. Myths and methodologies: Assessing glycaemic control and associated regulatory mechanisms in human physiology research. Exp.Physiol. 109(9): 1461–1477.