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2 **¹³C-glucose-fructose labelling reveals comparable exogenous CHO oxidation during**
3 **exercise when consuming 120 g/h in fluid, gel, jelly chew or co-ingestion**
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38 **Running head:** CHO oxidation from fluid, semi-solid and solid
39

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49

50 **Abstract**

51

52 We examined the effects of carbohydrate (CHO) delivery form on exogenous CHO
53 oxidation, gastrointestinal discomfort, and exercise capacity. In a randomised repeated
54 measures design (after 24 h of high CHO intake ($8 \text{ g}\cdot\text{kg}^{-1}$) and pre-exercise meal ($2 \text{ g}\cdot\text{kg}^{-1}$)),
55 nine trained males ingested $120 \text{ g CHO}\cdot\text{h}^{-1}$ from fluid (DRINK), semi-solid gel (GEL), solid
56 jelly chew (CHEW), or a co-ingestion approach (MIX). Participants cycled for 180 min at
57 95% lactate threshold followed by an exercise capacity test (150% lactate threshold). Peak
58 rates of exogenous CHO oxidation (DRINK, 1.56 ± 0.16 ; GEL, 1.58 ± 0.13 ; CHEW, $1.59 \pm$
59 0.08 ; MIX, $1.66 \pm 0.02 \text{ g}\cdot\text{min}^{-1}$) and oxidation efficiency (DRINK, 72 ± 8 ; GEL, 72 ± 5 ;
60 CHEW, 75 ± 5 ; MIX, $75 \pm 6\%$) were not different between trials (all $P > 0.05$). Despite
61 ingesting $120 \text{ g}\cdot\text{h}^{-1}$, participants reported minimal symptoms of gastrointestinal distress
62 across all trials. Exercise capacity was also not significantly different (all $P < 0.05$) between
63 conditions (DRINK, 446 ± 350 ; GEL, 529 ± 396 ; CHEW, 596 ± 416 ; MIX, $469 \pm 395 \text{ sec}$).
64 Data represent the first time that rates of exogenous CHO oxidation (via stable isotope
65 methodology) have been simultaneously assessed using feeding strategies (i.e., pre-exercise
66 CHO feeding and the different forms and combinations of CHO during exercise) commonly
67 adopted by elite endurance athletes. We conclude $120 \text{ g}\cdot\text{h}^{-1}$ CHO (in a 1:0.8 ratio of
68 maltodextrin or glucose:fructose) is a practically tolerable strategy to promote high CHO
69 availability and oxidation during exercise.

70

71 **Keywords**

72 Stable isotopes, fructose, maltodextrin, metabolism

73

74 **New & Noteworthy**

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

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99 **Introduction**

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

113

114 The oxidation of ingested CHO by skeletal muscle during exercise is thought to be limited by
115 CHO absorption through the intestinal membrane (11). In this regard, it is well established
116 that a mixture of multiple-source CHO blends (e.g. glucose polymers, glucose and fructose
117 etc.) are oxidised at 20-50% higher rates when compared to single source formulations (12-
118 14). Indeed, whereas the exogenous oxidation of single-transportable CHO plateaus at ~ 60
119 $\text{g}\cdot\text{h}^{-1}$, exogenous oxidation of multiple-transportable CHO continues to rise with CHO
120 ingestion up to $144 \text{ g}\cdot\text{h}^{-1}$ (15). When ingesting CHO at a rate $\geq 90 \text{ g}\cdot\text{h}^{-1}$, the ratio at which
121 sources of CHO are co-ingested also influences their subsequent oxidation, whereby a 1:0.8
122 ratio of maltodextrin to fructose yields higher rates of oxidation when compared with an
123 isocaloric 2:1 ratio (16, 17). It is noteworthy, however, that for an individual to achieve high

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

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

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

148 hours of steady-state cycling at 95% of lactate threshold. To assess rates of exogenous CHO
149 oxidation, all forms were uniformly enriched with both ^{13}C -glucose and ^{13}C -fructose during
150 the manufacturing process, thus representing the first study to incorporate dual stable isotope
151 tracers at high enrichment into both solid and semi-solid CHO sources ingested during
152 exercise. To assess the effects of CHO on exercise capacity, a time to exhaustion test (at
153 150% of lactate threshold) was also performed after the completion of the 3 h steady-state
154 protocol within each of the trials. We hypothesised that: 1) peak rates of exogenous CHO
155 oxidation would be comparable between all fuelling approaches, 2) consumption of $120 \text{ g}\cdot\text{h}^{-1}$
156 CHO would not cause negative gastrointestinal symptoms and 3) exercise capacity would not
157 differ between the various feeding forms and formats.

158

159 **Methodology**

160 **Ethical approval**

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

165

166 **Participants**

167 Nine endurance trained, amateur male cyclists (mean \pm SD: age, 25 ± 8 years; body mass,
168 75.6 ± 7.0 kg; height, 179.1 ± 4.7 cm) volunteered to participate in the study. Mean $\dot{V}\text{O}_{2\text{max}}$,
169 peak power output (PPO) and power output at lactate threshold were $64.9 \pm 6.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$,
170 438 ± 79 W and 226 ± 37 W, respectively. Subjects were defined as either highly-trained
171 (Tier 3) or trained (Tier 2) in accordance with the criteria specified by McKay et al. (23).

172 Sample size was determined according to our primary outcome variable (i.e. exogenous CHO
173 oxidation) assuming an effect of feeding form (liquid vs. solid) of $0.18 \text{ g}\cdot\text{min}^{-1}$ (0.96 ± 0.13
174 $\text{g}\cdot\text{min}^{-1}$ with solid vs $1.14 \pm 0.16 \text{ g}\cdot\text{min}^{-1}$ with liquid), as reported by Pfeiffer et al. (20)
175 between 60 and 180 minutes of exercise. These data give an effect size of $d_z = 1.22$, where a
176 sample size of 8 would provide an α -value of 0.05 and a power of 0.80 (G*Power, version
177 3.1.9.6). None of the subjects had any history of musculoskeletal or neurological disease, nor
178 were they under any pharmacological treatments during the testing period.

179

180 **Experimental overview**

181 In a repeated measures (> 6 days, but < 15 days apart), randomised, cross-over design, with
182 each experimental trial separated by a minimum of 7 days, participants completed a
183 prolonged endurance-based cycling exercise protocol, consisting of 180 min of submaximal
184 exercise (undertaken at 95% of lactate threshold) followed by an exercise capacity test to
185 exhaustion (undertaken at 150% of lactate threshold) on five separate occasions. The initial
186 trial (WATER; where water only was consumed during exercise) was performed to provide a
187 full familiarisation to the exercise protocol and to examine any background shifts in breath
188 $^{13}\text{CO}_2$ appearance. In the following four randomised trials, subjects ingested CHO at a rate of
189 $120 \text{ g}\cdot\text{h}^{-1}$ from fluid (DRINK), gels (GEL), jelly chews (CHEW) or a combination of all three
190 delivery forms (MIX). Each experimental trial was commenced following 24-h of high CHO
191 intake ($8 \text{ g}\cdot\text{kg}^{-1}$) and 3 h after the consumption of a CHO rich pre-exercise meal ($2 \text{ g}\cdot\text{kg}^{-1}$).
192 An overview of the experimental design and nutritional protocols is displayed in Figure 1.

193

194 **Preliminary testing**

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

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

206

$$\text{PPO} = W_{\text{final}} + (t/60) * \text{PI}$$

207

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

214

215 **Pre-experimental controls**

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

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

227

228 **180-min steady state cycling**

229 On the morning of the main experimental trials, subjects reported to the laboratory at ~10:00
230 h having consumed the pre-packaged, standardised breakfast provided (see above). Upon
231 arrival, an indwelling cannula (Safety Lock 22G; BD Biosciences, West Sussex, UK) was
232 inserted into the antecubital vein in the anterior crease of the forearm and a resting blood
233 sample drawn and subsequently flushed with ~5 ml of sterile saline (Kays Medical,
234 Liverpool, UK). Resting expired breath samples were collected in duplicate into evacuated 10
235 mL Exetainer tubes (Labco, High Wycombe, UK), sampled directly from the mixing
236 chamber, to determine the ¹³C/¹²C ratio in CO₂ at rest. Following the collection of resting
237 measures, subjects completed a 10-min warm-up at 100 W and began the 180 min cycling
238 protocol at 95% LT (215 ± 35 W). This relative exercise intensity was chosen as it has been
239 suggested as an appropriate method of matching metabolic stress between subjects when
240 compared with exercising at a percentage of $\dot{V}O_{2\max}$ (27). Heart rate (Polar H10; Polar,
241 Kempele, Finland), ratings of perceived exertion (RPE) (28) and cycling cadence were
242 obtained at 30 min intervals throughout. Expired gas was collected for a 5 min period at 30
243 min intervals to calculate whole body substrate utilisation. The final minute of this period
244 was used to collect expired gas into the evacuated Exetainer tubes to determine the ¹³C/¹²C
245 ratio in CO₂. Gastrointestinal (GI) symptoms (nausea, regurgitation, fullness, cramps, gas,

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

263

264 **Carbohydrate feeding**

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

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

286

287 **Blood sampling and analysis**

288 Venous blood samples were collected into vacutainers containing K₂ EDTA, lithium heparin
289 or serum separation tubes (BD Biosciences, UK) and stored on ice or at room temperature
290 until centrifugation at 1500 g for 10 min at 4°C. Following centrifugation, plasma and serum
291 was aliquoted and stored at -80°C for subsequent analysis. Samples were later analysed for
292 plasma glucose, lactate non-esterified fatty acids (NEFA), and glycerol using commercially
293 available enzymatic spectrophotometric assays (RX Daytona+ Analyser; Randox, UK) as per
294 the manufacturer's instructions.

295

296 **Estimates of whole-body substrate oxidation and energy expenditure**

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

303

304 **$^{13}\text{C}/^{12}\text{C}$ analysis of breath CO_2**

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

309

$$\text{Exogenous carbohydrate oxidation} = \dot{V}\text{CO}_2 \cdot \left(\frac{\delta\text{Exp} - \delta\text{EXP}_{\text{bkg}}}{\delta\text{Ing} - \delta\text{Exp}_{\text{bkg}}} \right) \left(\frac{1}{k} \right)$$

310

311 Where δExp is the ^{13}C enrichment of expired CO_2 , δIng is the ^{13}C enrichment of the ingested
312 carbohydrate, $\delta\text{EXP}_{\text{bkg}}$ is the ^{13}C enrichment of expired CO_2 during the water trial. and k is
313 the $\dot{V}\text{CO}_2$ with the oxidation of 1 g of glucose ($0.7467 \text{ L CO}_2\cdot\text{g}^{-1}$). For the MIX trial, the ^{13}C
314 enrichment of the ingested carbohydrate used the average ^{13}C enrichment (55.98 ‰ versus
315 PDB) from the three separate forms being consumed given that they were all equivalently
316 enriched (Table 1).

317

318 **Statistical analysis**

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

329

330 **Results**

331

332 **Physiological responses**

333 Heart rate and absolute oxygen uptake increased during exercise (time effect, $P < 0.001$ for
334 both, Table 2) although no differences were apparent between trials (treatment effect, $P =$
335 0.621 , $P = 0.155$ and $P = 0.596$, respectively). RPE also increased during exercise (time
336 effect, $P < 0.001$) and was significantly higher in the WATER trial compared with the GEL
337 trial at 120 minutes ($P = 0.018$) and compared with all CHO feeding trials from 150 minutes
338 onwards ($P < 0.001$ for DRINK, GEL and CHEW and $P = 0.033$ for MIX) (Table 2). Plasma
339 glucose and lactate concentrations were not significantly different between forms of CHO
340 ingestion (treatment effect, $P = 0.749$ and $P = 0.426$ respectively). Plasma glycerol and
341 NEFA progressively increased during exercise (time effect, $P < 0.001$ for both) although
342 concentrations were not significantly different between forms of CHO ingestion (treatment
343 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 $\text{g}\cdot\text{min}^{-1}$;
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 $\text{g}\cdot\text{min}^{-1}$; treatment effect, $P = 0.092$) between trials (Figure 5B).
365 There was also no significant difference in oxidation efficiency between trials (DRINK, $72 \pm$
366 8 ; GEL, 72 ± 5 ; CHEW, 75 ± 4.6 ; MIX, $75 \pm 6\%$; 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,

369 $1.66 \pm 0.02 \text{ g} \cdot \text{min}^{-1}$; treatment effect, $P = 0.189$) (Figure 5C). We also highlight individual
370 variability in the oxidation of each form across all participants in Figure 5C.

371

372 The contribution of exogenous CHO oxidation towards total energy expenditure was also
373 comparable between feeding forms during both hour 2 (DRINK, 41 ± 5 ; GEL, 41 ± 5 ;
374 CHEW, 43 ± 7 ; MIX, 42 ± 7 %, $P = 0.143$) and hour 3 (DRINK, 44 ± 5 ; GEL, 46 ± 5 ;
375 CHEW, 47 ± 7 ; Mix, 48 ± 7 %, $P = 0.329$). The contribution of endogenous CHO oxidation
376 towards total energy expenditure was significantly higher in the WATER trial compared with
377 all CHO feeding forms during both hour 2 (WATER; $55 \pm 6\%$; DRINK, 28 ± 5 , $P < 0.001$;
378 GEL, 32 ± 8 , $P = 0.002$; CHEW, 33 ± 9 , $P = 0.009$; MIX, $31 \pm 8\%$, $P = 0.001$) and hour 3
379 (WATER; $40 \pm 6\%$; DRINK, 17 ± 6 ; GEL, 17 ± 5 ; CHEW, 17 ± 4 ; MIX, $15 \pm 5\%$, $P < 0.001$
380 for all). The contribution of fat towards total energy expenditure was also significant higher
381 in the WATER trial compared with all feeding forms during both hour 2 (WATER; $45 \pm 6\%$;
382 DRINK, 31 ± 5 , $P = 0.001$; GEL, 27 ± 9 , $P < 0.001$; CHEW, 25 ± 7 , $P < 0.001$; MIX, $27 \pm$
383 5% , $P < 0.001$) and hour 3 (WATER; $60 \pm 6\%$; DRINK, 39 ± 9 ; GEL, 37 ± 8 ; CHEW, $36 \pm$
384 8 ; MIX, $38 \pm 6\%$, $P < 0.001$ for all) (Figure 5E and 3F).

385

386 **Gastrointestinal discomfort**

387 Mean cumulative scores for each gastrointestinal symptom were negligible (< 2 out of a
388 possible 60 for all) with no significant differences between conditions (treatment effect for
389 nausea; $P = 0.437$, regurgitation; $P = 0.580$, fullness; $P = 0.827$. cramps; $P = 0.422$, gas; $P =$
390 0.757 and urge to defecate; $P = 0.580$). Similarly, peak scores for each symptom were low,
391 with no participants reporting any symptoms > 3 in any trial and no significant differences
392 between conditions (treatment effect for nausea; $P = 0.827$, regurgitation; $P = 0.364$, fullness;
393 $P = 0.187$. cramps; $P = 580$, gas; $P = 0.804$ and urge to defecate; $P = 0.422$).

394

395

396 **Exercise capacity**

397 CHO feeding at a rate of $120 \text{ g}\cdot\text{h}^{-1}$ significantly improved exercise capacity (trial effect; $P =$
398 0.021) within all trials (DRINK, $446 \pm 350 \text{ s}$, $P = 0.004$; GEL, $529 \pm 396 \text{ s}$, $P = 0.005$;
399 CHEW, $596 \pm 416 \text{ s}$, $P = 0.028$; MIX, $470 \pm 395 \text{ s}$, $P = 0.035$; Figure 6A) when compared
400 with WATER only ($231 \pm 244 \text{ s}$). However, there were no significant differences in exercise
401 capacity between the different feeding forms ($P > 0.05$ for all). When data were analysed for
402 a trial order effect, there was a significant difference between conditions (trial effect, $P =$
403 0.044) which was explained by significant differences between Trial 1 (i.e. the WATER only
404 familiarisation trial; $231 \pm 244 \text{ sec}$) and all other trials (Trial 2, 475 ± 357 , $P < 0.001$; Trial 3,
405 499 ± 400 , $P = 0.016$; Trial 4, 458 ± 369 , $P = 0.034$; Trial 5, $609 \pm 429 \text{ sec}$, $P = 0.024$; Figure
406 6B) with no other pairwise differences apparent.

407

408

409 **Discussion**

410 Confirming our hypothesis, data demonstrate comparable rates of peak exogenous CHO
411 oxidation when trained male cyclists consume $120 \text{ g}\cdot\text{h}^{-1}$ in the form of a liquid (DRINK),
412 semi-solid (GEL), solid (CHEW) or a co-ingestion approach (MIX). Importantly, we
413 observed some of the highest peak rates of exogenous CHO oxidation (e.g. $1.66 \text{ g}\cdot\text{min}^{-1}$
414 during the co-ingestion approach) reported in the literature, the result of which was not
415 associated with any significant symptoms of gastrointestinal discomfort. When taken
416 together, our data suggest that the consumption of $120 \text{ g}\cdot\text{h}^{-1}$ CHO with a mixture of
417 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 ($8 \text{ g}\cdot\text{kg}^{-1}$ CHO for the previous 24 h) and CHO rich pre-exercise meal ($2 \text{ g}\cdot\text{kg}^{-1}$
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 $^{13}\text{CO}_2$ 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 $-23 \delta^{13}\text{C} \text{ ‰}$ 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 $^{13}\text{CO}_2$ 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 $\delta^{13}\text{C} \text{ ‰}$ 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 $90 \text{ g}\cdot\text{h}^{-1}$
461 (9, 39, 40). However, where the aim is to achieve high rates of exogenous CHO oxidation
462 (e.g. $1.5 \text{ g}\cdot\text{min}^{-1}$), individuals should likely consume $100\text{-}120 \text{ g}\cdot\text{h}^{-1}$ since oxidation efficiency
463 is not uniform (13, 14). Indeed, the upper limits of reported CHO intakes during competition
464 range from 107 to $137 \text{ g}\cdot\text{h}^{-1}$ (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 ($74 \pm 7\%$), peak rates of exogenous CHO oxidation ($\sim 1.2 \text{ g}\cdot\text{min}^{-1}$), and endurance
467 performance when compared with 2:1 formulations ($62 \pm 12\%$ and $\sim 1.0 \text{ g}\cdot\text{min}^{-1}$,

468 respectively) ingested at a rate of $90 \text{ g}\cdot\text{h}^{-1}$ (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 ($120 \text{ g}\cdot\text{h}^{-1}$), we observed higher rates of peak exogenous CHO oxidation during our
473 DRINK trial (i.e. $1.56 \text{ g}\cdot\text{min}^{-1}$) than has been previously reported ($\sim 1.2 \text{ g}\cdot\text{h}^{-1}$) when CHO was
474 ingested at $90 \text{ g}\cdot\text{h}^{-1}$ (17). Although previous researchers also reported peak rates of exogenous
475 CHO oxidation of $1.53 \text{ g}\cdot\text{min}^{-1}$ (range: $1.23\text{-}1.77 \text{ g}\cdot\text{min}^{-1}$) 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 $1.25\text{-}1.87 \text{ g}\cdot\text{min}^{-1}$) 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 $90 \text{ g}\cdot\text{h}^{-1}$ 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 $\sim 1.8 \text{ g}\cdot\text{min}^{-1}$ (42). Notwithstanding
486 potential effects of hyperinsulinemia and assuming an estimated oxidation efficiency of $\sim 70\text{-}$
487 75% , the ingestion of $140\text{-}150 \text{ g}\cdot\text{h}^{-1}$ may be considered as the maximal worthwhile dose to
488 achieve such high rates of oxidation. In support of this, the ingestion of $144 \text{ g}\cdot\text{h}^{-1}$ (in a 1:1
489 ratio of glucose to fructose) has been previously shown to elicit peak exogenous oxidation
490 rates of $1.75 \text{ g}\cdot\text{min}^{-1}$ 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 $1.8 \text{ g}\cdot\text{min}^{-1}$ can be achieved with the ingestion of $120 \text{ g}\cdot\text{h}^{-1}$ (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 ($1.42 \text{ g}\cdot\text{min}^{-1}$) and
502 gel form ($1.44 \text{ g}\cdot\text{min}^{-1}$) when CHO was ingested at a rate of $108 \text{ g}\cdot\text{h}^{-1}$ 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 ($1.25 \text{ g}\cdot\text{min}^{-1}$) versus a drink
505 ($1.34 \text{ g}\cdot\text{min}^{-1}$), when fed at a rate of $93 \text{ g}\cdot\text{h}^{-1}$ 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; $1.66 \text{ g}\cdot\text{min}^{-1}$), 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 $120 \text{ g}\cdot\text{h}^{-1}$ CHO during exercise, it is noteworthy that the present
517 participants reported trivial symptoms of gastrointestinal discomfort across all feeding forms.

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

540

541 To address the effects of CHO form on exercise capacity, participants completed an exercise
542 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 $90 \text{ g}\cdot\text{h}^{-1}$ extended exercise capacity when compared
546 with both $45 \text{ g}\cdot\text{h}^{-1}$ and $0 \text{ g}\cdot\text{h}^{-1}$ (24). This ergogenic effect was likely mediated by increased
547 liver glycogen and/or plasma glucose availability associated with the higher dose of CHO
548 ingestion. Interestingly, we also observed that the consumption of $90 \text{ g}\cdot\text{h}^{-1}$ delayed the point
549 at which lipid oxidation comprises the largest proportion of energy production by ~ 10 and
550 ~ 40 minutes when compared with $45 \text{ g}\cdot\text{h}^{-1}$ and $0 \text{ g}\cdot\text{h}^{-1}$, respectively (24). In consuming the
551 higher absolute dose of $120 \text{ g}\cdot\text{h}^{-1}$ 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 performance 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 $90 \text{ g}\cdot\text{h}^{-1}$ induces higher peak power during
572 a 30-minute time trial (completed after 3 hours of steady state exercise at $60\% \text{ VO}_{2\text{peak}}$) when
573 compared with both $80 \text{ g}\cdot\text{h}^{-1}$ (3.7%) and $100 \text{ g}\cdot\text{h}^{-1}$ (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 maintenance of whole-body CHO oxidation, and the lack of
579 gastrointestinal symptoms, data demonstrate that consumption of $120 \text{ g}\cdot\text{h}^{-1}$ (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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587

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605

606

607 **Author contributions**

608 MAH, JNP, CLE, SJM, JTG and JPM designed the study. MAH performed experiments;

609 MAH, JNP, JTG, and JPM analysed the data and interpreted the results. MAH, JNP, JTG and

610 JPM drafted the manuscript and CLE, SJM, TS and LB edited and revised the manuscript. All
611 authors approved the final version and agree to be accountable for all aspects of the work in
612 ensuring that questions related to the accuracy or integrity of any part of the work are
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615

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- 735
- 736
- 737
- 738
- 739

740 **Table 1**

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

744

745 **Table 2**

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

748

749 **Figure 1**

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

755

756 **Figure 2**

757 (A) Plasma glucose, (B) lactate, (C) glycerol and (D) NEFA at rest and during exercise in the
758 DRINK, GEL, CHEW and MIX trials. ^aSignificant difference from 0 min, ^bsignificant
759 difference from 30 min, ^csignificant difference from 60 min, ^dsignificant difference from 90
760 min, ^esignificant difference from 120 min, ^fsignificant difference from 150 min, *P* < 0.05.

761

762 **Figure 3**

763 (A) Rates of whole-body CHO oxidation during exercise, (B) total CHO oxidation, (C) rates
764 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 ^aSignificant difference from 30 min, ^bsignificant difference from 60 min, ^csignificant
767 difference from 90 min, ^dsignificant difference from 120 min, ^esignificant 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**

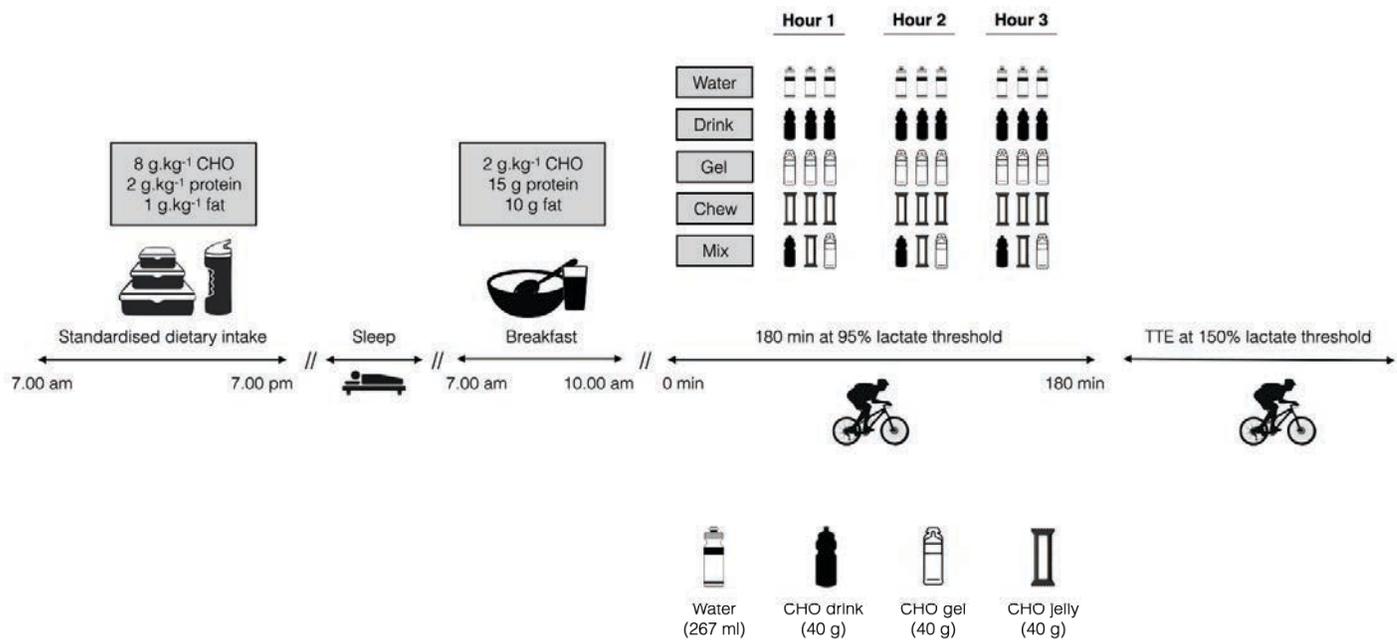
775 (A) Breath ¹³CO₂ enrichment and (B) exogenous CHO oxidation during 180 minutes of
776 exercise during the WATER, DRINK, GEL, CHEW and MIX trials. ^aSignificant difference
777 from 30 min, ^bsignificant difference from 60 min, ^csignificant difference from 90 min,
778 ^dsignificant difference from 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

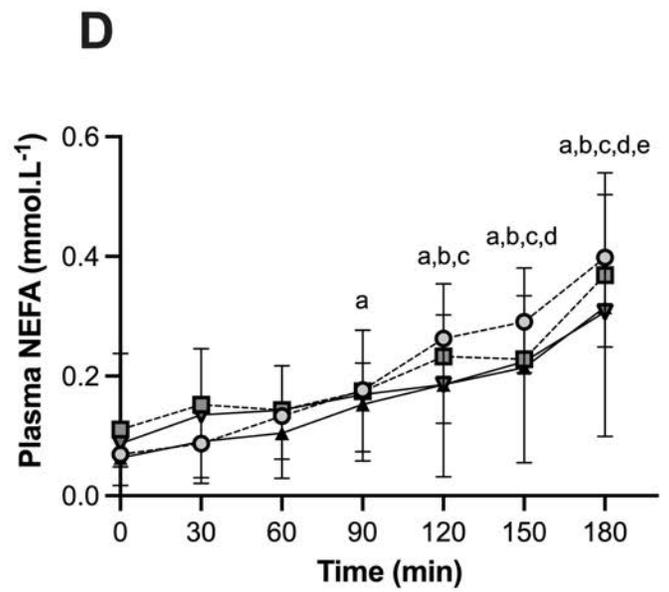
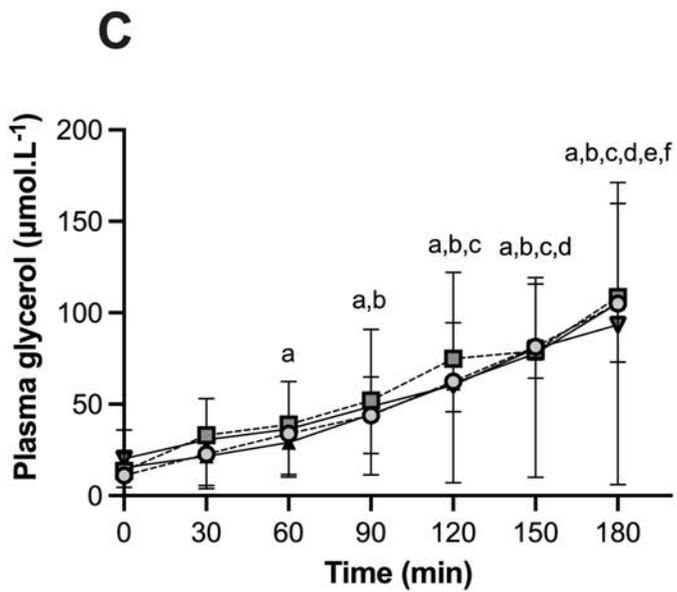
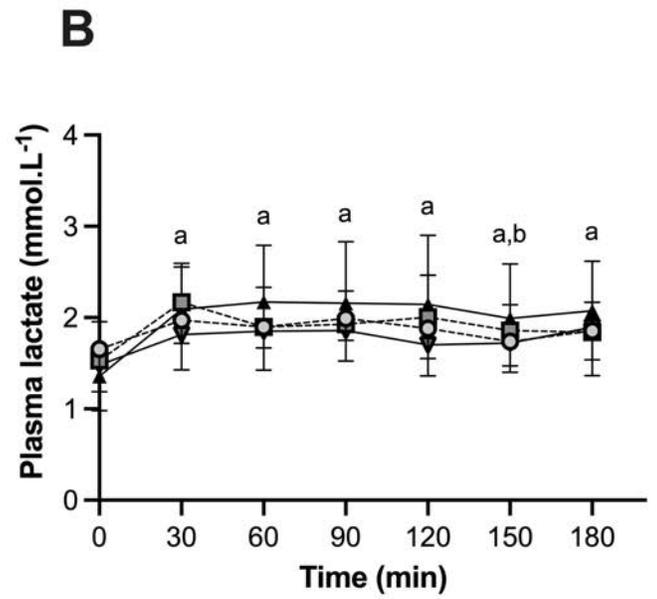
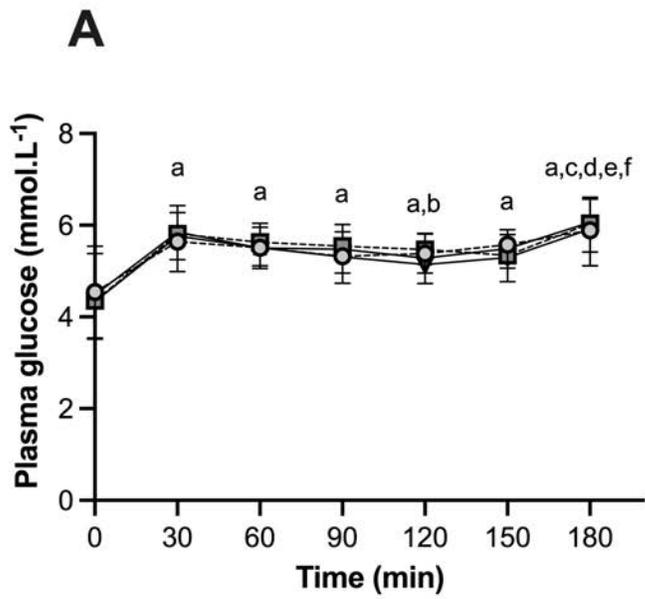
784 **Figure 6**

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

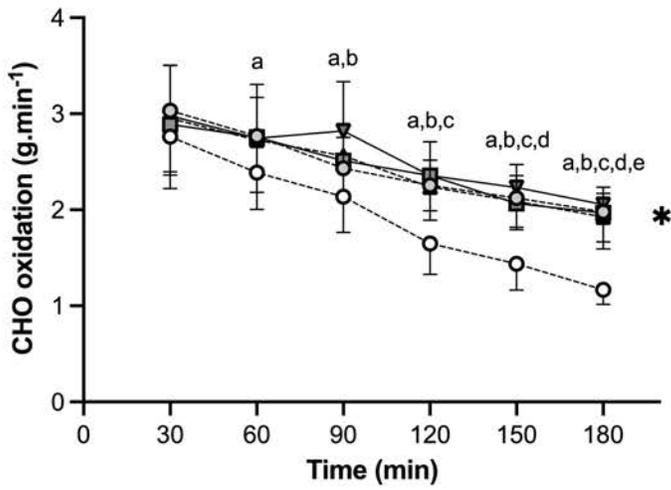


-○- DRINK -■- GEL -▼- CHEW -▲- MIX

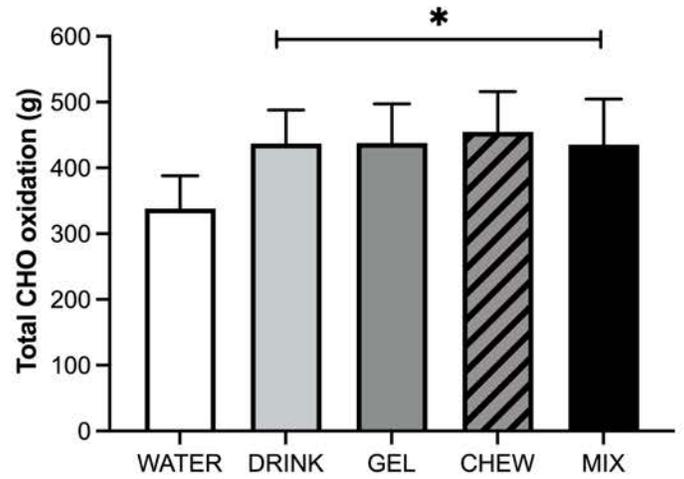


○ WATER ○ DRINK ■ GEL ▼ CHEW ▲ MIX

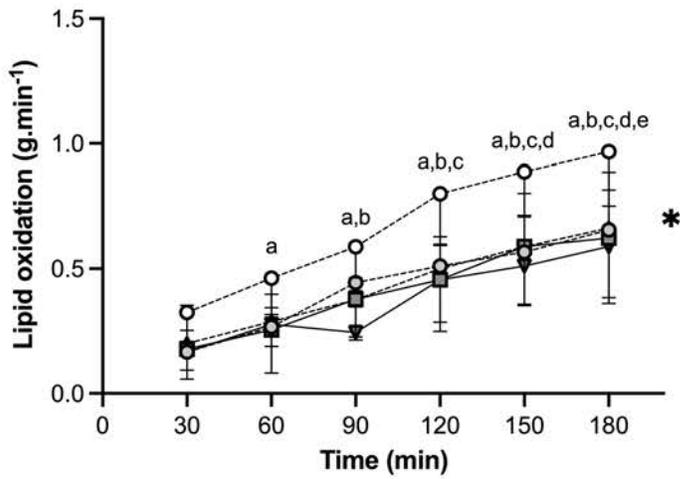
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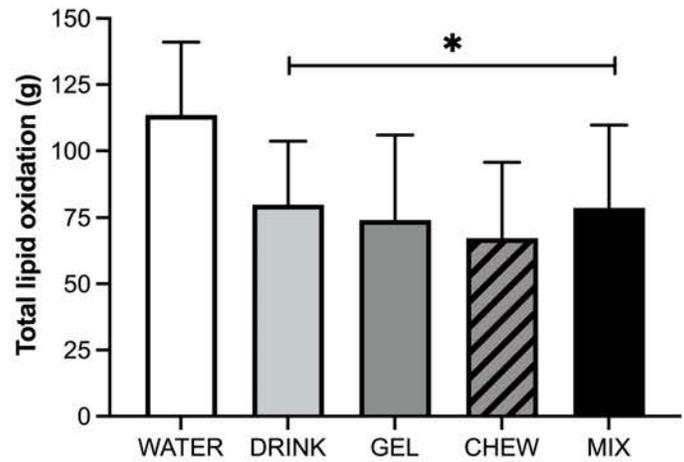
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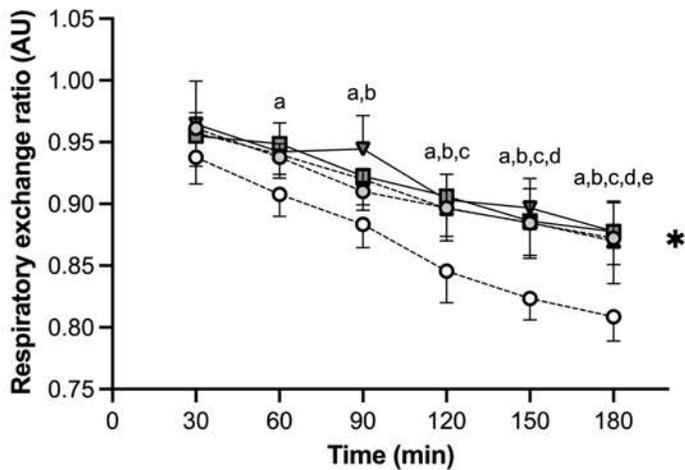
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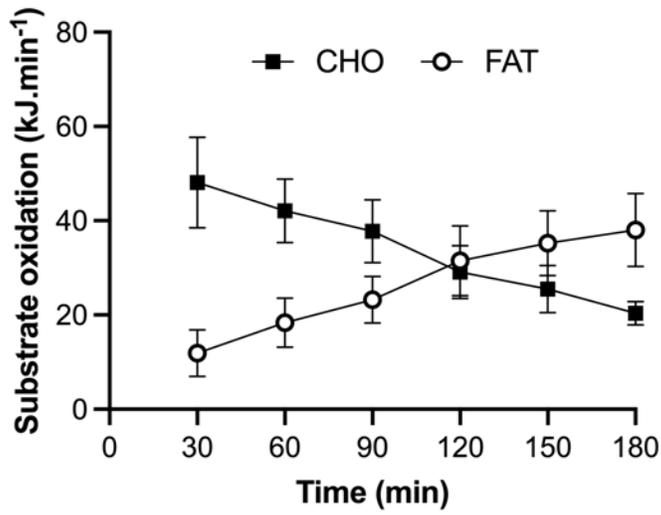
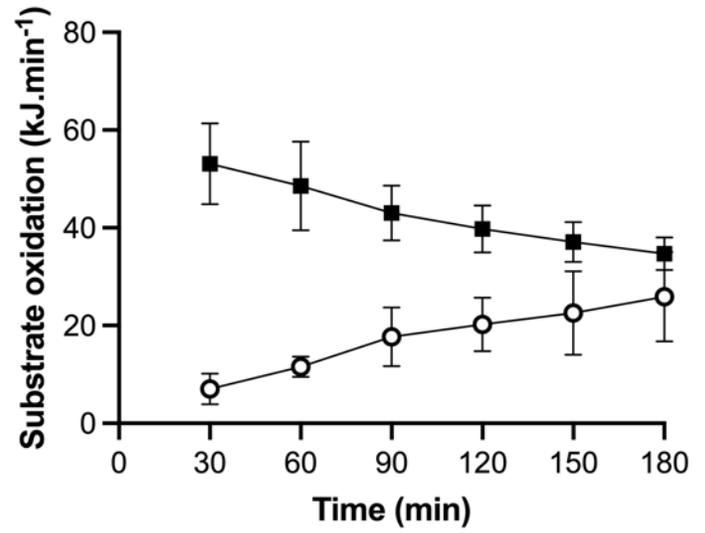
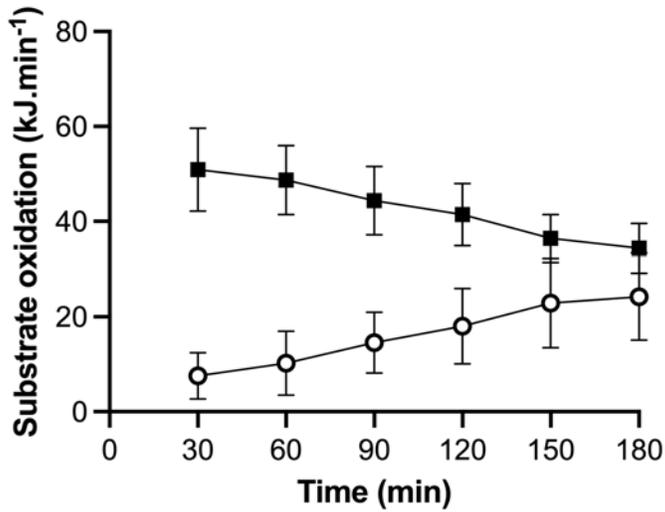
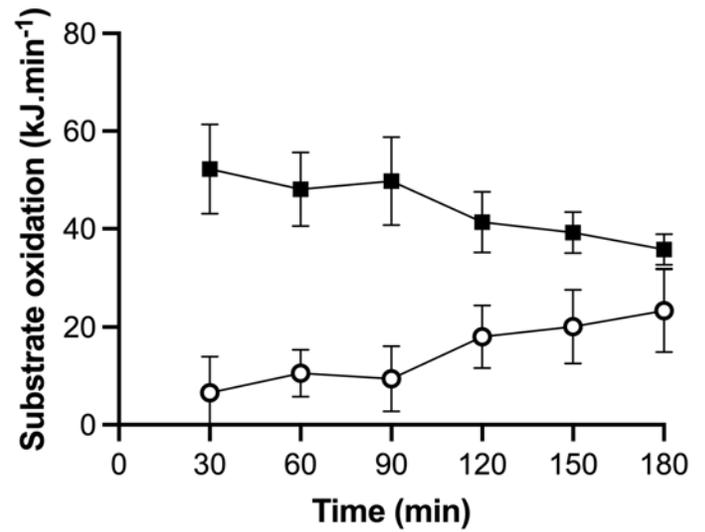
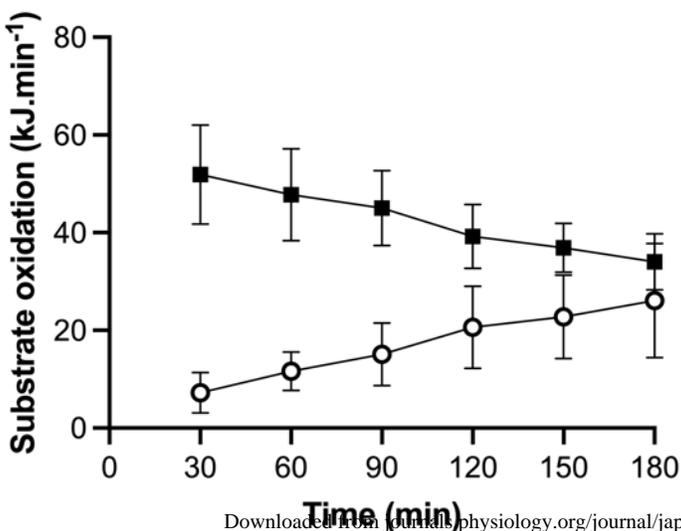


D

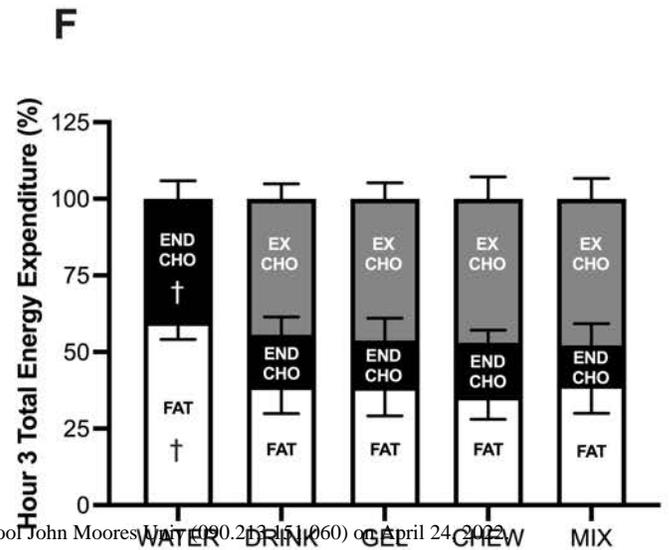
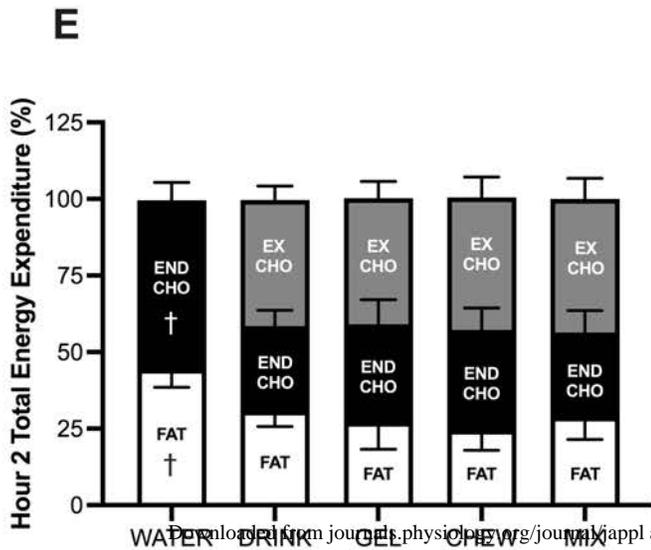
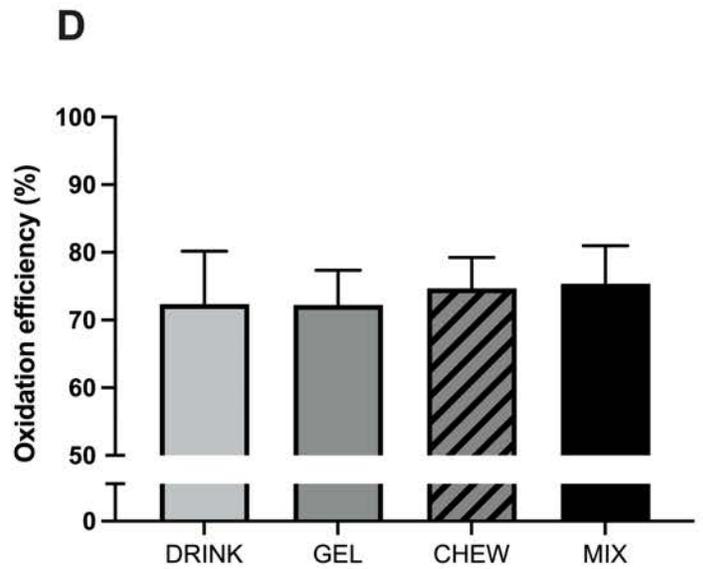
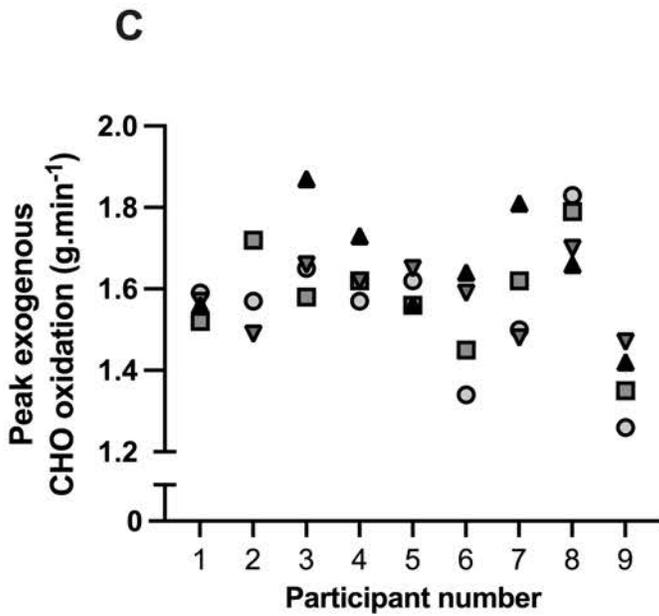
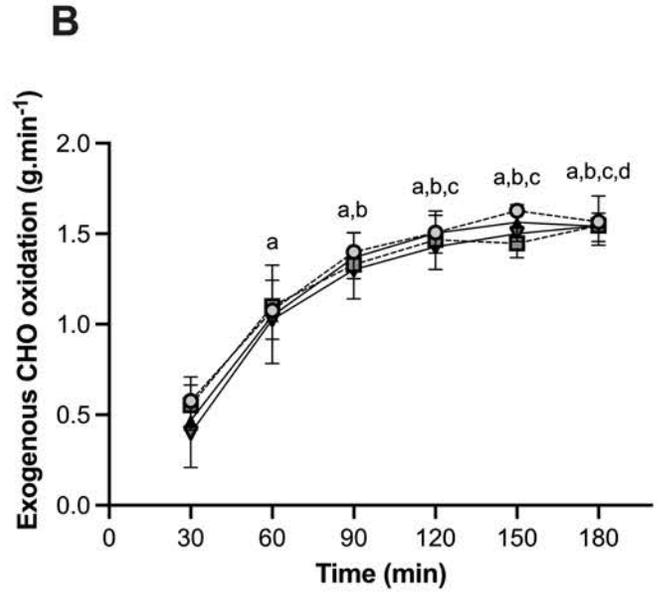
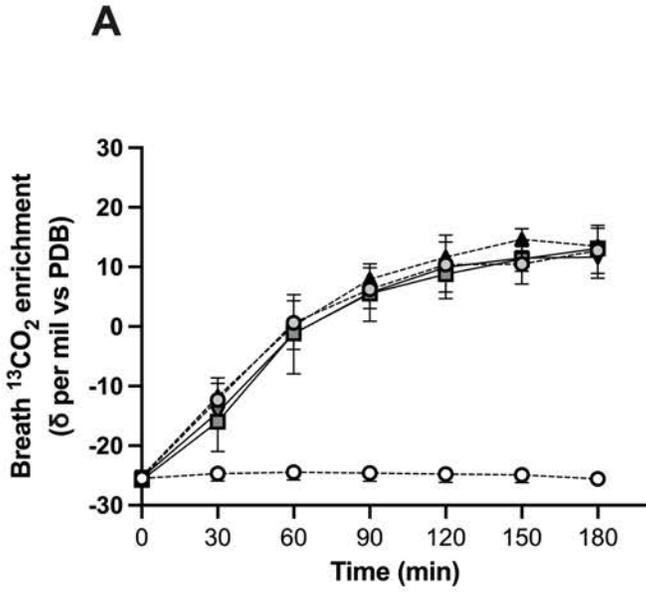


E



A (WATER)**B (DRINK)****C (GEL)****D (CHEW)****E (MIX)**

○ WATER ○ DRINK ■ GEL ▼ CHEW ▲ MIX



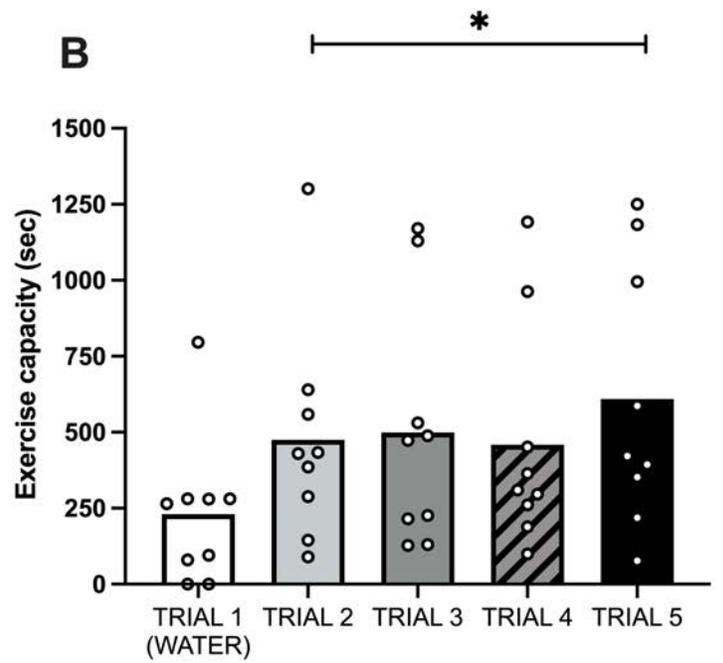
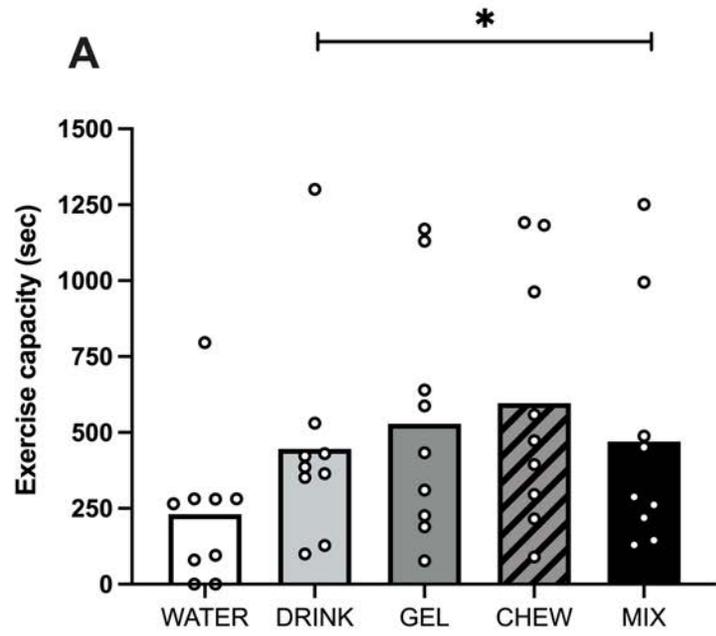


Table 1

Nutrition per 120 g CHO	DRINK	GEL	CHEW
Energy (kcal)	480	480	492
Fat (g)	0	0	0.1
Carbohydrate (g)	120	120	120
<i>maltodextrin (g)</i>	66.7	66.7	0
<i>glucose (g)</i>	-	-	66.7
<i>fructose (g)</i>	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 $\delta^{13}\text{C}$ 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 *}
ṠO₂ (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

^asignificant difference from 30 min time point,

^bsignificant difference from 60 min time point,

^csignificant difference from 90 min time point,

^dsignificant difference from 120 min time point and,

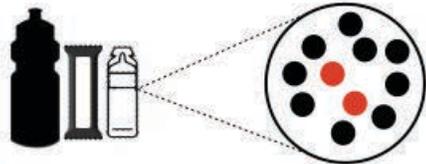
^esignificant difference from 150 min time point, $P < 0.05$

*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

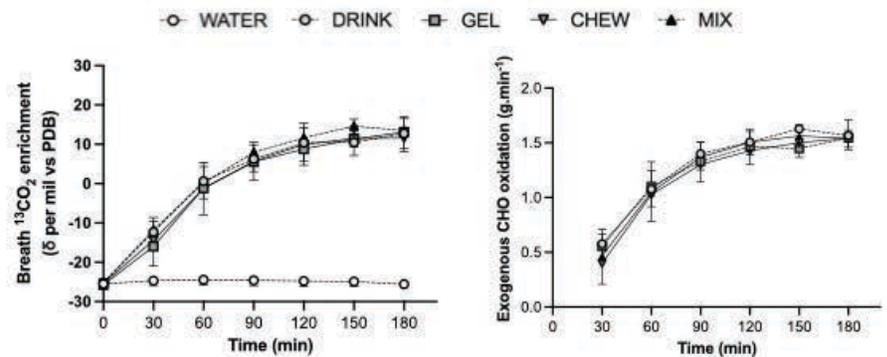
METHODS

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.