Post-exercise fructose-maltodextrin ingestion enhances subsequent endurance capacity

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ABSTRACT

Purpose: Restoring skeletal muscle and hepatic glycogen content during short-term (<6 h) recovery from prolonged exercise is pertinent for athletes seeking to maximize performance in repeated exercise bouts. Previous research suggests co-ingestion of fructose-glucose carbohydrate sources augments hepatic and has equivalent effects on skeletal muscle glycogen storage during short-term recovery from prolonged exercise compared to isocaloric glucose ingestion. The aim of the present investigation was to determine if this has a discernible effect on subsequent exercise capacity. *Methods:* Eight trained endurance runners and triathletes performed two experimental trials in a single-blind, randomised, and counterbalanced cross-over design. Trials involved treadmill running to exhaustion at 70 %$\dot{V}O_{2max}$, a four-hour recovery with 90 $g.h^{-1}$ of glucose-maltodextrin (GLU+MAL) or fructose-maltodextrin (FRU+MAL) ingestion (1:1.5 ratio), and a second bout of treadmill running to exhaustion at 70 %$\dot{V}O_{2max}$. *Results:* Exercise capacity in bout two was significantly greater with FRU+MAL (81.4 ± 22.3 vs. 61.4 ± 9.6 min, P = 0.02), a *large* magnitude effect (ES = 1.84 ± 1.12, 32.4 ± 19.9 %). Total carbohydrate oxidation rates were not significantly different during bout one or two between-trials, although total carbohydrate oxidized in bout two was significantly greater with FRU+MAL (223 ± 66 vs. 157 ± 26 g, P = 0.02). Ingested carbohydrate oxidation rates were greater during bout two with FRU+MAL (P = 0.001). Plasma glucose and non-esterified fatty acid concentrations were not significantly different between-trials. Plasma lactate concentrations were significantly greater during recovery prior to bout two with FRU+MAL (P = 0.001). Self-reported nausea and stomach fullness during bout two were marginally in favour of FRU+MAL. *Conclusion:* Short-term recovery of endurance capacity was significantly enhanced with FRU+MAL vs. GLU+MAL ingestion during recovery.

KEY WORDS: Nutrition, carbohydrates, prolonged exercise, substrate oxidation.

INTRODUCTION

Humans have capacity to store finite amounts of carbohydrate energy as glycogen, predominantly in skeletal muscle (1) and the liver (2). Carbohydrates provide quantitatively the most important metabolic substrate for fuel metabolism during exercise of moderate-to-high intensities (3). Most research has focused on the role of muscle glycogen and it has long been known that exercise of sufficient length and intensity will eventually deplete these stores to very low concentrations (1), implicating endogenous carbohydrate availability as a limiting factor during prolonged, thermoneutral exercise. This hypothesis is supported by recent suggestions that preferential, accelerated depletion of glycogen stored in the intramyofibrillar compartment has deleterious effects on muscle function and therefore elicits fatigue (4).

Maximizing recovery of muscle glycogen content in the post-exercise period is pertinent to athletes seeking to optimize performance in repeated bouts of prolonged exercise with limited recovery time. Indeed, recent evidence suggests the muscle glycogen-mediated limitation to prolonged exercise capacity holds true for repeated bouts (5). Current guidelines recommend ingestion of moderate-to-high-glycaemic index carbohydrates such as glucose-based sources at rates of 1-1.2 $g.kg^{-1}.h^{-1}$, beginning as soon as logistically possible following exercise, when recovery duration is short (<4 h) (6). This nutritional strategy should facilitate rapid and sufficient substrate availability to maximize insulin-dependent muscle glycogen synthesis (7), and take advantage of the insulin-independent contraction-mediated muscle glucose uptake and glycogen synthesis that occurs in the initial post-exercise period (8).

The liver functions as a carbohydrate reservoir for release into the circulation and resultant oxidation by working skeletal muscle, as well as in maintenance of euglycaemia (9). Whilst glucose is the primary carbohydrate substrate for muscle glycogen synthesis (10), fructose exerts a superior effect on hepatic glycogen synthesis (11). Indeed, some studies have now observed superior hepatic and equal muscle glycogen synthesis with co-ingestion of large amounts of fructose-glucose carbohydrate sources during acute recovery from prolonged exercise compared to isocaloric glucose ingestion (12–14). This may have implications for subsequent exercise capacity through increased whole-body carbohydrate availability.

To-date, no study has investigated if the apparent metabolic advantage ascertained through co-ingestion of fructose-glucose carbohydrate sources during short-term recovery from prolonged exhaustive exercise translates into a discernible effect on subsequent exercise performance or capacity. The purpose of the present investigation was to elucidate if such an effect exists, and to determine how any differences manifest metabolically and perceptually. It was hypothesized that fructose-maltodextrin co-ingestion during short-term recovery from prolonged exhaustive exercise would result in superior subsequent exercise capacity compared to isocaloric glucose-maltodextrin ingestion.

METHODS

Participants

Eight (six male, two female) healthy, trained endurance runners and triathletes participated in the present investigation (age, 31 ± 6 y; height, 176 ± 6 cm; mass, 68.4 ± 5.6 kg; $\dot{V}O_{2max}$, 3.76 ± 0.47 l.min^{-1}). The sample size was chosen based on pragmatic reasons, balancing logistical, financial and recruitment-related considerations for such an arduous experimental protocol, as well as reflecting the number of participants used in previous similar studies (15,16). All participants were engaging in training for endurance running events, habitually covering a self-reported 63 ± 19 km.week^{-1}. Experimental procedures were approved by the University of Birmingham (United Kingdom) Ethics Committee, and all participants provided written informed consent.

Study design

The present investigation adopted a single-blinded, randomized, and counterbalanced cross-over design involving four laboratory visits. In the first laboratory visit, a maximal treadmill test (*Preliminary test*) was performed to determine maximum oxygen uptake ($\dot{V}O_{2max}$). The second visit consisted of full familiarization to procedures performed in the subsequent experimental trials, without venous cannulation and blood collection. Thereafter, two experimental trials were conducted 4-16 d apart in a random, counterbalanced order (www.random.org). Participants were blinded to trial order. Experimental trials consisted of treadmill running to exhaustion at 70 %$\dot{V}O_{2max}$, a four-hour recovery with 90 g.h^{-1} maltodextrin and glucose (MAL+GLU) or maltodextrin and fructose (MAL+FRU) ingestion (1.5:1 ratio), and a second bout of treadmill running to exhaustion at 70 %$\dot{V}O_{2max}$.

Preliminary test

To determine $\dot{V}O_{2max}$, an incremental step test to volitional exhaustion was performed on a motorized treadmill (quasar, h/p cosmos, GER) during the first laboratory visit (18 ± 1°C, 48 ± 14 % rH). Height (Model 220, Seca, GER) and body mass (Champ II, OHAUS, SWI) of each participant was measured prior to the test. Participants then completed 4-min stages at 7, 9, 11, and 13 $km.h^{-1}$ against a 1 % gradient to simulate the energetic cost of level-gradient outdoor running (17). Heart rate (HR; Polar Electro, FIN) and perceived exertion (RPE) according to Borg's 6-20 scale (18) were recorded in the final 60 s of each stage. Oxygen uptake ($\dot{V}O_2$) was measured continuously using an automated analyzer (JAEGER® Vyntus CPX, CareFusion, GER), and calculated at each velocity as the average value during the final 30 s. Following completion of the 13 $km.h^{-1}$ stage, treadmill velocity was reduced to 11 $km.h^{-1}$ and subsequently increased by 0.5 $km.h^{-1}$ every 30 s until attainment of volitional exhaustion. Maximum oxygen uptake ($\dot{V}O_{2max}$) was accepted as the highest $\dot{V}O_2$ 15-breath rolling average if two of the following three criteria were met: respiratory exchange ratio ≥1.10, HR ± 10 $b.min^{-1}$ of age-predicted maximum (205.8 – 0.685[age (y)]) (19), and attainment of volitional exhaustion. Simple regression equations were used to estimate the speed required to elicit 70 %$\dot{V}O_{2max}$ for use in the subsequent trials.

Experimental trials

At least five days following the familiarization trial, participants reported to the laboratory at ~08:00hrs having fasted overnight and refrained from caffeine, alcohol, and vigorous exercise for 24 h, and having completed a three-day pre-trial diet diary

to be repeated in the run-up to the final experimental trial. Participants were fitted with an antecubital venous cannula (BD Venflon^{TM}, Helsingborg, SWE), and a 5-ml baseline venous blood sample was drawn. A treadmill run to volitional exhaustion at 70 %$\dot{V}O_{2max}$ then commenced (quasar, h/p cosmos, GER), with venous blood samples obtained after 30 min, 60 min, and at exhaustion from an extension line to minimise impact on running gait and technique. Expired gas samples were collected every 15 min and at exhaustion and analyzed for $\dot{V}O_2$ and $\dot{V}CO_2$ using an automated analyser (JAEGER® Vyntus CPX, CareFusion, GER). Water was consumed *ad libitum*. On attainment of volitional exhaustion, treadmill speed was reduced to 4.4 km.h^{-1} for two minutes. Treadmill speed was then restored to that eliciting 70 %$\dot{V}O_{2max}$ and the participant was again asked to run to volitional exhaustion. This process was repeated so only at the third attainment of volitional exhaustion was the test terminated. This protocol has lower coefficient of variation for exercise capacity compared to traditional single-exhaustion protocols (5.4 %, 1.4-9.6 [95 % confidence intervals]) (20).

Participants then passively rested for four hours, during which sedentary activities such as reading and use of laptops were permitted. Participants immediately ingested a 300-ml beverage containing 18 g glucose (GLU+MAL) or fructose (FRU+MAL) with 27 g maltodextrin, and therefore in a 1:1.5 ratio. Carbohydrates ingested during recovery were of high ^{13}C natural abundance (-11.36 and -11.39 $\delta^{13}C_{V\text{-}PDB}$ ‰; The Hut Group, Cheshire, UK; Sports Supplements Ltd., Essex, UK). Identical beverages were ingested every 30 min throughout recovery ending 30 min prior to the end of the recovery period, such that 2.4 l of fluid and 90 g.h^{-1} of carbohydrate was ingested over the four-hour period. Venous blood samples and scales for gastrointestinal comfort

(GC) (21) were obtained every hour during recovery. The GC scales assessed nausea, stomach fullness, and abdominal cramping using 1-10 point Likert scales.

Following the four-hour recovery period, participants commenced a second treadmill run to volitional exhaustion at 70 % $\dot{V}O_{2max}$ as before. Venous blood samples, GC scales, RPE, and a scale for lower-limb muscle soreness (22) were obtained every 15 min and at exhaustion. Expired gas samples were also obtained for 4 min every 15 min and at exhaustion, and analysed for $\dot{V}O_2$ and $\dot{V}CO_2$ using an automated analyzer (JAEGER® Vyntus CPX, CareFusion, GER). The exhaustion time-point expired gas sample was collected during a period of running between the first and final claim of volitional exhaustion. At these time-points, and also immediately following the first exercise bout, breath samples were collected into 10-ml evacuated tubes (Exetainer® Breath Vial, Labco Ltd., UK).

Blood analyses

Venous blood samples were aliquoted into ~5 ml pre-chilled ethylenediaminetetraacetic acid tubes, centrifuged for 10 min at 4°C and 3500 revs.min^{-1}, and stored at -25°C. Plasma glucose, non-esterified fatty acid (NEFA), and lactate concentrations were later determined through duplicate colorimetric assays using a semi-automatic analyser (ILab 650, Instrumentation Laboratory, Bedford, MA, USA) and commercially available kits (Randox Laboratories Ltd., County Antrim, UK).

Gas analyses

$\dot{V}O_2$ and $\dot{V}CO_2$ were calculated using an automated analyzer (JAEGER® Vyntus CPX, CareFusion, GER). This allowed for calculation of whole-body rates of fat and carbohydrate (CHO_{tot}) oxidation at each time-point during the first and second bouts of the experimental trials using the following equations, which assume a negligible contribution of protein oxidation to metabolism (Eq. 1-2) (23):

$$\text{Fat oxidation} = (1.695 \times \dot{V}O_2) - (1.701 \times \dot{V}CO_2)$$

Eq. 1

$$CHO_{tot}\ \text{oxidation} = (4.210 \times \dot{V}CO_2) - (2.962 \times \dot{V}O_2)$$

Eq. 2

Additionally, non-linear modelling software was used (Microsoft Excel 2011, Redmond, WAS) such that CHO_{tot} could be compared between-trials at the point of exhaustion in the second bout of the shorter duration trial (Eq. 3). For example, if exhaustion occurred for one individual at 55 min in the second bout of the GLU+MAL trial, and 70 min in the FRU+MAL trial, the curve for CHO_{tot} vs. time in the FRU+MAL trial was non-linearly modelled such that CHO_{tot} could be estimated at 55 min.

$$\text{Modelled } CHO_{tot} = a + (b/t) + c \ln (t)$$

Eq. 3 where t = time-point (min) and a, b, and c were solved such that the modelled equation produced the lowest cumulative deviation from known values in each individual.

The isotopic enrichment of breath samples collected into 10-ml evacuated tubes (Exetainer® Breath Vial, Labco Ltd., UK) at each time-point was determined by gas chromatography isotope ratio mass spectrometry (IsoAnalytical Ltd., Crewe, UK) using the following equation (24) (Eq. 4):

$$\delta^{13}C = [(^{13}C{:}^{12}C \text{ sample}/^{13}C{:}^{12}C \text{ standard}) - 1] \times 10^{3} \text{ ml}^{-1}$$

Eq. 4 where isotopic enrichment was expressed as $\delta.ml^{-1}$ and related to an international standard (PDB).

Subsequently, the oxidation rate of carbohydrate ingested during recovery (CHO_{ing}) at each time-point during the second bout could then be calculated according to the following equation (Eq. 5):

$$CHO_{ing} = \dot{V}CO_2 \times [(\delta Exp - Exp_{bkg})/(\delta Ing - Exp_{bkg})] \times (1/0.7467)$$

Eq. 5 where δExp = ^{13}C enrichment of expired gas sample, δIng = ^{13}C enrichment of ingested carbohydrate, Exp_{bkg} = ^{13}C enrichment of expired gas sampled following the first exercise bout, and 0.7467 = $\dot{V}CO_2$ of 1 g glucose oxidation.

241 A consideration when attempting to measure specific oxidation of ingested high
242 natural abundance ^{13}C carbohydrates in expired breath is temporary retention of the
243 ^{13}C label in the body's endogenous bicarbonate pool as $^{13}CO_2$ during the initial 60
244 min of moderate-intensity exercise, resulting in underestimation of calculated ingested
245 carbohydrate oxidation rates (25). As this underestimation is likely to be systematic
246 between-trials, no arbitrary correction factor was deemed necessary given the cross-
247 over design of the present investigation. Nonetheless, the ingested carbohydrate
248 oxidation rates presented here should be considered minimal estimates.
249
250 *Statistical analyses*
251 Data was analyzed using commercially available software (SPSS Statistics, v22, SPSS
252 Inc., Chicago, IL). Data collected in the first exercise bout, recovery period, and
253 second exercise bout was considered separately. Sample distribution data is expressed
254 mean ± standard deviation (SD). Statistical significance was inferred when $P \leq 0.05$.
255
256 Between- and within-trial time-point specific substrate oxidation rate comparisons
257 (CHO_{tot}, CHO_{ing}, fat oxidation), as well as those for plasma glucose, NEFA, and
258 lactate concentrations, and psychometric scales, were made using two-way repeated
259 measures analyses of variance. Non-spherical data was corrected using the
260 Greenhouse-Geisser (epsilon < 0.75) or Huynh-Feldt (epsilon > 0.75) adjustment.
261 Where a significant effect was indicated for these variables, Holm-Bonferroni
262 stepwise correction was made for location of variance post-hoc, and these *P* values
263 are reported.
264

Total substrate oxidation, *i.e.* CHO_{tot}, CHO_{ing}, and fat oxidation in grams, was estimated for the second exercise bout in each trial through manually calculated area under the curve ($g.min^{-1}$ vs. time). These variables, and exercise capacity, were compared between-trials using paired t-tests or Wilcoxon-signed rank tests, dependent on normality. The magnitude of statistically significant effects in these variables was determined through within-subject Cohen's *d* effect sizes (ES) computed using a purpose-built spreadsheet (26). ES, presented ± 90 % confidence limit, was interpreted according to Cohen's criteria: 0.2-0.5, small; 0.5-0.8, moderate; >0.8, large (27). Where appropriate, percent changes are presented ± confidence limit, and post-hoc calculation of achieved power was made using the ES, sample size, and *P* value (G*Power 3.1, Universität Düsseldorf, DEU).

RESULTS

Exercise capacity

Exercise intensity was matched between-trials in bout one (69.4 ± 2.5 vs. 69.3 ± 2.4 $\%\dot{V}O_{2max}$ in GLU+MAL and FRU+MAL, respectively, $P = 0.91$) and two (69.6 ± 1.3 vs. 69.3 ± 1.9 $\%\dot{V}O_{2max}$ in GLU+MAL and FRU+MAL, respectively, $P = 0.64$). Bout one exercise capacity was not significantly different between-trials (131.3 ± 36.1 vs. 134.6 ± 34.6 min in GLU+MAL and FRU+MAL, respectively, $P = 0.38$). The within-subject SD for bout one exercise capacity was 6.4 ± 3.4 min, with a coefficient of variation of 5.5 ± 3.2 %. No order effect was observed ($P = 0.41$).

Second bout exercise capacity was significantly greater in the FRU+MAL trial (81.4 ± 22.3 vs. 61.4 ± 9.6 min, $P = 0.02$, Figure 1), a *large* magnitude effect (ES = 1.84 ± 1.12, 32.4 ± 19.9 %). This effect was observed in seven of the eight participants. Post-

hoc analysis revealed the study had 95% statistical power to reveal an enhanced exercise capacity based on the sample size used and effect size observed. No order effect was observed (P = 0.69).

INSERT FIGURE 1 ABOUT HERE

Substrate metabolism

CHO_{tot} oxidation rates were not significantly different between-trials during bout one (P = 0.96). CHO_{tot} oxidation rates at 15 min, 30 min and exhaustion in bout two were not significantly different between-trials (P = 0.171, Table 1), but were significantly reduced at exhaustion vs. 15 and 30 min (P < 0.005). The modelled CHO_{tot} oxidation rate in bout two of the trial with superior exercise capacity at the point of exhaustion in the trial with inferior exercise capacity was significantly greater than the CHO_{tot} oxidation rate at the point of exhaustion in the trial with inferior exercise capacity (2.74 ± 0.52 vs. 1.88 ± 0.52 $g.min^{-1}$, P = 0.002). This effect was consistent in all eight participants and was of *large* magnitude (ES = 1.46 ± 0.89, 58 ± 28 %). In the seven participants who had greater second bout exercise capacity with FRU+MAL, the modelled CHO_{tot} oxidation rate in the FRU+MAL trial at the point of exhaustion in the GLU+MAL trial was significantly greater than the CHO_{tot} oxidation rate at exhaustion in the GLU+MAL trial (2.71 ± 0.55 vs. 1.84 ± 0.55 $g.min^{-1}$, P = 0.03). This effect was consistent in all seven participants and was of *large* magnitude (ES = 1.36 ± 0.97, 60 ± 34 %). The absolute amount of CHO_{tot} oxidised during bout two was significantly greater with FRU+MAL, a *large* magnitude effect (Table 1).

CHO_{ing} oxidation rates were significantly greater after 15 and 30 min in the FRU+MAL vs. GLU+MAL trial ($P < 0.002$, Table 1). CHO_{ing} oxidation rate at exhaustion was significantly decreased vs. 15 and 30 min in both trials ($P < 0.005$). In the GLU+MAL trial, CHO_{ing} was also significantly lower at 30 vs. 15 min ($P = 0.002$). The absolute amount of CHO_{ing} oxidised during bout two was significantly greater with FRU+MAL, a *large* magnitude effect (Table 1).

INSERT TABLE 1 ABOUT HERE

Plasma variables

Due to clotting, blood data sets in bout two are available for six participants (bout one and recovery, N = 8). Plasma variables were not significantly different between-trials, with the exception of plasma glucose concentration at the point of exhaustion in bout two (6.3 ± 1.0 vs. 5.3 ± 0.7 $mmol.l^{-1}$, in GLU+MAL and FRU+MAL, respectively, $P = 0.003$), and plasma lactate concentrations after 60, 120, and 180 min of recovery (FRU+MAL > GLU+MAL, $P < 0.02$, see Figure, SDC1, plasma metabolite responses to the experimental protocols).

Perceptual responses

Bout two RPE was significantly lower with FRU+MAL vs. GLU+MAL after 30 min (13 ± 1 vs. 14 ± 2 AU, $P = 0.02$). Muscle soreness in bout two was not significantly different between-trials ($P = 0.31$), but was significantly elevated in bout two at exhaustion vs. all other time-points in both trials ($P < 0.05$).

Nausea, stomach fullness, and abdominal cramping were not significantly different between-trials during recovery ($P > 0.27$). Between-trial differences in nausea ($P = 0.04$) and stomach fullness ($P = 0.03$) during bout two were not significant at any time-point after post-hoc analysis ($P > 0.10$). Stomach fullness was significantly lower at each time-point vs. all previous time-points during bout two with FRU+MAL ($P = 0.05$, Figure 2).

INSERT FIGURE 2 ABOUT HERE

DISCUSSION

The aim of the present investigation was to determine if the previously observed metabolic advantages ascertained through co-ingestion of fructose-glucose carbohydrate sources during short-term recovery from prolonged exercise translate into a discernible effect on subsequent exercise capacity. The main finding was that short-term recovery of endurance exercise capacity was significantly augmented with co-ingestion of fructose and maltodextrin during recovery compared to isocaloric glucose and maltodextrin ingestion by 32.4 ± 19.9 %. Using a conversion described previously (28), it can be estimated that this equates to an ~5.9 % improvement in time-trial performance. This novel finding provides functional relevance to previous metabolic investigations demonstrating enhanced hepatic and equivalent effects on skeletal muscle glycogen storage during acute recovery from prolonged exhaustive exercise with such nutritional regimens (12–14,29–32).

In the present investigation, improved recovery of exercise capacity was observed with FRU+MAL in seven of eight participants. This contradicts a previous study adopting a similar experimental design (12). Casey *et al.* (12) had participants ingest a single 1 $g.kg^{-1}$ glucose or sucrose bolus at the start of a four-hour recovery period. This amounted to ~19 $g.h^{-1}$ of carbohydrate on average, compared to 90 $g.h^{-1}$ throughout recovery in the present investigation. The dosing provided by Casey *et al.* (12) was substantially lower than those demonstrating enhanced hepatic, with similar muscle, glycogen synthesis during short-term recovery from prolonged exercise with fructose-glucose carbohydrate sources (~69-116 $g.h^{-1}$) (13,14,31). Indeed, Casey and colleagues observed no significant differences in muscle or hepatic glycogen synthesis between the sucrose and glucose trials. Therefore, whilst no measure of

glycogen synthesis was made presently, it is possible that the failure to observe an effect on subsequent exercise capacity by Casey *et al.* (12) occurred due to the lower carbohydrate doses and similar metabolic recovery provided between-conditions. The use of exercise capacity protocols has been questioned regarding issues of reliability (33), but a strong coefficient of variation for bout one exercise capacity was observed presently, replicating recent work (20). The larger carbohydrate doses used in the present investigation may have facilitated a metabolic advantage with FRU+MAL, and this may be required to ascertain the observed *large* beneficial effect on subsequent exercise capacity.

In the present investigation, there is some indication second bout exercise capacity was limited by carbohydrate availability for oxidation, presumably in skeletal muscle, as the CHO_{tot} oxidation rate significantly declined at exhaustion in both trials. This reduction in carbohydrate oxidation rate is in line with some (5,15,34,35), but not all (36,16,37), previous investigations adopting similar repeated exercise capacity protocols. While speculative, carbohydrate oxidation rates during the second bout in the present study may have become unsustainable to fuel the exercise intensity. It is possible the enhanced second bout exercise capacity observed with FRU+MAL is attributable to an ability to maintain whole-body carbohydrate oxidation rates for longer prior to the reduction seemingly associated with fatigue. Accordingly, the absolute CHO_{tot} oxidised in bout two was significantly greater with FRU+MAL (Table 1), although this could be an artefact of the enhanced bout two exercise duration. The existence of this effect is supported by the modelled relationship between CHO_{tot} oxidation rate and time with FRU+MAL. That is, CHO_{tot} in FRU+MAL was estimated to be significantly greater at the point of exhaustion in

GLU+MAL in the seven participants who performed better in the FRU+MAL trial. This suggests the augmented bout two exercise capacity seen with FRU+MAL might be attributed to enhanced ability to sustain whole-body carbohydrate oxidation at the rate required to support the exercise intensity. In further support of a metabolic explanation for the observed effect is that the one participant who demonstrated reduced bout two exercise capacity with FRU+MAL exhibited poorer maintenance of carbohydrate oxidation rate in that trial.

As compared to GLU+MAL, greater CHO_{ing} oxidation rates were observed at 15 and 30 min with FRU+MAL, alongside similar declines at exhaustion. This supports to the suggestion that enhanced carbohydrate availability facilitated the greater second bout exercise capacity with FRU+MAL. Greater CHO_{ing} oxidation rates may reflect augmented hepatic, and similar muscle, glycogen synthesis with FRU+MAL, an effect observed previously with similar dosing regimens (13,14,31). Greater whole-body glycogen synthesis, derived from the ingested carbohydrate, may therefore facilitate greater carbohydrate availability for oxidation by working skeletal muscle during bout two. It must also be acknowledged that the source of the additional oxidised ingested carbohydrates cannot be discerned in the present investigation. That is, it is not possible to determine what proportion of the oxidised ingested carbohydrate was first stored in muscle, in liver, or oxidised directly after absorption. There is a wealth of literature describing the more rapid intestinal absorption and oxidation of glucose-fructose carbohydrate sources ingested during exercise compared to glucose alone (10), which could plausibly contribute to the observed effect on CHO_{ing} oxidation rates if participants began bout two with any unabsorbed carbohydrate residing in the gut. Furthermore, greater plasma lactate concentrations

were observed during the recovery period with FRU+MAL, a finding in line with previous investigations (14,30–32). This likely reflects augmented hepatic lactate production derived from ingested fructose (10). Lactate is a glycogenic precursor (10) and carbohydrate substrate that can be oxidised directly (38). The observed greater plasma lactate concentrations during recovery with FRU+MAL may therefore be derived from ingested fructose-derived hepatic lactate production, and provide substrate for whole-body glycogen synthesis or direct oxidation in the early stages of bout two, thereby supporting the greater CHO_{ing} oxidation rates with FRU+MAL. Further mechanistic work is required in order to establish the metabolic route by which carbohydrate ingested during recovery is oxidized during bout two.

Similar to previous investigations adopting similar repeated exercise capacity protocols (5,15,34–36,16,37), it does not appear that hypoglycaemia limited exercise in the present investigation, as evidenced by the absence of low plasma glucose concentrations at exhaustion in both trials (Suppl. Figure 1). However, there is now acknowledgement that differences in gut comfort can impact prolonged exercise performance (39). In the present investigation, no clear significant differences between-trials were observed for gut comfort during recovery, which is in contradiction to previous investigations reporting greater self-reported symptoms of gastrointestinal distress with glucose ingestion alone, although the severity of these symptoms was unclear, and a second bout of exercise was not performed (14,31). Any differences during bout two were of small numeric magnitude (Figure 2). The mean value for nausea in the GLU+MAL trial at exhaustion (3.1 ± 2.2 AU) reflects symptoms between “slight” and “moderate”. Interestingly, during bout two, stomach fullness progressively, and significantly, declined with FRU+MAL, but this was not

observed with GLU+MAL. Greater stomach fullness with MAL+GLU might be explained by accumulation of carbohydrate in the gut, given the more rapid intestinal absorption of fructose-glucose sources (40). Again, stomach fullness at exhaustion with GLU+MAL was less than "moderate" (3.8 ± 2.4 AU). However, whilst these values appear of small magnitude, it is not possible to discern the threshold nausea and stomach fullness values likely to impact exercise cessation, and so between-trial differences in gastrointestinal comfort cannot be dismissed as an explanation for the observed effect on exercise capacity.

In conclusion, the present investigation has for the first time demonstrated maltodextrin-fructose co-ingestion enhances short-term recovery of endurance exercise capacity. Secondly, accompanying data suggests some of the effect may be explained by increased carbohydrate availability, although a contribution from improved gastrointestinal comfort cannot be dismissed. If verified in future work, these results have implications for endurance athletes aiming to optimize performance in repeated bouts of prolonged exhaustive exercise with limited recovery duration.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest. The results of the present study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation, and do not constitute endorsement by the ACSM.

REFERENCES

1. Bergström J, Hermansen L, Hultman E, Saltin B. Diet, muscle glycogen and physical performance. Acta Physiol Scand. 1967;71(2):140–50.
2. Nilsson LH, Fürst P, Hultman E. Carbohydrate metabolism of the liver in normal man under varying dietary conditions. Scand J Clin Lab Invest. 1973;32(4):331–7.
3. Romijn JA, Gastadelli A, Horowitz JF, Endert E, Wolfe RR. Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. Am J Physiol - Endocrinol Metab. 1993;265(3):380–91.
4. Ørtenblad N, Westerblad H, Nielsen J. Muscle glycogen stores and fatigue. J Physiol. 2013;591(18):4405–13.
5. Alghannam AF, Jedrzejewski D, Tweddle MG, et al. Impact of muscle glycogen availability on the capacity for repeated exercise in man. Med Sci Sports Exerc. 2016;48(1):123–31.
6. Burke LM, Hawley JA, Wong SHS, Jeukendrup AE. Carbohydrates for training and competition. J Sports Sci. 2011;29(Suppl. 1):S17-27.
7. van Loon LJC, Saris WHM, Krujishoop M, Wagenmakers AJM. Maximizing postexercise muscle glycogen synthesis: Carbohydrate supplementation and the application of amino acid or protein hydrolysate mixtures. Am J Clin Nutr. 2000;72(1):106–11.
8. Richter EA, Garetto LP, Goodman MN, Ruderman NB. Enhanced muscle glucose metabolism after exercise: modulation by local factors. Am J Physiol -

Endocrinol Metab. 1984;246(6):E476–82.

9. Gonzalez JT, Fuchs CJ, Betts JA, van Loon LJC. Liver glycogen metabolism during and after prolonged endurance-type exercise. Am J Physiol - Endocrinol Metab. 2016;311(3):E543–53.

10. Gonzalez JT, Fuchs CJ, Betts JA, van Loon LJC. Glucose plus fructose ingestion for post-exercise recovery: Greater than the sum of its parts? Nutrients. 2017;9(4):344.

11. Nilsson LH, Hultman E. Liver and muscle glycogen in man after glucose and fructose infusion. Scand J Clin Lab Invest. 1974;33(1):5–10.

12. Casey A, Mann R, Banister K, et al. Effect of carbohydrate ingestion on glycogen resynthesis in human liver and skeletal muscle, measured by 13C MRS. Am J Physiol - Endocrinol Metab. 2000;278(1):E65–75.

13. Décombaz J, Jentjens RLPG, Ith M, et al. Fructose and galactose enhance postexercise human liver glycogen synthesis. Med Sci Sports Exerc. 2011;43(10):1964–71.

14. Fuchs CJ, Gonzalez JT, Beelen M, et al. Sucrose ingestion after exhaustive exercise accelerates liver, but not muscle glycogen repletion when compared to glucose ingestion in trained athletes. J Appl Physiol. 2016;120(11):1328–34.

15. Wong SH, Chen VJ, Fung WM, Morris JG. Effect of glycemic index meals on recovery and subsequent endurance capacity. Int J Sports Med. 2009;30(12):898–905.

16. Betts JA, Stevenson EJ, Williams C, Sheppard C, Grey E, Griffin J. Recovery of endurance running capacity: Effect of carbohydrate-protein mixtures. Int J Sport Nutr Exerc Metab. 2005;15(6):590–609.

17. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the

energetic cost of outdoor running. J Sports Sci. 1996;14(4):321–7.

18. Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med. 1970;2(2):92–8.

19. Inbar O, Oren A, Scheinowitz M, Rotstein A, Dlin R, Casaburi R. Normal cardiopulmonary responses during incremental exercise in 20- to 70-yr-old men. Med Sci Sports Exerc. 1994;26(5):538–46.

20. Alghannam AF, Jedrzejewski D, Tweddle M, Gribble H, Bilzon JLJ, Betts JA. Reliability of time to exhaustion treadmill running as a measure of human endurance capacity. Int J Sports Med. 2016;37(3):219–23.

21. Thorburn MS, Vistisen B, Thorp RM, et al. Attenuated gastric distress but no benefit to performance with adaptation to octanoate-rich esterified oils in well-trained male cyclists. J Appl Physiol. 2006;101(6):1733–43.

22. Ihsan M, Tan F, Sahrom S, Choo HC, Chia M, Aziz AR. Pre-game perceived wellness highly associates with match running performances during an international field hockey tournament. Eur J Sport Sci. 2017;17(5):593–602.

23. Frayn KN. Calculation of substrate oxidation rates in vivo from gaseous exchange. J Appl Physiol. 1983;55(2):628–34.

24. Craig H. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide. Geochim Cosmochim Acta. 1957;12(1–2):133–49.

25. Leese GP, Nicol AE, Varnier M, Thompson J, Scrimgeour CM, Rennie MJ. Kinetics of 13CO2 elimination after ingestion of 13C bicarbonate: the effects of exercise and acid base balance. Eur J Clin Invest. 1994;24(12):818–23.

26. Hopkins WG. Spreadsheets for analysis of controlled trials with adjustment for a predictor. Sportscience. 2006;10:46–50.

27. Cohen J. Statistical power for the behavioural sciences. Oxford, UK: Routledge; 1977. 1-17 p.
28. Vandenbogaerde TJ, Hopkins WG. Effects of acute carbohydrate supplementation on endurance performance: A meta-analysis. Sport Med. 2011;41(9):773–92.
29. Blom PCS, Høstmark AT, Vaage O, Kardel KR, Maehlum S. Effect of different post-exercise sugar diets on the rate of muscle glycogen synthesis. Med Sci Sports Exerc. 1987;19(5):491–6.
30. Bowtell JL, Gelly K, Jackman ML, Patel A, Simeoni M, Rennie MJ. Effect of different carbohydrate drinks on whole body carbohydrate storage after exhaustive exercise. J Appl Physiol. 2000;88(5):1529–36.
31. Trommelen J, Beelen M, Pinckaers PJM, Senden JM, Cermak NM, Van Loon LJC. Fructose coingestion does not accelerate postexercise muscle glycogen repletion. Med Sci Sports Exerc. 2016;48(5):907–12.
32. Wallis GA, Hulston CJ, Mann CH, Roper HP, Tipton KD, Jeukendrup AE. Postexercise muscle glycogen synthesis with combined glucose and fructose ingestion. Med Sci Sports Exerc. 2008;40(10):1789–94.
33. Currell K, Jeukendrup AE. Validity, reliability and sensitivity of measures of sporting performance. Sport Med. 2008;38(4):297–316.
34. Wong SH, Williams C. Influence of different amounts of carbohydrate on endurance running capacity following short term recovery. Int J Sports Med. 2000;21(6):444–52.
35. Wong SH, Williams C, Adams N. Effects of ingesting a large volume of carbohydrate-electrolyte solution on rehydration during recovery and subsequent exercise capacity. Int J Sport Nutr Exerc Metab. 2000;10(4):375–

93.

36. Alghannam AF, Jedrzejewski D, Bilzon JLJ, Thompson D, Tsintzas K, Betts JA. Influence of post-exercise carbohydrate-protein ingestion on muscle glycogen metabolism in recovery and subsequent running exercise. Int J Sport Nutr Exerc Metab. 2016;26(5):572–80.

37. Siu PM, Wong SHS, Morris JG, Lam CW, Chung PK, Chung S. Effect of frequency of carbohydrate feedings on recovery and subsequent endurance run. Med Sci Sports Exerc. 2004;36(2):315–23.

38. Lecoultre V, Benoit R, Carrel G, et al. Fructose and glucose co-ingestion during prolonged exercise increases lactate and glucose fluxes and oxidation compared with an equimolar intake of glucose. Am J Clin Nutr. 2010;92(5):1071–9.

39. Rowlands DS, Houltham S, Musa-Veloso K, Brown F, Paulionis L, Bailey D. Fructose–glucose composite carbohydrates and endurance performance: Critical review and future perspectives. Sport Med. 2015;45(11):1561–76.

40. Shi X, Summers RM, Schedl HP, Flanagan SW, Chang R, Gisolfi CV. Effects of carbohydrate type and concentration and solution osmolality on water absorption. Med Sci Sports Exerc. 1995;27(12):1607–15.

FIGURE HEADINGS

Fig. 1. Mean responses for second bout exercise capacity (min) in the GLU+MAL and FRU+MAL trials (N = 8). ***** denotes *P* = 0.02 between-trials.

Fig. 2. Self-reported (a) nausea, (b) stomach fullness, and (c) abdominal cramping (1-10, AU) during recovery and bout two of the GLU+MAL and FRU+MAL trials (N = 8).

Suppl. Fig. 1. Plasma concentrations of (a) glucose, (b) NEFA, and (c) lactate ($mmol.l^{-1}$) throughout bout one (N = 8), recovery (N = 8), and bout two (N = 6) of the GLU+MAL and FRU+MAL trials. "PreEx1" refers to samples obtained immediately prior to bout one, "Ex1-30" refers to samples obtained after 30 min of bout one, "Ex1-ex" refers to samples obtained at exhaustion of bout one, "Rec-60" refers to samples obtained after 60 min of recovery, *etc*., ***** denotes $P < 0.05$ between-trials, ♯ denotes $P < 0.01$ between-trials.