13C-glucose-fructose labelling reveals comparable exogenous CHO oxidation during exercise when consuming 120 g/h in fluid, gel, jelly chew or co-ingestion

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Running head: CHO oxidation from fluid, semi-solid and solid

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Abstract

We examined the effects of carbohydrate (CHO) delivery form on exogenous CHO oxidation, gastrointestinal discomfort, and exercise capacity. In a randomised repeated measures design (after 24 h of high CHO intake (8 $g \cdot kg^{-1}$) and pre-exercise meal (2 $g \cdot kg^{-1}$)), nine trained males ingested 120 g $CHO \cdot h^{-1}$ from fluid (DRINK), semi-solid gel (GEL), solid jelly chew (CHEW), or a co-ingestion approach (MIX). Participants cycled for 180 min at 95% lactate threshold followed by an exercise capacity test (150% lactate threshold). Peak rates of exogenous CHO oxidation (DRINK, 1.56 ± 0.16; GEL, 1.58 ± 0.13; CHEW, 1.59 ± 0.08; MIX, 1.66 ± 0.02 $g \cdot min^{-1}$) and oxidation efficiency (DRINK, 72 ± 8; GEL, 72 ± 5; CHEW, 75 ± 5; MIX, 75 ± 6%) were not different between trials (all $P > 0.05$). Despite ingesting 120 $g \cdot h^{-1}$, participants reported minimal symptoms of gastrointestinal distress across all trials. Exercise capacity was also not significantly different (all $P < 0.05$) between conditions (DRINK, 446 ± 350; GEL, 529 ± 396; CHEW, 596 ± 416; MIX, 469 ± 395 sec). Data represent the first time that rates of exogenous CHO oxidation (via stable isotope methodology) have been simultaneously assessed using feeding strategies (i.e., pre-exercise CHO feeding and the different forms and combinations of CHO during exercise) commonly adopted by elite endurance athletes. We conclude 120 $g \cdot h^{-1}$ CHO (in a 1:0.8 ratio of maltodextrin or glucose:fructose) is a practically tolerable strategy to promote high CHO availability and oxidation during exercise.

Keywords

Stable isotopes, fructose, maltodextrin, metabolism

New & Noteworthy

We demonstrate comparable rates of exogenous CHO oxidation from fluid, semi-solid, solid or a combination of sources. Considering the sustained high rates of total and exogenous carbohydrate oxidation, and relative lack of gastrointestinal symptoms, consuming 120 g $CHO \cdot h^{-1}$ appears a well-tolerated strategy to promote high CHO availability during exercise. Additionally, this is the first time that rates of exogenous CHO oxidation have been assessed using feeding strategies (e.g., co-ingestion of multiple CHO forms) typically reported by endurance athletes.

Introduction

The introduction of the muscle biopsy technique in the late 1960s (1) has allowed robust documentation of the importance of muscle glycogen in determining exercise capacity and performance in endurance events (2). In addition to high endogenous carbohydrate (CHO) availability, consumption of CHO during exercise can also enhance exercise performance (3-5), an effect likely mediated by liver glycogen sparing (6), the maintenance of plasma glucose concentrations and CHO oxidation rates (7) and/or via direct effects on the central nervous system (8). Indeed, the provision of exogenous CHO during exercise can address the finite capacity of muscle glycogen stores, particularly during prolonged strenuous events (> 2.5 h). In such scenarios, current consensus guidelines recommend a CHO intake of 90 $g \cdot h^{-1}$ (9) while other contemporary reviews recommend CHO intakes rates of 100+ $g \cdot h^{-1}$, if gastrointestinal (GI) outcomes are individually tolerated (10). However, the latter recommendations are based more on practitioner experience and field data, and have not yet been tested using multiple forms of CHO sources, in ecologically valid conditions.

The oxidation of ingested CHO by skeletal muscle during exercise is thought to be limited by CHO absorption through the intestinal membrane (11). In this regard, it is well established that a mixture of multiple-source CHO blends (e.g. glucose polymers, glucose and fructose etc.) are oxidised at 20-50% higher rates when compared to single source formulations (12-14). Indeed, whereas the exogenous oxidation of single-transportable CHO plateaus at ~60 $g \cdot h^{-1}$, exogenous oxidation of multiple-transportable CHO continues to rise with CHO ingestion up to 144 $g \cdot h^{-1}$ (15). When ingesting CHO at a rate ≥ 90 $g \cdot h^{-1}$, the ratio at which sources of CHO are co-ingested also influences their subsequent oxidation, whereby a 1:0.8 ratio of maltodextrin to fructose yields higher rates of oxidation when compared with an isocaloric 2:1 ratio (16, 17). It is noteworthy, however, that for an individual to achieve high

rates of oxidation (e.g. ≥ 1.5 g·min^{-1}), they should likely ingest 90-120 g·h^{-1} to account for an oxidation efficiency of less than 100% (15). Taken together, these data suggest that to maximise CHO availability and oxidation, athletes should ingest multiple-transportable CHO's, co-ingested in ratios closer to unity (18) and at absolute intakes above 90 g·h^{-1}.

In practice, athletes typically utilise a variety of CHO forms to meet these targets, including liquids (i.e. sports drinks), semi-solids (i.e. energy gels) and solids (i.e. energy bars) (19). Previous comparisons between liquid, semi-solid and solid carbohydrates have demonstrated these forms are oxidised at similar rates (albeit ingested at 93-108 g·h^{-1} using a 2:1 ratio of glucose and fructose) during prolonged endurance exercise (20, 21), thus suggesting that athletes can tailor their chosen feeding strategy to meet their personalised CHO intake targets. However, given that elite endurance athletes (e.g., Grand Tour cyclists, triathletes) often ingest a mix of such forms during prolonged exercise, at rates of up to at least 120 g·h^{-1} (19), an examination of oxidation rates when multiple forms of CHO are co-ingested at these high ingestion rates is highly warranted. Furthermore, recent food innovations have led to the development of commercially available "jelly chews", providing a "solid" food form with the absence of the protein, fat, and fibre content of energy bars, which are often associated with gastrointestinal complaints during exercise (22). Despite the popular use of jelly chews among athletic populations, it is currently unknown if this delivery form achieves similar peak rates of CHO oxidation to CHO fluids (i.e. sports drinks) and semi-solid forms (i.e. gels).

With this in mind, the primary aim of the present study was to quantify rates of exogenous CHO oxidation from the individual ingestion of liquid, gel and jelly chew forms of CHO as well as the combination of the three forms. To this end, trained male cyclists consumed CHO at a rate of 120 g·h^{-1} (using a 1:0.8 ratio of maltodextrin or glucose to fructose) during three

hours of steady-state cycling at 95% of lactate threshold. To assess rates of exogenous CHO oxidation, all forms were uniformly enriched with both ^{13}C-glucose and ^{13}C-fructose during the manufacturing process, thus representing the first study to incorporate dual stable isotope tracers at high enrichment into both solid and semi-solid CHO sources ingested during exercise. To assess the effects of CHO on exercise capacity, a time to exhaustion test (at 150% of lactate threshold) was also performed after the completion of the 3 h steady-state protocol within each of the trials. We hypothesised that: 1) peak rates of exogenous CHO oxidation would be comparable between all fuelling approaches, 2) consumption of 120 $g \cdot h^{-1}$ CHO would not cause negative gastrointestinal symptoms and 3) exercise capacity would not differ between the various feeding forms and formats.

Methodology

Ethical approval

All participants gave written informed consent prior to participation after all experimental procedures and potential risks had been fully explained. The study was approved by the Ethics Committee of Liverpool John Moores University and conformed to the standards set by the latest revision of the *Declaration of Helsinki* (except for registration in a database).

Participants

Nine endurance trained, amateur male cyclists (mean ± SD: age, 25 ± 8 years; body mass, 75.6 ± 7.0 kg; height, 179.1 ± 4.7 cm) volunteered to participate in the study. Mean $\dot{V}O_{2max}$, peak power output (PPO) and power output at lactate threshold were 64.9 ± 6.8 $ml \cdot kg^{-1} \cdot min^{-1}$, 438 ± 79 W and 226 ± 37 W, respectively. Subjects were defined as either highly-trained (Tier 3) or trained (Tier 2) in accordance with the criteria specified by McKay et al. (23).

Sample size was determined according to our primary outcome variable (i.e. exogenous CHO oxidation) assuming an effect of feeding form (liquid vs. solid) of 0.18 $g.min^{-1}$ (0.96 ± 0.13 $g.min^{-1}$ with solid vs 1.14 ± 0.16 $g.min^{-1}$ with liquid), as reported by Pfeiffer et al. (20) between 60 and 180 minutes of exercise. These data give an effect size of dz = 1.22, where a sample size of 8 would provide an α-value of 0.05 and a power of 0.80 (G*Power, version 3.1.9.6). None of the subjects had any history of musculoskeletal or neurological disease, nor were they under any pharmacological treatments during the testing period.

Experimental overview

In a repeated measures (> 6 days, but < 15 days apart), randomised, cross-over design, with each experimental trial separated by a minimum of 7 days, participants completed a prolonged endurance-based cycling exercise protocol, consisting of 180 min of submaximal exercise (undertaken at 95% of lactate threshold) followed by an exercise capacity test to exhaustion (undertaken at 150% of lactate threshold) on five separate occasions. The initial trial (WATER; where water only was consumed during exercise) was performed to provide a full familiarisation to the exercise protocol and to examine any background shifts in breath $^{13}CO_2$ appearance. In the following four randomised trials, subjects ingested CHO at a rate of 120 $g \cdot h^{-1}$ from fluid (DRINK), gels (GEL), jelly chews (CHEW) or a combination of all three delivery forms (MIX). Each experimental trial was commenced following 24-h of high CHO intake (8 $g \cdot kg^{-1}$) and 3 h after the consumption of a CHO rich pre-exercise meal (2 $g \cdot kg^{-1}$). An overview of the experimental design and nutritional protocols is displayed in Figure 1.

Preliminary testing

At least 7 days prior to experimental trials, subjects performed a two-part incremental cycle test (Lode Excalibur Sport, Groningen, Netherlands) to determine lactate threshold, maximal

oxygen consumption ($\dot{V}O_{2max}$) and PPO as previously described (24). Briefly, the first part of the test was commenced at 100 W and increased by 25 W at the end of each 4-minute stage. A fingertip blood sample was collected during the final 30 seconds of each stage for the determination of blood lactate concentrations (Biosen C-Line; EKF Diagnostics, Cardiff, UK) and the lactate threshold (LT) was determined using the D_{max} method (25). Subjects commenced the second part of the test at an intensity corresponding to that of the penultimate stage completed in the previous part, whereby exercise intensity increased by 25 W every minute until volitional exhaustion. The end time and power output at the point of exhaustion were used to calculate PPO using the following equation (26):

$$\mathrm{PPO} = \mathrm{W}_{\mathrm{final}} + (t/60) * \mathrm{PI})$$

where W_{final} is the power output of the final completed stage, *t* is the time spent in the final uncompleted stage (seconds), 60 is the duration of each stage (seconds) and PI is the increase in power output between stages. During the test, gas exchange measurements were made using an online gas analysis system (Moxus Modular Metabolic System; AEI Technologies, IL, USA) and $\dot{V}O_{2max}$ was determined as the highest $\dot{V}O_2$ captured over a 30 second period. The same gas analyser was used during all subsequent trials.

Pre-experimental controls

For 2-days prior to all experimental trials, subjects were asked to minimise the consumption of foods with a high natural abundance of ^{13}C to minimise the background shift from glycogen stores during exercise. Foods with a high natural abundance of ^{13}C (e.g. corn and sugar cane) were also avoided in the standardised diet and pre-exercise breakfast. Twenty-four hours prior to experimental trials, subjects were provided with a pre-packaged high CHO

diet containing precisely 8 $g \cdot kg^{-1}$ CHO, 2 $g \cdot kg^{-1}$ protein and 1 $g \cdot kg^{-1}$ fat to standardise dietary intake between trials. During this period, subjects also refrained from any form of exercise as well as caffeine and alcohol consumption. Subjects were also provided with a pre-packaged high CHO breakfast containing 2 $g \cdot kg^{-1}$ CHO, ~20 g protein and ~5 g fat, which was consumed 3 hours prior to the commencement of exercise in accordance with contemporary sports nutrition guidelines for endurance exercise (9).

180-min steady state cycling

On the morning of the main experimental trials, subjects reported to the laboratory at ~10:00 h having consumed the pre-packaged, standardised breakfast provided (see above). Upon arrival, an indwelling cannula (Safety Lock 22G; BD Biosciences, West Sussex, UK) was inserted into the antecubital vein in the anterior crease of the forearm and a resting blood sample drawn and subsequently flushed with ~5 ml of sterile saline (Kays Medical, Liverpool, UK). Resting expired breath samples were collected in duplicate into evacuated 10 mL Exetainer tubes (Labco, High Wycombe, UK), sampled directly from the mixing chamber, to determine the $^{13}C/^{12}C$ ratio in CO_2 at rest. Following the collection of resting measures, subjects completed a 10-min warm-up at 100 W and began the 180 min cycling protocol at 95% LT (215 ± 35 W). This relative exercise intensity was chosen as it has been suggested as an appropriate method of matching metabolic stress between subjects when compared with exercising at a percentage of $\dot{V}O_{2max}$ (27). Heart rate (Polar H10; Polar, Kempele, Finland), ratings of perceived exertion (RPE) (28) and cycling cadence were obtained at 30 min intervals throughout. Expired gas was collected for a 5 min period at 30 min intervals to calculate whole body substrate utilisation. The final minute of this period was used to collect expired gas into the evacuated Exetainer tubes to determine the $^{13}C/^{12}C$ ratio in CO_2. Gastrointestinal (GI) symptoms (nausea, regurgitation, fullness, cramps, gas,

and urge to defecate) were recorded at 30-min intervals during exercise using a 0-10 visual analogue scale (0 = no discomfort, and 10 = very severe discomfort) (29). Subjects were instructed that a score > 4 should be regarded as a moderate symptom that was detrimental to their ability to exercise. The sum of scores at each time point were collated for each gastrointestinal symptom, resulting in maximum scores of 60 for each symptom. Immediately following the 180 min submaximal cycle, subjects began the exercise capacity test, where they cycled at 150% LT (339 ± 55 W) until task failure, defined as an inability to maintain a cadence > 60 rpm. During the capacity test, the only information available to the subjects was the fixed power output and pedal cadence and no performance results were provided to subjects until they had completed all experimental trials. All exercise tests were performed at the same time of day under normal laboratory conditions (20-22^{o}C and 50-60% humidity) using the same electrically braked cycle ergometer (Lode Excalibur Sport, Groningen, Netherlands) and automated gas analyser (Moxus Modular Metabolic System; AEI Technologies, IL, USA). During all exercise trials, subjects were cooled with a floor fan to minimise thermal stress. Particpants were not provided with any prior information from the researchers that would influence their bias on which form of CHO would be superior for exercise performance.

Carbohydrate feeding

During exercise, subjects consumed CHO at a rate of 120 g·h^{-1} using multiple transportable carbohydrates in a 1:0.8 ratio of maltodextrin (or glucose for CHEW) to fructose. Carbohydrate drinks (Beta Fuel powder, Science in Sport, UK) and gels (Beta Fuel gels, Science in Sport, UK) were made from maltodextrin and fructose whilst the jelly chew (Beta Fuel chew, Science in Sport, UK) was made from glucose and fructose. This ratio was chosen as it has been previously shown to allow for improved rates of oxidation and gastrointestinal

comfort during exercise (16, 17, 30). Furthermore, maltodextrin and glucose can be considered as broadly interchangeable with respect to exogenous carbohydrate oxidation rates during exercise, since the rate of hydrolysis and exogenous oxidation between carbohydrate monomers and polymers are comparable (31, 32). Carbohydrate was ingested immediately prior to exercise and subsequently at 20 min intervals during exercise in equal amounts of 40 g CHO per serving. During production, all forms were equivalently enriched with 100 mg of U-^{13}C-glucose (56 mg) and U-^{13}C-fructose (44 mg; CK isotopes, Ibstock, UK) per 120 g CHO to ensure equivalent proportions in relation to their tracee and match the ratio of maltodextrin (glucose) and fructose in each form (Table 1). The MIX condition provided an equal mixture of all three forms and was consumed in the same order for all subjects (e.g., DRINK, CHEW, GEL) at 20 min intervals. Carbohydrate drinks were mixed with 800 ml water (per 120 g CHO), resulting in a 15% CHO solution and a fluid intake of 800 ml.h^{-1}. During all other trials, subjects consumed an equivalent amount of water (267 ml at each feeding point) to ensure total fluid intake and the pattern of ingestion was matched across all trials.

Blood sampling and analysis

Venous blood samples were collected into vacutainers containing K_2 EDTA, lithium heparin or serum separation tubes (BD Biosciences, UK) and stored on ice or at room temperature until centrifugation at 1500 g for 10 min at 4^{o}C. Following centrifugation, plasma and serum was aliquoted and stored at -80^{o}C for subsequent analysis. Samples were later analysed for plasma glucose, lactate non-esterified fatty acids (NEFA), and glycerol using commercially available enzymatic spectrophotometric assays (RX Daytona+ Analyser; Randox, UK) as per the manufacturer's instructions.

Estimates of whole-body substrate oxidation and energy expenditure

Rates of whole-body CHO and fat oxidation ($g \cdot min^{-1}$) were calculated at 30 min intervals during the 180 min submaximal cycle using the equations of Jeukendrup and Wallis (33). Total energy expenditure was estimated for each trial assuming an energy yield of 17.57 kJ and 39.33 kJ for 1 g of CHO and fat, respectively. Substrate utilisation data during the MIX trial is missing for one participant due to a technical error and at the 180 min time point during the WATER trial for two participants due to volitational fatigue.

$^{13}C/^{12}C$ analysis of breath CO_2

Isotopic enrichment of breath samples was determined using gas chromatography isotope ratio mass spectrometry (Iso-analytical, Crewe, UK). The ^{13}C enrichment from breath samples are expressed as $\delta^{13}C$ ‰ versus Pee Dee Belemnite (PDB). Exogenous carbohydrate oxidation was calculated using the following formula

$$\text{Exogenous carbohydrate oxidation} = \dot{V}CO_2 \cdot \left(\frac{\delta Exp - \delta EXP_{bkg}}{\delta Ing - \delta Exp_{bkg}}\right)\left(\frac{1}{k}\right)$$

Where δExp is the ^{13}C enrichment of expired CO_2, δIng is the ^{13}C enrichment of the ingested carbohydrate, δEXP_{bkg} is the ^{13}C enrichment of expired CO_2 during the water trial. and *k* is the $\dot{V}CO_2$ with the oxidation of 1 g of glucose (0.7467 L $CO_2 \cdot g^{-1}$). For the MIX trial, the ^{13}C enrichment of the ingested carbohydrate used the average ^{13}C enrichment (55.98 ‰ versus PDB) from the three separate forms being consumed given that they were all equivalently enriched (Table 1).

Statistical analysis

All statistical analyses were performed using SPSS Statistics Version 27 (IBM, US). Differences in mean and peak exogenous CHO oxidation, gastrointestinal symptoms, heart rate, RPE, energy expenditure, and exercise capacity were all analysed using one-way repeated-measures ANOVA. Mauchly's test for sphericity was used and, in cases where this assumption was violated, the Greenhouse-Geisser correction was applied. A two-way repeated measures ANOVA was used to analyse differences over time (e.g., 30-180 min) and between conditions for substrate utilisation and plasma metabolites. Where a significant main effect was observed, pairwise comparisons were analysed using post-hoc LSD tests to locate specific differences. All data in text, figures and tables are presented as means ± SD with P values ≤ 0.05 indicating statistical significance.

Results

Physiological responses

Heart rate and absolute oxygen uptake increased during exercise (time effect, $P < 0.001$ for both, Table 2) although no differences were apparent between trials (treatment effect, $P = 0.621$, $P = 0.155$ and $P = 0.596$, respectively). RPE also increased during exercise (time effect, $P < 0.001$) and was significantly higher in the WATER trial compared with the GEL trial at 120 minutes ($P = 0.018$) and compared with all CHO feeding trials from 150 minutes onwards ($P < 0.001$ for DRINK, GEL and CHEW and $P = 0.033$ for MIX) (Table 2). Plasma glucose and lactate concentrations were not significantly different between forms of CHO ingestion (treatment effect, $P = 0.749$ and $P = 0.426$ respectively). Plasma glycerol and NEFA progressively increased during exercise (time effect, $P < 0.001$ for both) although concentrations were not significantly different between forms of CHO ingestion (treatment effect, $P = 0.735$ and $P = 0.983$, respectively) (Figure 2).

344

345 **Substrate utilisation**

346 Rates of whole-body CHO oxidation (Figure 3A) progressively decreased during exercise
347 (time effect, $P < 0.001$), whereby rates of CHO oxidation were significantly lower during the
348 WATER trial when compared with all CHO feeding trials (trial effect, $P < 0.001$; interaction
349 effect, $P < 0.001$). Compared to the WATER trial, rates of whole-body CHO oxidation were
350 higher during DRINK ($P = 0.024$) and MIX ($P = 0.041$) at 30 min, and higher during GEL (P
351 $= 0.002$) and CHEW trials ($P = 0.005$) from 60 min onwards. Rates of whole-body fat
352 oxidation (Figure 3C) progressively increased during exercise (time effect, $P < 0.001$),
353 whereby rates of fat oxidation were significantly higher during the WATER trial when
354 compared with all CHO feeding trials (trial effect, $P < 0.001$; interaction effect, $P < 0.001$).
355 Compared to the WATER trial, rates of whole-body fat oxidation were lower during both
356 DRINK ($P = 0.035$) and CHEW trials ($P = 0.023$) at 30 min, and lower during GEL ($P <$
357 0.001) and MIX trials ($P = 0.009$) from 60 min onwards. The contribution of both CHO and
358 lipid towards energy expenditure throughout exercise is also presented in Figure 4.

359

360 **Exogenous and endogenous CHO oxidation**

361 There were no significant differences in mean exogenous CHO oxidation during hour 2
362 (DRINK, 1.40 ± 0.17; GEL, 1.36 ± 0.14; CHEW, 1.44 ± 0.11; MIX, 1.44 ± 0.13 $g \cdot min^{-1}$;
363 treatment effect, $P = 0.138$) or hour 3 (DRINK, 1.50 ± 0.17; GEL, 1.52 ± 0.10; CHEW, 1.55
364 ± 0.08; MIX, 1.6 ± 0.13 $g \cdot min^{-1}$; treatment effect, $P = 0.092$) between trials (Figure 5B).
365 There was also no significant difference in oxidation efficiency between trials (DRINK, 72 ±
366 8; GEL, 72 ± 5; CHEW, 75 ± 4.6; MIX, 75 ± 6%; treatment effect, $P = 0.179$) (Figure 5D).
367 Furthermore, no significant differences in peak rates of exogenous CHO oxidation were
368 apparent between trials (DRINK, 1.56 ± 0.16; GEL, 1.58 ± 0.13; CHEW, 1.59 ± 0.08; MIX,

1.66 ± 0.02 g·min^{-1}; treatment effect, P = 0.189) (Figure 5C). We also highlight individual variability in the oxidation of each form across all participants in Figure 5C.

The contribution of exogenous CHO oxidation towards total energy expenditure was also comparable between feeding forms during both hour 2 (DRINK, 41 ± 5; GEL, 41 ± 5; CHEW, 43 ± 7; MIX, 42 ± 7 %, P = 0.143) and hour 3 (DRINK, 44 ± 5; GEL, 46 ± 5; CHEW, 47 ± 7; Mix, 48 ± 7 %, P = 0.329). The contribution of endogenous CHO oxidation towards total energy expenditure was significantly higher in the WATER trial compared with all CHO feeding forms during both hour 2 (WATER; 55 ± 6%; DRINK, 28 ± 5, P < 0.001; GEL, 32 ± 8, P = 0.002; CHEW, 33 ± 9, P = 0.009; MIX, 31 ± 8%, P = 0.001) and hour 3 (WATER; 40 ± 6%; DRINK, 17 ± 6; GEL, 17 ± 5; CHEW, 17 ± 4; MIX, 15 ± 5%, P < 0.001 for all). The contribution of fat towards total energy expenditure was also significant higher in the WATER trial compared with all feeding forms during both hour 2 (WATER; 45 ± 6%; DRINK, 31 ± 5, P = 0.001; GEL, 27 ± 9, P < 0.001; CHEW, 25 ± 7, P < 0.001; MIX, 27 ± 5%, P < 0.001) and hour 3 (WATER; 60 ± 6%; DRINK, 39 ± 9; GEL, 37 ± 8; CHEW, 36 ± 8; MIX, 38 ± 6%, P < 0.001 for all) (Figure 5E and 3F).

Gastrointestinal discomfort

Mean cumulative scores for each gastrointestinal symptom were negligible (< 2 out of a possible 60 for all) with no significant differences between conditions (treatment effect for nausea; P = 0.437, regurgitation; P = 0.580, fullness; P = 0.827. cramps; P = 0.422, gas; P = 0.757 and urge to defecate; P = 0.580). Similarly, peak scores for each symptom were low, with no participants reporting any symptoms > 3 in any trial and no significant differences between conditions (treatment effect for nausea; P = 0.827, regurgitation; P = 0.364, fullness; P = 0.187. cramps; P = 580, gas; P = 0.804 and urge to defecate; P = 0.422).

Exercise capacity

CHO feeding at a rate of 120 $g \cdot h^{-1}$ significantly improved exercise capacity (trial effect; P = 0.021) within all trials (DRINK, 446 ± 350 s, P = 0.004; GEL, 529 ± 396 s, P = 0.005; CHEW, 596 ± 416 s, P = 0.028; MIX, 470 ± 395 s, P = 0.035; Figure 6A) when compared with WATER only (231 ± 244 s). However, there were no significant differences in exercise capacity between the different feeding forms ($P > 0.05$ for all). When data were analysed for a trial order effect, there was a significant difference between conditions (trial effect, P = 0.044) which was explained by significant differences between Trial 1 (i.e. the WATER only familiarisation trial; 231 ± 244 sec) and all other trials (Trial 2, 475 ± 357, $P < 0.001$; Trial 3, 499 ± 400, P = 0.016; Trial 4, 458 ± 369, P = 0.034; Trial 5, 609 ± 429 sec, P = 0.024; Figure 6B) with no other pairwise differences apparent.

Discussion

Confirming our hypothesis, data demonstrate comparable rates of peak exogenous CHO oxidation when trained male cyclists consume 120 $g \cdot h^{-1}$ in the form of a liquid (DRINK), semi-solid (GEL), solid (CHEW) or a co-ingestion approach (MIX). Importantly, we observed some of the highest peak rates of exogenous CHO oxidation (e.g. 1.66 $g \cdot min^{-1}$ during the co-ingestion approach) reported in the literature, the result of which was not associated with any significant symptoms of gastrointestinal discomfort. When taken together, our data suggest that the consumption of 120 $g \cdot h^{-1}$ CHO with a mixture of carbohydrate sources in a ratio close to unity, is a practically feasible and well-tolerated

418 protocol to achieve high CHO availability and oxidation during prolonged endurance
419 exercise.
420
421 To address our aims, we studied a cohort of trained male cyclists who completed an exercise
422 protocol previously studied in our laboratory (i.e. 3 h of steady-state cycling at 95% of lactate
423 threshold followed by an exercise capacity test at 150% of lactate threshold) (24).
424 Importantly, this exercise protocol was commenced after participants had consumed a high
425 CHO diet (8 $g \cdot kg^{-1}$ CHO for the previous 24 h) and CHO rich pre-exercise meal (2 $g \cdot kg^{-1}$
426 CHO), nutritional strategies which are considered best practice in preparation for competitive
427 endurance events or prolonged training (9). To quantify exogenous rates of CHO oxidation,
428 we equivalently enriched all feeding forms with ^{13}C-glucose and ^{13}C-fructose during product
429 manufacture to facilitate accurate estimates of exogenous oxidation rates. To our knowledge,
430 this approach represents the first time that stable isotope tracers have been *simultaneously*
431 incorporated into the fluid (DRINK), semi-solid (GEL) and solid (CHEW) CHO delivery
432 forms that are typically ingested by endurance athletes during exercise. Furthermore, the
433 incorporation of stable isotope tracers into the jelly chews, not only provides the first
434 demonstration of the oxidation of this novel food form, but also circumvents previous
435 technical difficulties associated with the assessment of other solid CHO sources (i.e., food
436 bars). Indeed, such bars naturally consist of several different CHOs and other ingredients
437 with different natural enrichments in ^{13}C, thereby making the calculation of exogenous CHO
438 oxidation challenging. Principles of stable isotope methods assume that the tracer represents
439 the tracee of interest (i.e. ^{13}C-glucose to trace ^{12}C-glucose). While we employed ^{13}C-glucose
440 to trace maltodextrin, the hydrolysis of maltodextrin is rapid, and not rate limiting to
441 absorption. Thus, maltodextrin displays equivalent digestion, absorption and exogenous
442 oxidation kinetics to glucose (34), and enrichment with ^{13}C-glucose thereby provides an

443 appropriate method to study the oxidation of maltodextrin. This approach has been studied
444 previously both in our laboratory (35) and elsewhere (36).
445
446 Another principle of the methodology of measurement of exogenous CHO oxidation relates
447 to the appropriate background expired $^{13}CO_2$ enrichment. When ingesting CHO at natural
448 abundance of ^{13}C, the optimal background is to perform a trial with identical CHO ingestion
449 rates with an even low enrichment of ^{13}C (37). This increases the sensitivity to detect breath
450 enrichment with naturally enriched carbohydrates, as the breath ^{13}C enrichment might still be
451 as low as -23 $\delta^{13}C$ ‰ versus PDB in the higher enriched trials (38). However, this issue
452 becomes negligible when spiking the ingested CHO with sufficient amounts of >99%
453 enriched ^{13}C-carbohydrates, as fluctuations in the background expired $^{13}CO_2$ enrichment are
454 too small to influence the calculations of exogenous CHO oxidation in the presence of highly
455 enriched ingested CHO. In the present study, breath enrichment reached in excess of +10
456 $\delta^{13}C$ ‰ versus PDB (Figure 5A), thereby illustrating the substantial enrichment achieved by
457 spiking the ingested CHO with stable isotopes.
458
459 When considering prolonged endurance exercise >2.5 h in duration, contemporary nutrition
460 guidelines recommend the intake of multiple-transportable CHO's at a rate of up to 90 $g \cdot h^{-1}$
461 (9, 39, 40). However, where the aim is to achieve high rates of exogenous CHO oxidation
462 (e.g. 1.5 $g \cdot min^{-1}$), individuals should likely consume 100-120 $g \cdot h^{-1}$ since oxidation efficiency
463 is not uniform (13, 14). Indeed, the upper limits of reported CHO intakes during competition
464 range from 107 to 137 $g \cdot h^{-1}$ (19). It has previously been reported that blends of maltodextrin
465 and fructose (formulated in drink form at a ratio of 1:0.8) induce greater oxidation efficiency
466 (74 ± 7%), peak rates of exogenous CHO oxidation (~1.2 $g \cdot min^{-1}$), and endurance
467 performance when compared with 2:1 formulations (62 ± 12% and ~1.0 $g \cdot min^{-1}$,

468 respectively) ingested at a rate of 90 g·h^{-1}(17). In keeping with these data, our chosen
469 formulation of maltodextrin and fructose in a 1:0.8 ratio also induced a similar oxidation
470 efficiency, the values of which were comparable between forms (DRINK; 72, GEL; 72,
471 CHEW; 75, MIX; 75%). However, in accordance with the higher CHO ingestion rate studied
472 here (120 g·h^{-1}), we observed higher rates of peak exogenous CHO oxidation during our
473 DRINK trial (i.e. 1.56 g·min^{-1}) than has been previously reported (~1.2 g·h^{-1}) when CHO was
474 ingested at 90 g·h^{-1} (17). Although previous researchers also reported peak rates of exogenous
475 CHO oxidation of 1.53 g·min^{-1} (range: 1.23-1.77 g·min^{-1}) when consuming 108 g per hour (of
476 a beverage formulated in a 2:1 ratio) (41), examination of individual oxidation rates reported
477 in the present study (see Figure 5C; range 1.25 -1.87 g·min^{-1}) suggest that higher rates of
478 oxidation may be achieved with the strategy adopted here (i.e. 120 g per hour of a 1:0.8
479 ratio). When taken together, such data further support the suggestion that athletes should
480 ingest multiple-transportable CHO's, co-ingested in ratios closer to unity (18), and at absolute
481 intakes exceeding 90 g·h^{-1} in order to optimise CHO availability and oxidation.
482
483 Based on previous glucose infusion studies which bypass the limitations of the GI system and
484 directly infuse glucose into the circulation, it is assumed that the maximal rate of exogenous
485 CHO oxidation that working skeletal muscle can use is ~1.8 g·min^{-1} (42), Notwithstanding
486 potential effects of hyperinsulinemia and assuming an estimated oxidation efficiency of ~70-
487 75%, the ingestion of 140-150 g·h^{-1} may be considered as the maximal worthwhile dose to
488 achieve such high rates of oxidation. In support of this, the ingestion of 144 g·h^{-1} (in a 1:1
489 ratio of glucose to fructose) has been previously shown to elicit peak exogenous oxidation
490 rates of 1.75 g·min^{-1} which remain the highest reported rates of oxidation within the literature
491 (14). Nonetheless, given that the individual responses in the present study demonstrate peak
492 oxidation rates of 1.8 g·min^{-1} can be achieved with the ingestion of 120 g·h^{-1} (Figure 5C) it

493 may be possible to achieve maximal rates of oxidation from lower dose of CHO amongst
494 individuals with high oxidation efficiency. We also highlight the inter-individual variability
495 in peak oxidation rates (Figure 5C) and suggest that individual responses should be
496 considered when providing CHO intake recommendations to avoid the potential for large
497 amounts of ingested CHO to remain within the intestine.
498
499 To our knowledge, there are only two previous reports that have compared exogenous rates
500 of CHO oxidation from the ingestion of a drink, gel, or energy bar (20, 21). These studies
501 reported comparable rates of peak exogenous CHO oxidation from a drink (1.42 $g \cdot min^{-1}$) and
502 gel form (1.44 $g \cdot min^{-1}$) when CHO was ingested at a rate of 108 $g \cdot h^{-1}$ in a 2:1 ratio (21). In
503 contrast, lower rates (albeit not statistically significant) of peak exogenous CHO oxidation
504 were reported when CHO was ingested in the form of a bar (1.25 $g \cdot min^{-1}$) versus a drink
505 (1.34 $g \cdot min^{-1}$), when fed at a rate of 93 $g \cdot h^{-1}$ and delivered in a 2:1 ratio (20). The present
506 study provides novel data and an extension to our understanding by investigating CHO
507 oxidation rates from an alternative solid form (i.e. jelly chews) that is typically used by
508 athletes. To this end, we observed comparable rates of peak exogenous CHO oxidation
509 between trials (DRINK; 1.56, GEL; 1.58, CHEW; 1.59, MIX; 1.66 $g \cdot min^{-1}$), noting that these
510 values are some of the highest reported in the current literature and provided almost half of
511 the energy requirements of exercise just below lactate threshold. Furthermore, the inclusion
512 of a co-ingestion trial (i.e. MIX) is a highly novel aspect of the present study and mimics the
513 self-chosen protocols of fuelling observed in the real-life practices of endurance and ultra-
514 endurance athletes (19, 43).
515
516 Despite the consumption of 120 $g \cdot h^{-1}$ CHO during exercise, it is noteworthy that the present
517 participants reported trivial symptoms of gastrointestinal discomfort across all feeding forms.

These data are consistent with previous reports that demonstrate the ingestion of multiple source carbohydrates (as opposed to single source solutions) at a rate of 144 $g \cdot h^{-1}$ is generally well tolerated during steady-state cycling (13, 14). However, in contrast to such studies who report "individual" cases of severe discomfort (e.g., stomach cramping and bloating), no gastrointestinal discomfort was reported by any of the present participants across individual trials. Although previous studies support the notion that gastrointestinal symptoms do not differ between liquid (e.g., drinks) and semi-solid (e.g., gels) form of CHO intake, greater feelings of nausea, stomach fullness and abdominal cramps have been previously reported with the ingestion of solid CHO sources such as energy bars (20, 22). Given that these symptoms are typically associated with the presence of other nutrients (such as fat, protein, and fibre), the lack of reported symptoms in solid form studied here (i.e. CHEW) could be attributed to relative absence of such nutrients and a ratio of glucose (polymers) to fructose that increases the oxidation efficiency of the ingested CHO. Importantly, we also observed minimal gastrointestinal symptoms during our MIX trial that combined all three CHO forms. These findings have important implications given that this pattern of ingestion reflects the real-world fuelling practices of elite endurance athletes, who typically ingest a mix of CHO forms across exercise durations of 3-6 hours (19). Although the exercise intensity in the present study was deliberately chosen to reflect the sub-maximal intensity of "riding in the bunch" during professional road races (i.e. below lactate threshold), it would also be beneficial to include frequent high-intensity efforts in future studies so as to assess the effects of high CHO ingestion on potential GI symptoms when exercising at intensities above lactate threshold.

To address the effects of CHO form on exercise capacity, participants completed an exercise capacity test undertaken at 150% of lactate threshold immediately after the completion of the

543 3 h steady-state sub-maximal exercise protocol. This protocol has been previously studied in
544 our laboratory (also using trained male cyclists) where we observed a dose response effect of
545 CHO feeding, in that the consumption of 90 $g \cdot h^{-1}$ extended exercise capacity when compared
546 with both 45 $g \cdot h^{-1}$ and 0 $g \cdot h^{-1}$ (24). This ergogenic effect was likely mediated by increased
547 liver glycogen and/or plasma glucose availability associated wth the higher dose of CHO
548 ingestion. Interestingly, we also observed that the consumption of 90 $g \cdot h^{-1}$ delayed the point
549 at which lipid oxidation comprises the largest proportion of energy production by ~10 and
550 ~40 minutes when compared with 45 $g \cdot h^{-1}$ and 0 $g \cdot h^{-1}$, respectively (24). In consuming the
551 higher absolute dose of 120 $g \cdot h^{-1}$ in the present study, it is noteworthy that CHO remained the
552 predominant source of substrate utilisation throughout exercise in all trials (Figure 4) and no
553 statistical differences in exercise capacity were observed between feeding forms (Figure 6).
554 These data are unsurprising given the similar rates of whole body and exogenous CHO
555 oxidation and lack of gastrointestinal distress observed between feeding forms, two potential
556 mechanisms by which feeding form may impact upon performance (22). Indeed, Guillochon
557 and Rowlands (22) recently reported reductions in peak power that was associated with the
558 increased gastrointestinal distress arising from repeated intake of solid CHO (e.g. bar). We
559 readily acknowledge, however, that a potential lack of statistical power may have limited our
560 ability to detect small differences in performance between trials given that the study was
561 primarily powered to detect changes in exogenous CHO oxidation and the high inter-
562 individual variability in exercise capacity. Although the participants were given no prior
563 information to influence their beliefs on what form of CHO may be superior for performance,
564 we also acknowledge that our study design was not a true double blind design (i.e.
565 participants and researchers were consciously aware of what form of CHO they were
566 consuming). Furthermore, the inclusion of a known water only trial (that served as our
567 familiarisation trial) does not allow us to assess the effects of CHO versus a true placebo trial.

568 Despite the high rates of peak exogenous CHO oxidation observed here, further studies are
569 therefore required to assess the dose response effects on exercise performane and capacity
570 when ingesting the feeding forms observed here. Indeed, it was recently demonstrated (albeit
571 using 2:1 drink formulations) that consumption of 90 $g \cdot h^{-1}$ induces higher peak power during
572 a 30-minute time trial (completed after 3 hours of steady state exercise at 60% VO_{2peak}) when
573 compared with both 80 $g \cdot h^{-1}$ (3.7%) and 100 $g \cdot h^{-1}$ (7.5%) (44).
574
575 In summary, the present data demonstrate comparable rates of exogenous CHO oxidation
576 when CHO is ingested during exercise in a liquid, semi-solid or solid form, as well as a
577 feeding strategy that combined all forms. When considering the high absolute rates of
578 exogenous CHO oxidation, the maintainence of whole-body CHO oxidation, and the lack of
579 gastrointestinal symptoms, data demonstrate that consumption of 120 $g \cdot h^{-1}$ (as achieved via
580 1:0.8 formulations of maltodextrin or glucose: fructose) is a practically feasible and well-
581 tolerated strategy to promote high CHO availability during exercise. Indeed, the present data
582 represent some of the highest rates of exogenous CHO oxidation reported in the literature and
583 were achieved via feeding forms and formats that are commonly adopted by elite endurance
584 athletes.

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Disclosures

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Author contributions

MAH, JNP, CLE, SJM, JTG and JPM designed the study. MAH performed experiments; MAH, JNP, JTG, and JPM analysed the data and interpreted the results. MAH, JNP, JTG and

JPM drafted the manuscript and CLE, SJM, TS and LB edited and revised the manuscript. All authors approved the final version and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

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Table 1

Nutritional composition and mean enrichment of each carbohydrate form. pH and osmolality for GEL trial is measured when 3 gels (equivalent to 120 g CHO) are mixed with 800 ml water as per trial conditions.

Table 2

Heart rate, RPE, absolute oxygen consumption and energy expenditure during 180 min steady-state cycling.

Figure 1

Schematic overview of the experimental protocol employed in each trial. Following 24 h of a high CHO diet, subjects consumed a high CHO pre-exercise meal before undertaking 180 min steady-state submaximal exercise during which they consumed 120 $g \cdot h^{-1}$ CHO from fluid (DRINK), gels (GEL), jelly chews (CHEW) or a co-ingestion approach (MIX), followed by a time to exhaustion (TTE) exercise capacity test. TTE; time to exhaustion.

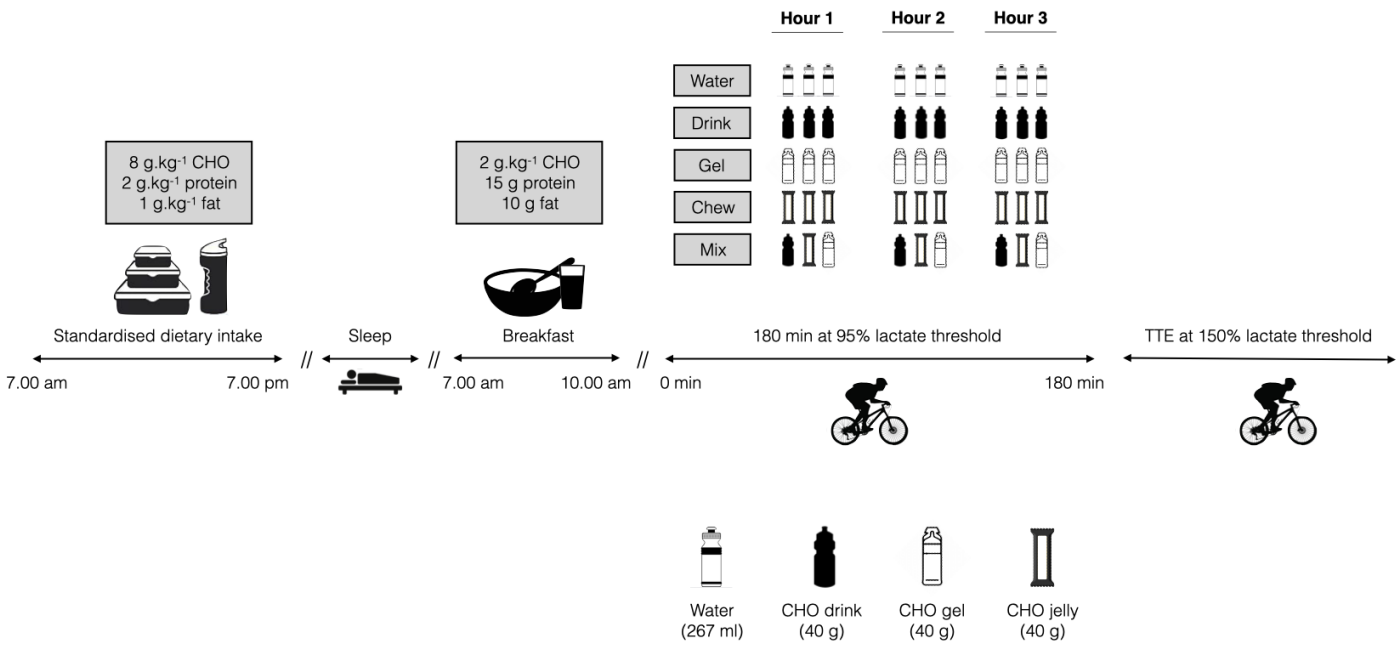
Figure 2

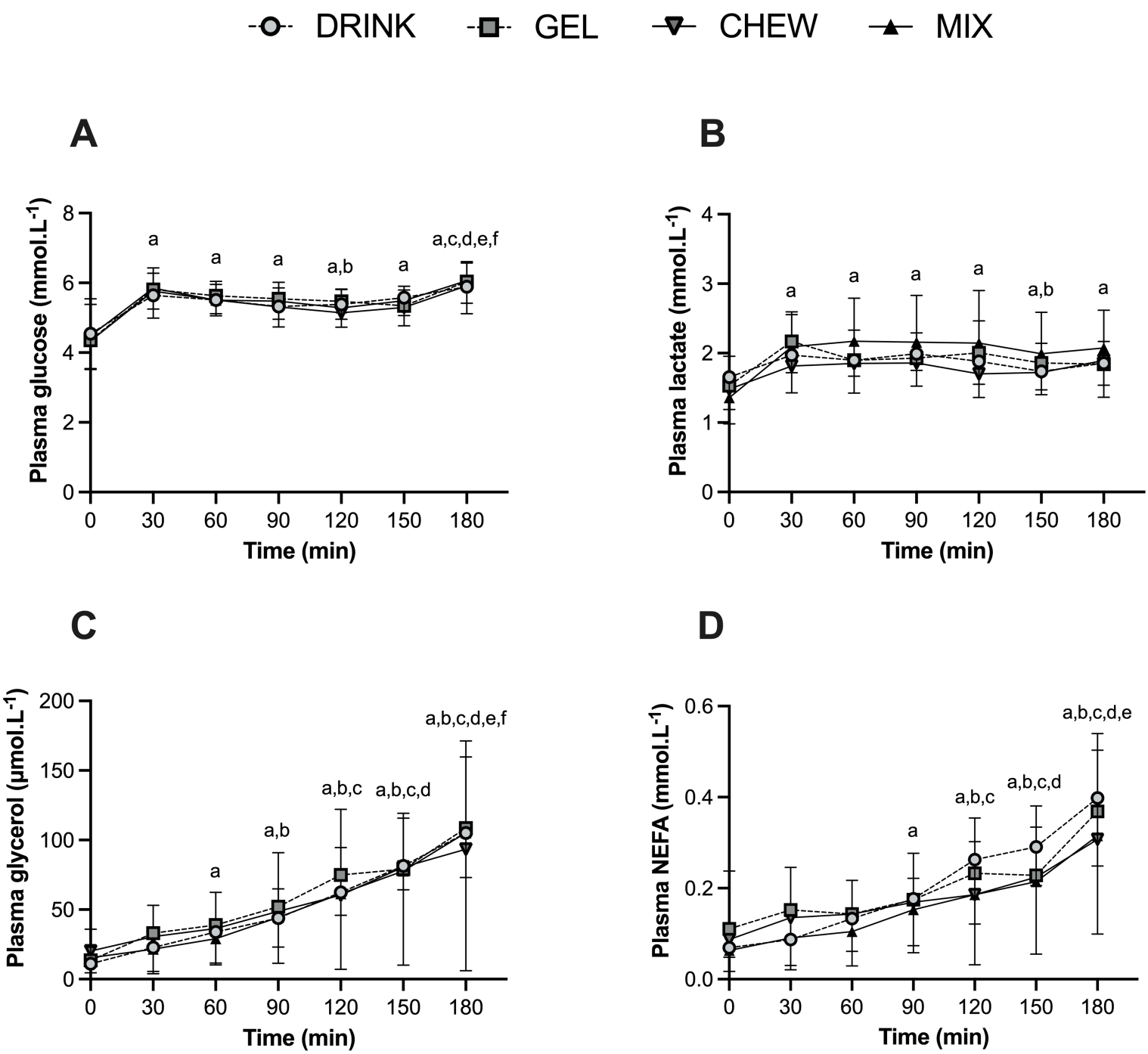
(A) Plasma glucose, (B) lactate, (C) glycerol and (D) NEFA at rest and during exercise in the DRINK, GEL, CHEW and MIX trials. [a]Significant difference from 0 min, [b]significant difference from 30 min, [c]significant difference from 60 min, [d]significant difference from 90 min, [e]significant difference from 120 min, [f]significant difference from 150 min, $P < 0.05$.

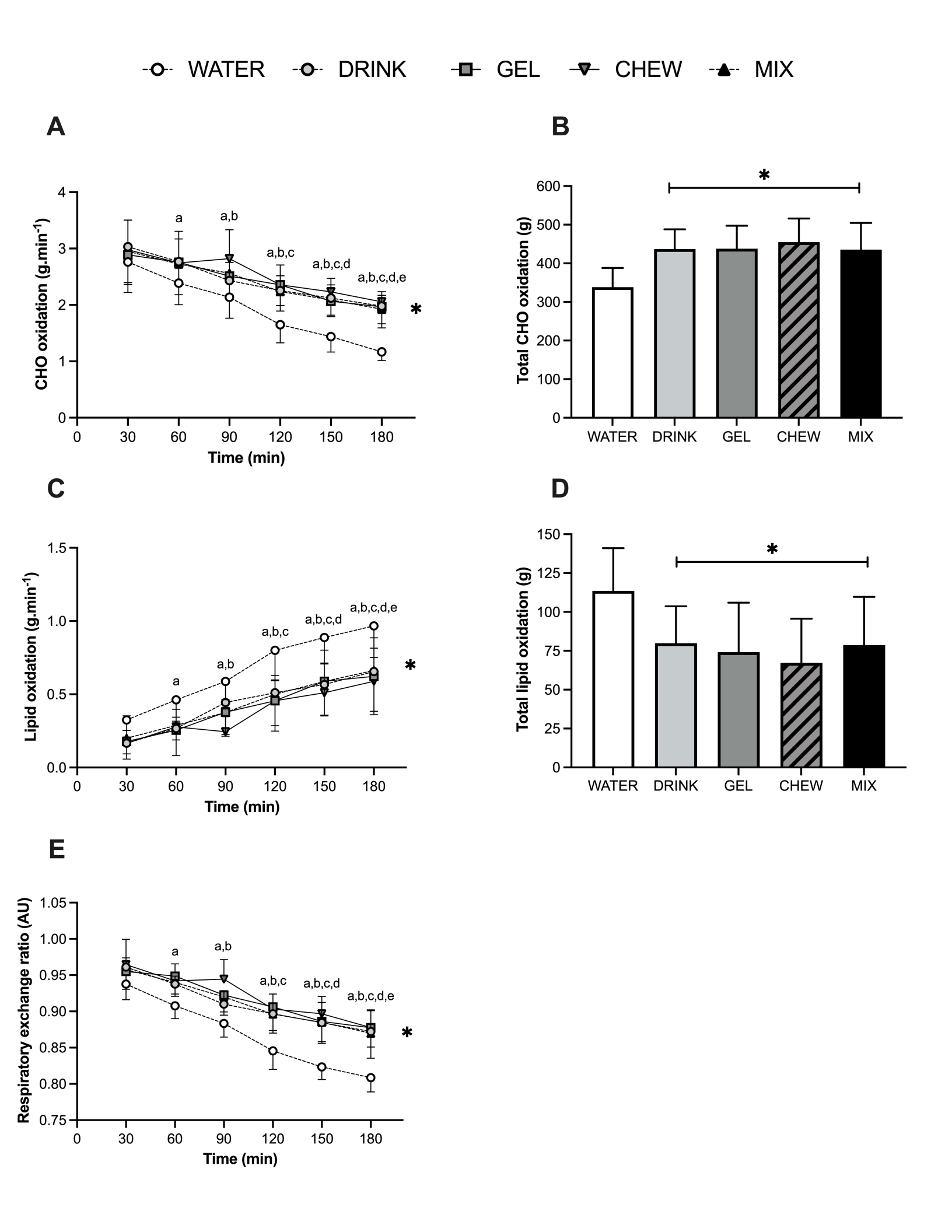
Figure 3

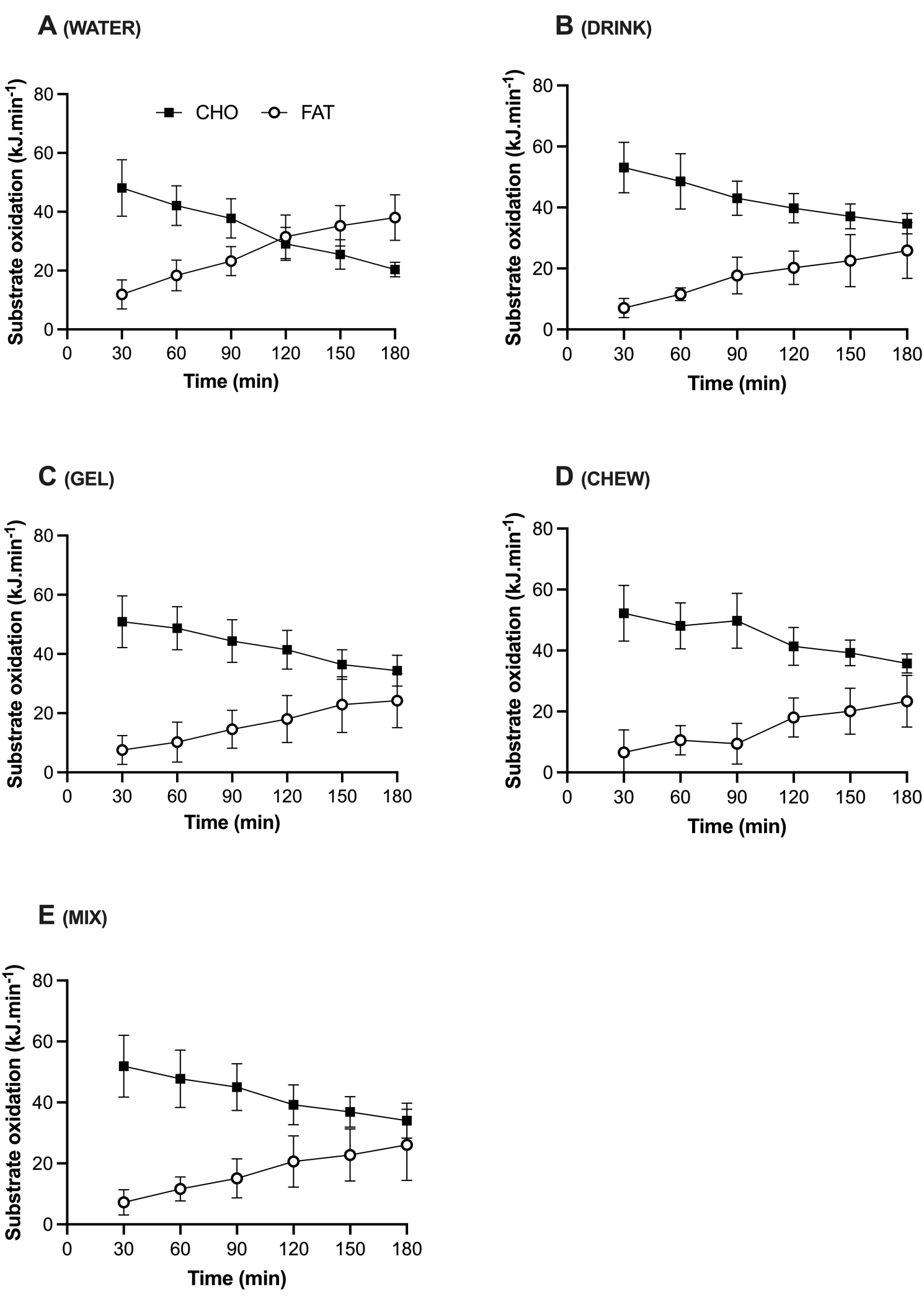
(A) Rates of whole-body CHO oxidation during exercise, (B) total CHO oxidation, (C) rates of whole-body fat oxidation during exercise, (D) total fat oxidation, and (E) respiratory

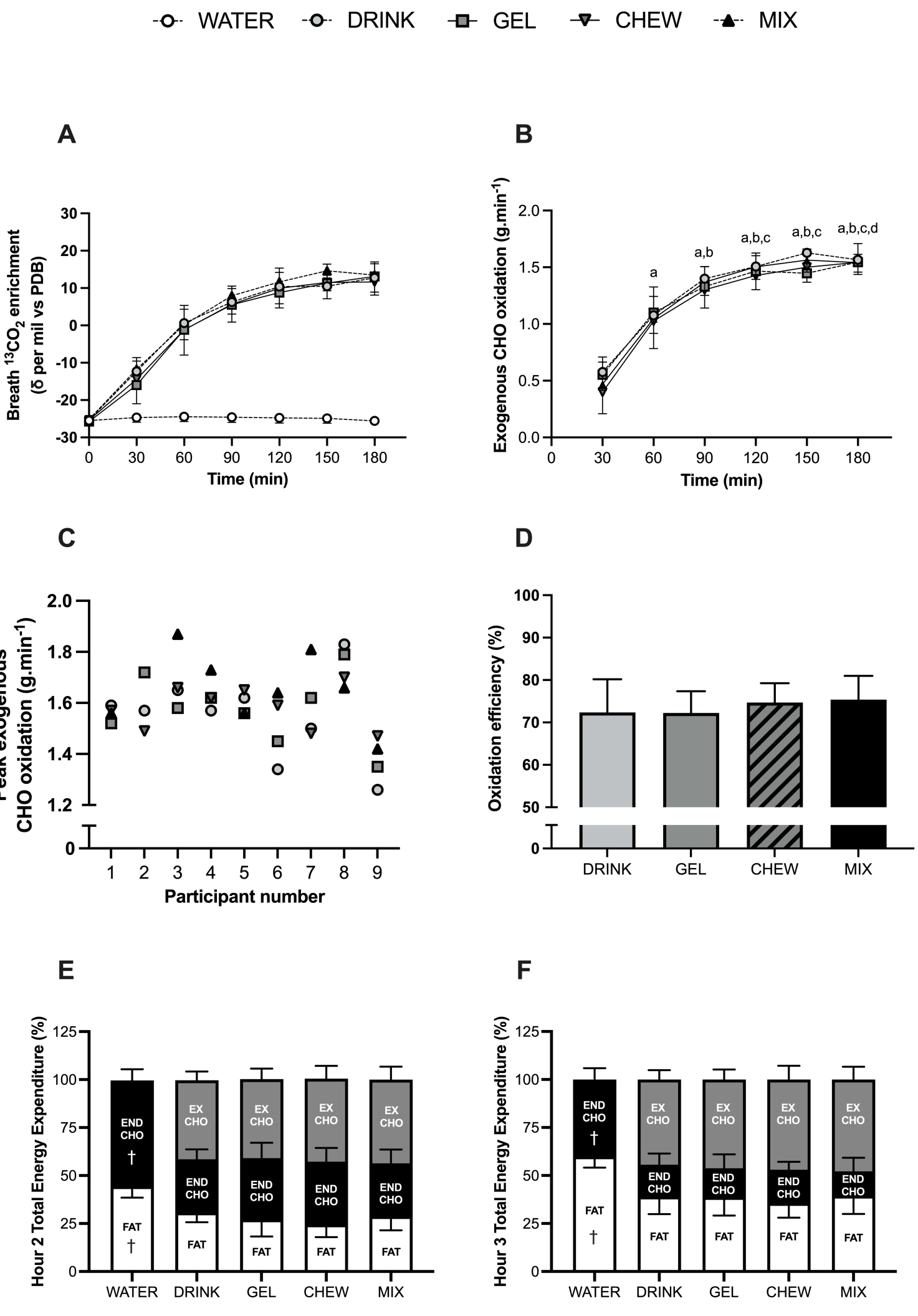
765 exchange ratio (RER) during exercise in the WATER**,** DRINK, GEL, CHEW and MIX trials.
766 [a]Significant difference from 30 min, [b]significant difference from 60 min, [c]significant
767 difference from 90 min, [d]significant difference from 120 min, [e]significant difference from
768 150 min, $P < 0.05$. *Significant difference from water, $P < 0.05$.
769
770 **Figure 4**
771 Rates of energy provision from carbohydrate and fat oxidation during the (A) WATER, (B)
772 DRINK, (C) GEL, (D) CHEW and (E) MIX trials.
773
774 **Figure 5**
775 (A) Breath $^{13}CO_2$ enrichment and (B) exogenous CHO oxidation during 180 minutes of
776 exercise during the WATER**,** DRINK, GEL, CHEW and MIX trials. [a]Significant difference
777 from 30 min, [b]significant difference from 60 min, [c]significant difference from 90 min,
778 [d]significant difference from 120 min, $P < 0.05$. (C) Individual participant's peak exogenous
779 CHO oxidation during exercise and (D) mean oxidation efficiency. $N = 8$ for MIX trial
780 (missing individual data point for participant 2). Substrate contributions to total energy
781 expenditure during the (E) second and (F) third hour of exercise. †Significant difference
782 between water and all other feeding trials, $P < 0.05$.
783
784 **Figure 6**
785 (A) Exercise capacity time (time to exhaustion) during the WATER only (familiarisation),
786 DRINK, GEL, CHEW and MIX trials and (B) trial order exercise capacity time.
787 *Significantly different from WATER, $P < 0.05$. Bars represent group means and circles
788 represent individual data points.
789


Hour 1
Hour 2
Hour 3
Water
Drink
Gel
Chew
Mix
8 g.kg-1 CHO
2 g.kg-1 protein
1 g.kg-1 fat
2 g.kg-1 CHO
15 g protein
10 g fat
Standardised dietary intake
Sleep
Breakfast
180 min at 95% lactate threshold
TTE at 150% lactate threshold
7.00 am
7.00 pm
7.00 am
10.00 am
0 min
180 min
Water
(267 ml)
CHO drink
(40 g)
CHO gel
(40 g)
CHO jelly
(40 g)


DRINK
GEL
CHEW
MIX
A
Plasma glucose (mmol.L-1)
Time (min)
a
a
a
a,b
a
a,c,d,e,f
B
Plasma lactate (mmol.L-1)
Time (min)
a
a
a
a
a,b
a
C
Plasma glycerol (µmol.L-1)
Time (min)
a
a,b
a,b,c
a,b,c,d
a,b,c,d,e,f
D
Plasma NEFA (mmol.L-1)
Time (min)
a
a,b,c
a,b,c,d
a,b,c,d,e


WATER
DRINK
GEL
CHEW
MIX
A
CHO oxidation (g.min-1)
Time (min)
a
a,b
a,b,c
a,b,c,d
a,b,c,d,e
*
B
Total CHO oxidation (g)
WATER
DRINK
GEL
CHEW
MIX
*
C
Lipid oxidation (g.min-1)
Time (min)
a
a,b
a,b,c
a,b,c,d
a,b,c,d,e
*
D
Total lipid oxidation (g)
WATER
DRINK
GEL
CHEW
MIX
*
E
Respiratory exchange ratio (AU)
Time (min)
a
a,b
a,b,c
a,b,c,d
a,b,c,d,e
*


A (WATER)
B (DRINK)
C (GEL)
D (CHEW)
E (MIX)
CHO
FAT
Substrate oxidation (kJ.min-1)
Time (min)
0
20
40
60
80
0
30
60
90
120
150
180


WATER
DRINK
GEL
CHEW
MIX
A
Breath $^{13}CO_2$ enrichment (δ per mil vs PDB)
Time (min)
B
Exogenous CHO oxidation (g.min^{-1})
a
a,b
a,b,c
a,b,c
a,b,c,d
Time (min)
C
Peak exogenous CHO oxidation (g.min^{-1})
Participant number
D
Oxidation efficiency (%)
DRINK
GEL
CHEW
MIX
E
Hour 2 Total Energy Expenditure (%)
END CHO †
EX CHO
END CHO
FAT †
FAT
WATER
DRINK
GEL
CHEW
MIX
F
Hour 3 Total Energy Expenditure (%)
END CHO †
EX CHO
END CHO
FAT †
FAT
WATER
DRINK
GEL
CHEW
MIX

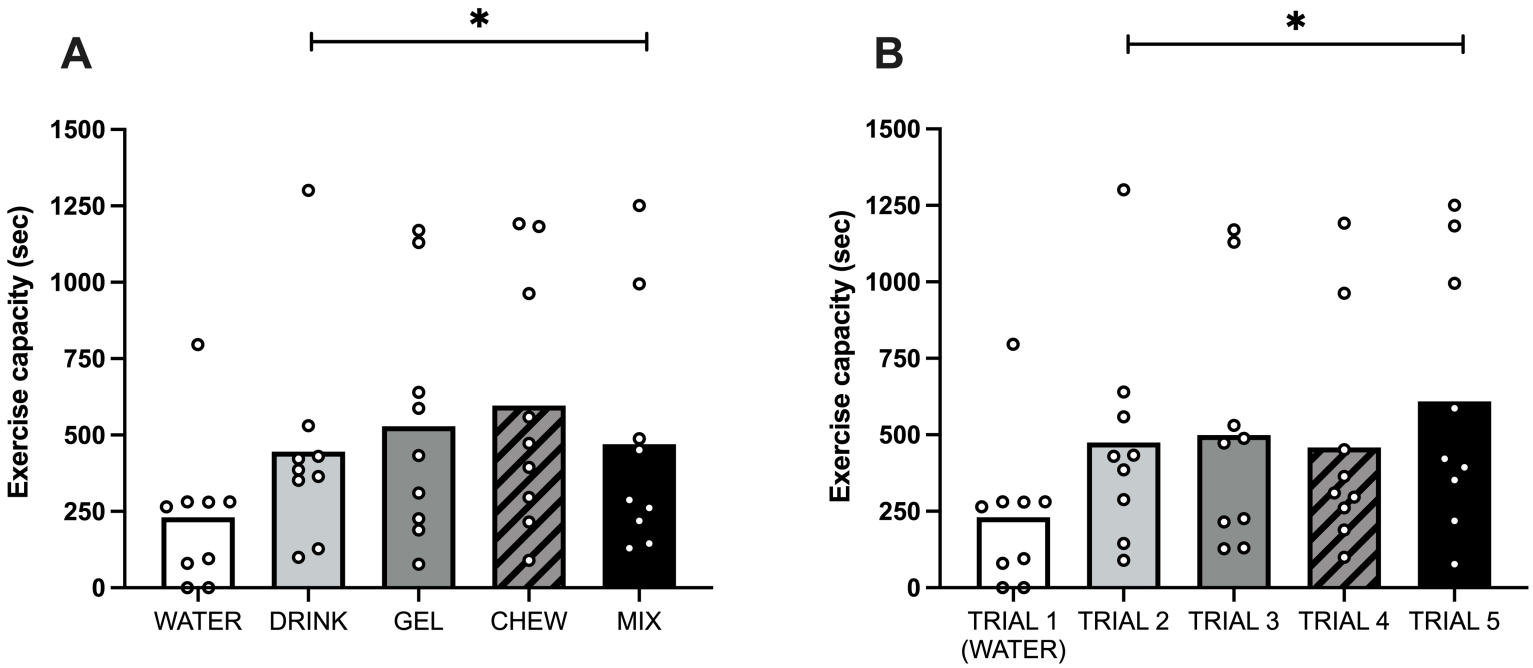

A
*
Exercise capacity (sec)
1500
1250
1000
750
500
250
0
WATER
DRINK
GEL
CHEW
MIX
B
*
Exercise capacity (sec)
1500
1250
1000
750
500
250
0
TRIAL 1 (WATER)
TRIAL 2
TRIAL 3
TRIAL 4
TRIAL 5

Table 1

Nutrition per 120 g CHO	**DRINK**	**GEL**	**CHEW**
Energy (kcal)	480	480	492
Fat (g)	0	0	0.1
Carbohydrate (g)	120	120	120
maltodextrin (g)	66.7	66.7	0
glucose (g)	-	-	66.7
fructose (g)	53.3	53.3	53.3
Protein (g)	0.0	0.0	0.3
Sodium (g)	0.00	0.05	0.12
Fibre (g)	0	0	5.7
Osmolality ($mOsmol.kg^{-1}$)	380	386	-
pH	6.5	4.3	-
Mean enrichment $\delta\ ^{13}C$ vs PDB (‰)	57.33	56.38	54.23

	Time (min)					
	30	**60**	**90**	**120**	**150**	**180**
Heart rate (beats.min^{-1})						
WATER	136 ± 13	140 ± 13^{a}	143 ± 12 $^{a.b}$	146 ± 10^{a,b,c}	150 ± 10^{a,b,c,d}	150 ± 10^{a,b,c,d,e}
DRINK	140 ± 10	143 ± 16^{a}	147 ± 16$^{a.b}$	149 ± 16^{a,b,c}	151 ± 16^{a,b,c,d}	153 ± 14^{a,b,c,d,e}
GEL	139 ± 15	142 ± 16^{a}	142 ± 16^{a,b}	147 ± 16^{a,b,c}	148 ± 16^{a,b,c,d}	150 ± 15^{a,b,c,d,e}
CHEW	137 ± 13	141 ± 13^{a}	144 ± 13^{a,b}	147 ± 12^{a,b,c}	149 ± 13^{a,b,c,d}	151 ± 13^{a,b,c,d,e}
MIX	141 ± 16	144 ± 17^{a}	146 ± 16^{a,b}	150 ± 18^{a,b,c}	152 ± 17^{a,b,c,d}	154 ± 19^{a,b,c,d,e}
RPE (AU)						
WATER	10 ± 2	11 ± 1	12 ± 1^{a}	13 ± 2^{a,b}	14 ± 2^{a,b,c,d} *	16 ± 2^{a,b,c,d} *
DRINK	11 ± 1	11 ± 1	12 ± 1^{a}	12 ± 1^{a,b}	13 ± 2^{a,b,c,d} *	13 ± 2^{a,b,c,d} *
GEL	10 ± 2	11 ± 1	11 ± 2^{a}	11 ± 2^{a,b} *	12 ± 2^{a,b,c,d} *	14 ± 3^{a,b,c,d} *
CHEW	11 ± 1	11 ± 1	12 ± 1^{a}	12 ± 1^{a,b}	13 ± 1^{a,b,c,d} *	13 ± 1^{a,b,c,d} *
MIX	11 ± 2	11 ± 2	11 ± 2^{a}	12 ± 2^{a,b}	13 ± 1^{a,b,c,d} *	14 ± 2^{a,b,c,d} *
$\dot{V}O_2$ (L.min^{-1})						
WATER	2.81 ± 0.48	2.84 ± 0.48	2.89 ± 0.47$^{a.b}$	2.93 ± 0.45$^{a.b}$	2.94 ± 0.45$^{a.b}$	2.85 ± 0.45$^{a.b}$
DRINK	2.82 ± 0.48	2.85 ± 0.49	2.90 ± 0.46$^{a.b}$	2.89 ± 0.45$^{a.b}$	2.88 ± 0..47$^{a.b}$	2.94 ± 0.51$^{a.b}$
GEL	2.76 ± 0.48	2.78 ± 0.48	2.81 ± 0.45$^{a.b}$	2.85 ± 0.48$^{a.b}$	2.86 ± 0.49$^{a.b}$	2.84 ± 0.51$^{a.b}$
CHEW	2.74 ± 0.41	2.78 ± 0.40	2.81 ± 0.42$^{a.b}$	2.85 ± 0.42$^{a.b}$	2.86 ± 0.46$^{a.b}$	2.86 ± 0.46$^{a.b}$

MIX	2.83 ± 0.49	2.86 ± 0.52	2.90 ± 0.53[a.b]	2.92 ± 0.56[a.b]	2.93 ± 0.52[a.b]	2.97 ± 0.56[a.b]
Energy expenditure (kJ.min^{-1})						
WATER	59.2 ± 10.8	59.2 ± 10.0	59.5 ± 10.0	58.7 ± 9.3	59.0 ± 9.4	54.9 ± 6.8
DRINK	60.0 ± 10	60.1 ± 10.4	60.1 ± 9.4	60.0 ± 9.2	59.5 ± 9.5	60.6 ± 10.0
GEL	58.5 ± 10.0	58.8 ± 9.8	58.9 ± 9.3	59.3 ± 9.6	59.2 ± 9.8	58.5 ± 10.0
CHEW	58.3 ± 8.5	58.7 ± 8.3	59.4 ± 8.8	59.3 ± 8.6	59.4 ± 9.2	59.1 ± 9.0
MIX	59.3 ± 10.7	59.4 ± 11.3	60.0 ± 11.3	59.8 ± 11.7	59.7 ± 10.8	60.1 ± 11.4

[a]significant difference from 30 min time point,

[b]significant difference from 60 min time point,

[c]significant difference from 90 min time point,

[d]significant difference from 120 min time point and,

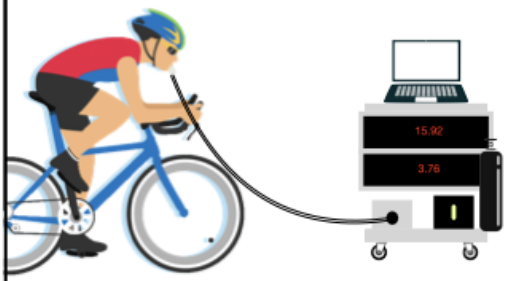
[e]significant difference from 150 min time point, $P < 0.05$

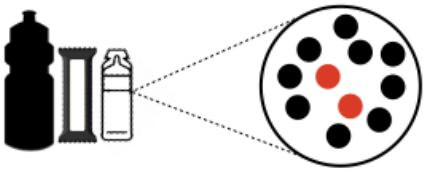
*significant difference from water, $P < 0.05$

13-C-glucose-fructose labelling reveals comparable exogenous CHO oxidation during exercise when consuming 120 g/h in fluid, gel, jelly chew or co-ingestion

METHODS

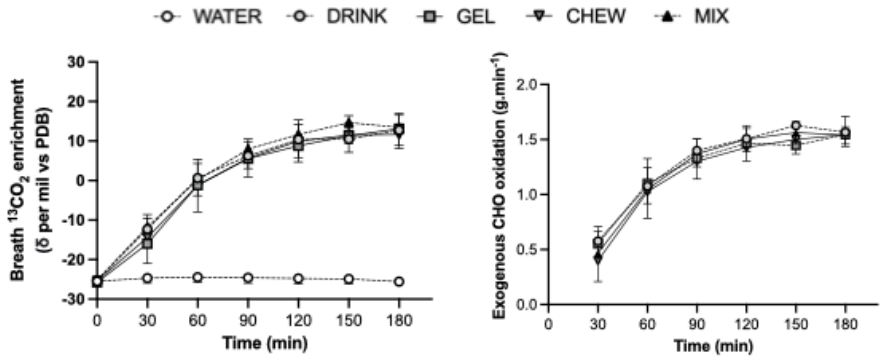
Stable isotope tracers were incorporated into a range of commonly available forms of CHO typically ingested by endurance athletes





OUTCOME

Comparable high rates of exogenous CHO oxidation across feeding forms



CONCLUSION

We demonstrate comparable high rates of exogenous CHO oxidation from fluid, semi-solid, solid or a combination of forms with negligible gastrointestinal symptoms. Considering the sustained high rates of total and exogenous carbohydrate oxidation, and relative lack of gastrointestinal symptoms, consuming 120 g CHO·h^{-1} appears a well-tolerated strategy to promote high CHO availability during exercise.