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ORIGINAL ARTICLE

Carbohydrate hydrogel beverage provides no additional cycling performance benefit versus carbohydrate alone

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Abstract

Purpose This study examined the effects of a novel maltodextrin-fructose hydrogel supplement (MF-H) on cycling performance and gastrointestinal distress symptoms.

Methods Nine endurance-trained male cyclists (age = 26.1 ± 6.6, mass = 80.9 ± 10.4 kg, VO_{2max} = 55.5 ± 3.6 mL·kg·min^{-1}) completed three experimental trials consisting of a 98-min varied-intensity cycling protocol followed by a performance test of ten consecutive sprint intervals. In a cross-over design, subjects consumed 250 mL of a treatment beverage every 15 min of cycling. Treatments consisted of 78 g·hr^{-1} of either (a) MF-H, (b) isocaloric maltodextrin-fructose (ratio-matched 2:1; MF), and (c) isocaloric maltodextrin only (MD).

Results There were no differences in average sprint power between treatments (MF-H, 284 ± 51 W; MF, 281 ± 46 W; and MD, 277 ± 48 W), or power output for any individual sprint. Subjective ratings of gastrointestinal distress symptoms (nausea, fullness, and abdominal cramping) increased significantly over time during the cycling trials, but few individuals exceeded moderate levels in any trial with no systematic differences in gastrointestinal discomfort symptoms observed between treatments.

Conclusions In conclusion, ingestion of a maltodextrin/fructose hydrogel beverage during high-intensity cycling does not improve gastrointestinal comfort or performance compared to MF or MD beverages.

Keywords Multiple transportable carbohydrates · Gastrointestinal distress · Maltodextrin · Fructose · Ergogenic aids · Supplements

Abbreviations

CHO	Carbohydrate
ES	Effect size
GI	Gastrointestinal
HR	Heart rate
MD	Maltodextrin
MF	Maltodextrin and fructose
MF-H	Maltodextrin and fructose hydrogel
MTC	Multiple transportable carbohydrates
VO_2	Oxygen uptake
VO_{2max}	Maximal oxygen consumption
W	Watts
W_{max}	Maximal wattage attained during graded exercise test

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Introduction

Carbohydrate (CHO) ingestion during endurance exercise has been consistently reported to enhance performance (Cermak and Van Loon 2013; Stellingwerff and Cox 2014) likely due to a combination of mechanisms including maintenance of plasma glucose and CHO oxidation rates, sparing of liver/muscle glycogen, and centrally-mediated stimulation of motor output (Karelis et al. 2010). Although not universally supported (Baur et al. 2014; Newell et al. 2015), ergogenic effects of CHO seem to be dose-responsive at ingestion rates up to 1.0 g·min^{-1} with glucose and up to 1.3 g·min^{-1} with mixed CHO solutions containing glucose/

fructose/maltodextrin (Smith et al. 2010, 2013). Based on this evidence, it is currently recommended that endurance athletes consume CHO during training and competition at high rates (1–1.5 g·min^{-1}) (Thomas et al. 2016).

Although these high rates benefit performance, they also may potentiate gastrointestinal (GI) distress (Rehrer et al. 1992; Peters et al. 1993; de Oliveira and Burini 2014). Indeed, Pfeiffer et al. (2011) reported a positive correlation between CHO intake and race performance among competitive triathletes, runners, and cyclists. However, CHO intake was also associated with symptoms of GI distress. This finding is supported by other field and laboratory studies reporting GI distress with consumption of large doses of CHO (Triplett et al. 2010; Rowlands et al. 2012; O'Brien et al. 2013). CHO-induced GI distress is likely due to malabsorption and gastric distension caused by a duodenal receptor inhibition of gastric emptying in response to high CHO concentration and osmolality (de Oliveira et al. 2014). Importantly, GI distress is associated with impaired performance (Thorburn et al. 2006; Pfeiffer et al. 2009; Rowlands et al. 2012; O'Brien et al. 2013; Baur et al. 2016). As such, the potential reward of consuming CHO during exercise must be weighed against the risk of GI distress. Moreover, a competitive advantage may be drawn from an athlete's ability to tolerate large quantities of CHO.

Recently, a supplement was developed with the aim of enhancing GI tolerance to high doses of CHO during exercise. In addition to CHO, this product contains alginate, a naturally-occurring polymer utilized in drug delivery and wound healing that can be modified through various processes to form watery gels (i.e. hydrogels) that encapsulate substrates at desired pH levels (Lee and Mooney 2012). This product purportedly forms a hydrogel at pH levels found in the stomach, resulting in the encapsulation of ingested CHO and effectively blocking stimulation of duodenal receptors that inhibit gastric emptying (Sutehall et al. 2018). Recent evidence appears to confirm that this supplement enhances gastric emptying at rest relative to CHO-matched beverages of similar and higher osmolalities (Sutehall et al. 2019). However, this potential benefit does not seem to translate to ergogenic effects during exercise. McCubbin et al. (2019) recently reported no differences in substrate oxidation, GI comfort, or performance between a hydrogel supplement and energy/CHO-matched control (90 g h^{-1}) during ~ 3.25 h running (3 h at 60% VO_{2max} followed by an incremental performance test to exhaustion). While this finding is somewhat surprising, it is possible that the chosen methodology in this study prevented detection of small, but meaningful effects. Indeed, CHO-induced GI distress is typically reported during exercise that elicits higher intensities (i.e. > 60% VO_{2max}; time trials, intermittent exercise, etc.) (Rowlands et al. 2012; O'Brien et al. 2013; Baur et al. 2016). Additionally, the chosen fluid intake rate in this study (~500 mL·h^{-1}), while externally valid to the population (i.e. runners) (Pfeiffer et al. 2011), may have been insufficient to cause significant malabsorption/GI distress. As such, ergogenic effects may be more apparent in trained cyclists who typically consume CHO and fluid at higher rates than runners and often experience higher exercise intensities (i.e. continuously or intermittently) relative to this study (Pfeiffer et al. 2011).

Therefore, the purpose of this study was to investigate the effects of consuming a CHO hydrogel supplement on metabolism, GI comfort, and cycling performance in an externally valid intermittent exercise protocol.

Methods

Study design and ethical approval

This was a multi-site, randomized, counterbalanced, double-blinded, and crossover study examining the impact of CHO hydrogel ingestion on GI comfort and cycling performance. Data collection occurred in human performance laboratories at Elon University, Virginia Military Institute, and James Madison University. All sites utilized identical equipment and procedures. The study consisted of four total laboratory visits including 1 visit for baseline testing to determine VO_{2max} and highest wattage achieved (W_{max}) followed by a familiarization trial and 3 separate visits for the experimental trials. Each experimental trial was separated by 5–10 days. Prior to giving their oral and written informed consent, all subjects received information regarding the requirements of the study and potential risks. All procedures were approved by the institutional review boards of the participating institutions and were in accordance with the Declaration of Helsinki.

Subjects

Eleven trained male cyclists ($VO_{2max} \geq 50$ mL·kg^{-1}·min) from Elon University, Virginia Military Institute, and James Madison University and surrounding communities enrolled in this study. Nine of the eleven subjects completed the study [age = 26.1 ± 6.6, mass = 80.9 ± 10.4 kg, VO_{2max} = 55.5 ± 3.6 mL·kg·min^{-1}, and peak power (W_{max}) = 356 ± 39 W, years competing = 4.8 ± 3.2], as one withdrew due to an injury unrelated to the study, and another failed to complete an experimental trial. Subjects were recruited from the student body and local populations of the institutions involved via word-of-mouth and flyers posted on social media and university bulletin boards.

Control procedures

Subjects were asked to maintain consistent dietary and training habits throughout the duration of the study. For the day prior to experimental trials, subjects were asked to refrain from exercise and replicate dietary intake across trials. Before the experimental trials, subjects were asked to fast overnight prior to consuming a standardized breakfast, which consisted of a commercially available energy bar (Clif Bar and Company, Emeryville, CA; energy content = 250 kcals, CHO = 45 g, fat = 5 g; protein = 9 g, dietary fiber = 4 g, sodium = 140 mg; potassium = 210 mg) and 300 mL of water. Subjects were required to consume their breakfast 2 h prior to the commencement of experimental trials. Finally, subjects were asked to abstain from alcohol and caffeine prior to experimental trials for 48 h and 24 h, respectively. Compliance with pre-trial controls was confirmed via 72-h and 24-h exercise and diet logs, respectively.

Baseline testing and familiarization

The initial laboratory visit consisted of anthropometric assessment, a graded exercise test to determine VO_{2max} and W_{max}, and a familiarization trial of the experimental exercise protocol. All exercise testing was completed on a cycle ergometer (Velotron, SRAM Corporation, Chicago, IL) adjusted for subject comfort. For the graded exercise test, subjects commenced cycling at a power output corresponding to 3 $W \cdot kg^{-1}$, and the wattage was increased 25 W every 2.5 min until volitional exhaustion. Throughout the test, gas exchange was measured via indirect calorimetry (TrueOne 2400, Parvo Medics, Inc., Sandy, UT, USA), and VO_{2max} was defined as the highest 15-sec average oxygen consumption. W_{max} was defined as the power output in the final completed stage plus the fraction of the last attempted stage. Familiarization immediately followed the graded exercise test and consisted of a shortened version (i.e. 30 min shorter preload portion, identical performance test) of the experimental exercise protocol (described below).

Experimental beverages

This study compared three experimental beverages: (1) a commercially available hydrogel supplement (MF-H; Maurten 160 Mix, Maurten AB, Gothenburg, Sweden), (2) an isocaloric solution containing maltodextrin (MF; Star-Dri 100; Tate and Lyle, Decatur, IL) and fructose (Krystar 300; Tate and Lyle, Decatur, IL), and 3) an isocaloric solution containing only maltodextrin (MD; Star-Dri 100). All solutions were matched for CHO concentration (7.8%) and ingested at a rate of 1 $L \cdot h^{-1}$ (250 mL doses) resulting in a CHO ingestion rate of 78 $g \cdot h^{-1}$ and a total fluid intake of 3 L per trial. MF-H and MF contained maltodextrin and fructose at a 2:1 ratio (52:26 $g \cdot h^{-1}$). All beverages were matched for sodium chloride (0.8 $g \cdot h^{-1}$).

Experimental trials

Experimental procedures were modified from methods described previously (Baur et al. 2016). Subjects arrived to the laboratory in the morning 2 h following consumption of the standardized breakfast. Subjects were weighed in cycling shorts and then fitted with a heart rate monitor (Polar FTM4, Polar, Inc., Kempele, Finland). Immediately prior to exercise, following 5 min of seated rest, an initial fingerprick blood draw was done to assess blood glucose and lactate concentration (YSI 2300 Stat Plus, YSI, Inc., Yellow Springs, OH). During exercise, blood glucose/lactate, gas exchange, perceptual responses, and heart rate were measured.

The exercise protocol and timing of beverage consumption/measurements are presented in Fig. 1. Exercise consisted of the following: (1) a 5-min warmup at 30% W_{max}, (2) 55 min at 50% W_{max}, (3) two sets of 4 × 2-min intervals at 80% W_{max} with intervals and sets separated by 2 min and 5 min at 50% W_{max}, respectively, (4) 5 min at 50% W_{max}, and (5) 10 maximal sprints of 2–3 min each with 5–6 min of active recovery between each. Sprint duration was based on the time required for subjects to complete a fixed amount of work (kcals = 0.125 × W_{max}) as fast as possible, and recovery duration was the time required to complete the same amount of work at 40% W_{max}.

Heart rate was measured every 15 min during the pre-load and at the approximate mid-point of every sprint and during the final min of recovery periods.

All testing was completed in thermoneutral conditions (21.9 ± 1.3 °C, 40.1 ± 4.9% humidity) with uniform cooling provided by a pedestal fan on the medium setting. Subjects received no verbal encouragement during the performance

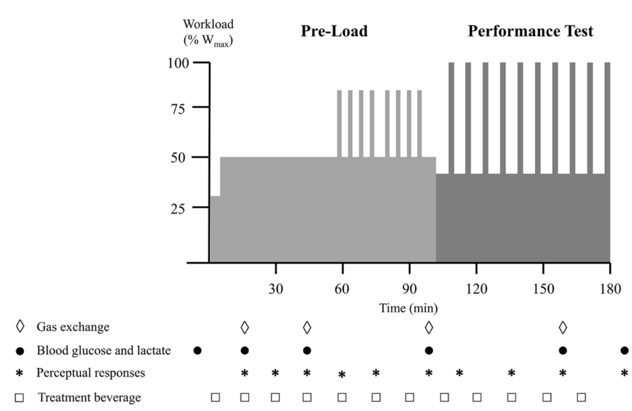

Fig. 1 Timeline of experimental protocol, physiological, and perceptual measurements

test and were only permitted to see work (kcal) completed in each sprint and wattage during recovery segments.

Perceptual response assessment

To assess GI symptoms (nausea, fullness, and abdominal cramping) and perceived exertion (effort of cycling, tiredness, and leg strength), 100-mm Likert scales were administered during exercise, as previously described (Baur et al. 2016). Subjects rated symptom intensity and exertion by placing a horizontal line on the appropriate scale relative to specific descriptors including: nothing at all, extremely weak, very weak, weak or mild, moderate, strong, very strong, extremely strong, and absolute maximum. Line height (mm) was utilized in subsequent analysis.

Calculations

Total carbohydrate and fat oxidation rates during exercise were calculated via application of stoichiochemical equations to gas exchange results (Jeukendrup and Wallis 2005).

Statistical analysis

Mean values and standard deviations (SD) were calculated and reported for all dependent measures. All variables were assessed for normality via Shapiro–Wilk test, and non-normal variables were log transformed prior to analyses. Performance responses were assessed via one-way repeated measures ANOVA for mean power output. Additionally, two-way (treatment × time) repeated measures ANOVA with Greenhouse–Geisser correction for sphericity violations was used to determine differences at specific time points or periods (e.g. late exercise sprint power). Perceptual and physiological variables were also assessed via two-way repeated measures ANOVA. Post hoc Fisher's least square differences tests were run in the case of significant interactions or when visual inspection revealed likely trends. Worth noting, the analysis of VAS scale data via distribution-based methods (e.g. Two-Way RMANOVA) has been criticized by some (Wewers and Lowe 1990), particularly in studies with small sample sizes. However, it is generally accepted that these methods provide sufficient statistical validity when data is normally distributed as was the case in this study (Heller et al. 2016). Moreover, parametric analysis of VAS data is common in the sport nutrition literature (Rowlands et al. 2012; O'Brien et al. 2013; Wilson and Ingraham 2015). Statistical significance was accepted as $p < 0.05$.

For all variables, effect sizes (ES) and 95% confidence intervals were calculated to describe the magnitude of differences. For physiological and perceptual responses, ES was determined by standardizing mean differences to the pooled SD for each condition at the time point under evaluation. For performance, ES was determined by standardizing mean differences to the pooled SD for mean sprint power across all treatments. ES values were qualified as follows: trivial, 0.0–0.2; small, 0.2–0.6; moderate, 0.6–1.2; large, 1.2–2.0; very large, 2.0–4.0; and extremely large, > 4.0. Statistical analyses were performed using Statistical Package for the Social Sciences (SPSS).

Results

Performance

Performance results are presented in Fig. 2. Average power output over the 10 sprint intervals was not different between MF (281 ± 46 W), MF-H (284 ± 51 W) and MD (277 ± 48 W). In addition, average power output during recovery periods between sprints was the same between MF (140 ± 13 W), MF-H (139 ± 14 W), and MD (139 ± 13 W). There were also no between-treatment differences in power output for any individual sprint. There was a visual trend

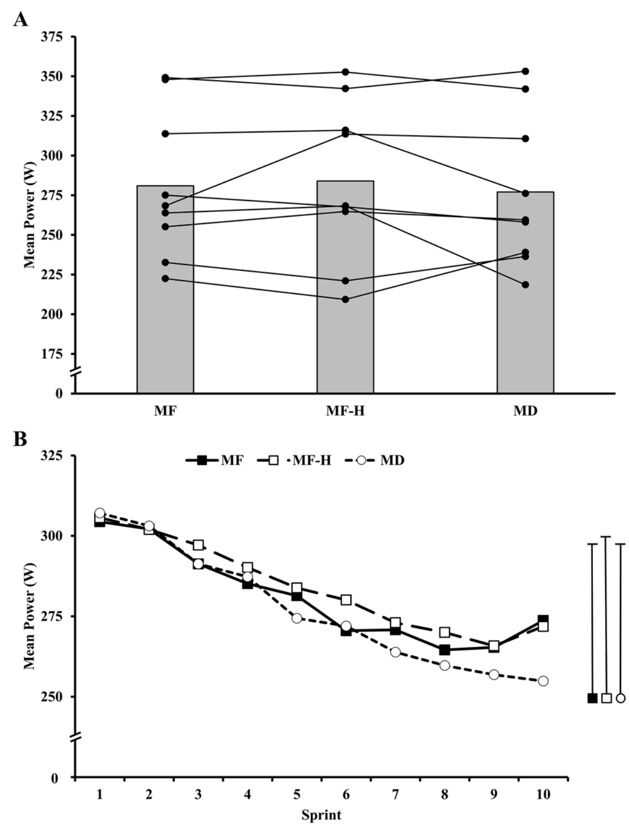

Fig. 2 Effect of carbohydrate beverages on cycling performance. **a** Bars represent mean power output across all sprints, lines represent individualized responses; **b** mean power for each sprint of the performance test, bars represent mean standard deviation for all sprints. *MF* (maltodextrin + fructose) 1.3 g·min^{-1}, *MF-H* (maltodextrin + fructose hydrogel) 1.3 g·min^{-1}, *MD* (maltodextrin only) 1.3 g·min^{-1}

suggesting a tendency for power output to be lower in the MD trial during the latter stages of the sprint trial (i.e. sprints 7–10). Post hoc analysis comparing mean sprint power for sprints 7–10 across treatments revealed small, but non-significant, reductions in performance with MD vs. MF (3.9 ± 9.0%; ES = 0.21; $p = 0.657$) and MF-H (4.2 ± 8.6%; ES = 0.22; $p = 0.607$).

Physiological responses

Physiological responses during the cycling trials (VO_2, CHO oxidation, fat oxidation, heart rate, blood glucose, and blood lactate) are displayed in Table 1 and Fig. 3. There were significant main time effects for VO_2 ($p < 0.001$), heart rate (p < 0.001), blood glucose ($p = 0.01$), and blood lactate ($p = 0.049$). However, there were no treatment × time interactions for any physiological variable. Though not statistically significant, following sprint 7, blood glucose was slightly lower (small ES) with MD vs. MF (5.6 ± 5.4 mg·dL^{-1}; ES = 0.36; $p = 0.43$) and MFH (7.1 ± 9.3 mg·dL^{-1}; ES = 0.45; $p = 0.32$). Data for lactate and glucose are reported for only eight subjects due to instrumentation errors during the exercise trials of one subject.

Perceptual responses

Subjective rating scores for effort, tiredness, and leg strength during cycling are displayed in Table 2. Effort and tiredness generally increased over time ($p < 0.01$). Ratings were generally ≤ 50 mm (less than a "moderate" rating) during the pre-load trials and ≥ 67 mm ("strong" to "very strong") during sprinting in all trials. There were no significant treatment*time interactions for effort or tiredness. Similarly, perceived leg strength declined over time ($p < 0.001$), with no significant treatment*time effects. Perceived leg strength was ≥ 67 mm ("strong" or greater) during the pre-load portion, and ≤ 50 mm ("moderate" to "weak or mild") during the performance trial.

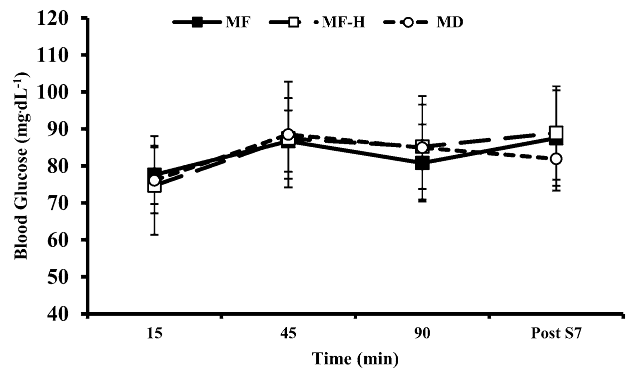

Fig. 3 Effect of carbohydrate beverages on blood glucose concentrations. *MF* (maltodextrin + fructose) 1.3 g·min^{-1}, *MF-H* (maltodextrin + fructose hydrogel) 1.3 g·min^{-1}, *MD* (maltodextrin only) 1.3 g·min^{-1}, *Post S7* post sprint 7 of the performance test. Data is presented as mean ± SD

Table 1 Physiological responses during the cycling protocol

Variable	Treatment	15 min	45 min	90 min	Sprint 7
VO_2 (mL·min^{-1})	MF	2476 ± 225	2486 ± 204	2725 ± 213	2325 ± 262
	MF-H	2528 ± 191	2622 ± 204	2740 ± 226	2302 ± 281
	MD	2392 ± 232	2457 ± 248	2677 ± 270	2269 ± 158
CHO oxidation (g·min^{-1})	MF	1.42 ± 1.22	1.47 ± 1.29	1.53 ± 1.37	1.28 ± 1.18
	MF-H	1.47 ± 1.12	1.49 ± 1.27	1.50 ± 1.26	1.51 ± 1.38
	MD	1.34 ± 1.15	1.13 ± 1.13	1.40 ± 1.21	1.22 ± 1..06
Fat oxidation (g·min^{-1})	MF	0.22 ± 0.27	0.20 ± 0.28	0.19 ± 0.27	0.23 ± 0.28
	MF-H	0.21 ± 0.22	0.24 ± 0.29	0.25 ± 0.26	0.18 ± 0.24
	MD	0.21 ± 0.27	0.33 ± 0.39	0.26 ± 0.29	0.24 ± 0.26
Heart rate (bpm)	MF	131 ± 8	132 ± 6	145 ± 11	166 ± 7
	MF-H	132 ± 10	134 ± 11	145 ± 11	166 ± 6
	MD	131 ± 10	133 ± 9	145 ± 13	167 ± 8
Glucose (mg·dL^{-1})	MF	77.6 ± 7.9	86.7 ± 8.3	80.8 ± 10.4	87.5 ± 12.9
	MF-H	74.7 ± 13.3	87.4 ± 10.9	85.2 ± 11.4	88.9 ± 12.6
	MD	76.1 ± 8.9	88.5 ± 14.3	84.9 ± 14.0	81.9 ± 8.6
Lactate (mmol·L^{-1})	MF	0.97 ± 0.39	0.91 ± 0.37	2.76 ± 2.52	3.36 ± 3.14
	MF-H	0.98 ± 0.39	1.02 ± 0.31	3.01 ± 2.30	3.26 ± 2.44
	MD	1.04 ± 0.38	1.78 ± 2.85	2.84 ± 2.06	3.42 ± 2.55

Data are displayed as mean ± SD

MF (maltodextrin + fructose) 1.3 g·min^{-1}, *MF-H* (maltodextrin + fructose hydrogel) 1.3 g·min^{-1}, *MD* (maltodextrin only) 1.3 g·min^{-1}

Table 2 Subjective ratings of effort, tiredness, and leg strength during cycling

Variable	Treatment	15-min	45-min	90-min	Sprint-7
Effort of cycling (0–100 mm)	MF	29.9 ± 21.9	34.2 ± 19.2	53.7 ± 17.2	75.1 ± 14.6
	MF-H	26.5 ± 13.9	34.9 ± 16.9	52.3 ± 15.3	72.2 ± 15.2
	MD	20.3 ± 15.3	29.8 ± 16.3	46.3 ± 11.6	75.6 ± 13.1
Tiredness (0–100 mm)	MF	19.3 ± 14.4	29.8 ± 16.2	51.5 ± 18.7	72.6 ± 11.5
	MF-H	14.9 ± 9.4	27.4 ± 15.4	49.4 ± 14.6	70.4 ± 9.7
	MD	16.5 ± 13.8	27.5 ± 13.7	46.9 ± 12.5	70.6 ± 14.3
Leg strength (0–100 mm)	MF	79.4 ± 11.1	74.3 ± 10.5	58.1 ± 15.4	35.9 ± 14.8
	MF-H	81.4 ± 9.4	75.1 ± 8.2	60.8 ± 11.3	43.3 ± 12.3
	MD	83.2 ± 10.5	77.1 ± 7.6	58.6 ± 6.6	36.4 ± 9.9

Data are represented as mean ± SD

MF (maltodextrin + fructose) 1.3 g·min^{-1}, *MF-H* (maltodextrin + fructose hydrogel) 1.3 g·min^{-1}, *MD* (maltodextrin-only) 1.3 g·min^{-1}

GI symptoms (nausea, fullness, and abdominal cramping) are shown in Fig. 4. In general, GI symptoms increased over time ($p < 0.05$ for all symptoms). Symptoms increased from "extremely weak" (≤ 10 mm) at the onset of exercise to "weak or mild" (≤ 30 mm) by the end of the pre-load trials. Despite further increases in symptoms during the sprint intervals, average values did not surpass "moderate" ratings of discomfort.

No significant treatment × time interactions were observed for any GI symptoms. However, there was a tendency, albeit non-significant, for small increases in average fullness with MF-H vs. MD (7.0 ± 9.2 units; ES = 0.54; $p = 0.21$) and MF (4.5 ± 8.9 units; ES = 0.35; $p = 0.42$) throughout the trial. There was also small, but non-significant, decreases in nausea following sprint four with MF vs. MF-H (14.3 ± 18.6 units; ES = 0.53; $p = 0.23$) and MD (9.6 ± 20.5 units; ES = 0.35; $p = 0.42$).

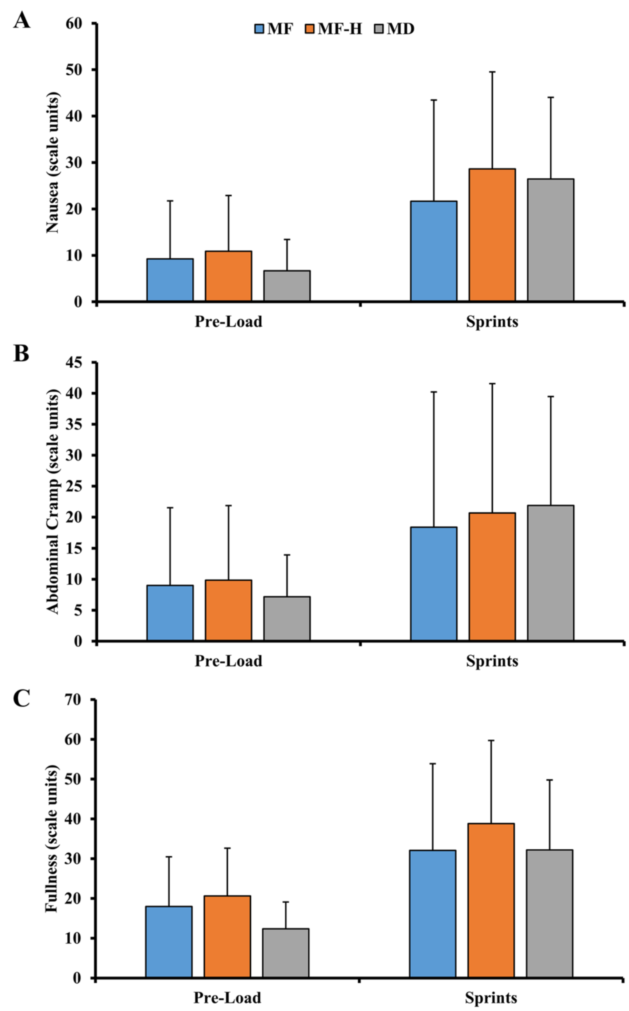

Fig. 4 Effect of carbohydrate beverages on gastrointestinal comfort during pre-load and performance test. **a** Ratings for nausea; **b** ratings for abdominal cramp; **c** ratings for fullness. *MF* (maltodextrin + fructose) 1.3 g·min^{-1}, *MF-H* (maltodextrin + fructose hydrogel) 1.3 g·min^{-1}, *MD* (maltodextrin only) 1.3 g·min^{-1}. Data is presented as means ± SD

Discussion

The goal of this study was to determine the effects of a carbohydrate hydrogel beverage on metabolism, GI comfort, and cycling performance. To our knowledge, this is the first study to examine the effects of this supplement in this population. The primary finding of this study was that MF-H consumption did not enhance performance or GI comfort relative to isocaloric MF or MD. Additionally, MF did not provide any ergogenic effects versus MD.

MF-H and MF consumption did not result in enhanced average sprint performance relative to MD. This observation contrasts a number of prior studies that have reported enhanced performance with consumption of multiple transportable carbohydrates (maltodextrin/glucose + fructose; MTC) at a variety of ingestion rates (1.2–2.4 g·min^{-1}) relative to isocaloric doses of maltodextrin or glucose alone (see review: Rowlands et al. 2015). While this finding was unexpected, prior research indicates that the ergogenic effects of MTC are quite variable (0.5–14.6%) and seem to be highly dependent upon the composition of the beverages used for comparison. Some studies have reported substantial improvements in average time trial power (~ 8–15%) with MTC relative to isocaloric maltodextrin/glucose (Currell and Jeukendrup 2008; Triplett et al. 2010; Roberts et al. 2014). However, these studies utilized high CHO ingestion rates (1.7–2.4 g·min^{-1}) that necessitated ingestion of comparison beverages that contained maltodextrin/glucose in amounts far exceeding maximal exogenous maltodextrin/glucose oxidation capacity (1.0–1.2 g·min^{-1}) (Jeukendrup 2004). Ingesting maltodextrin/glucose at these rates has been associated with GI distress and increased reliance on endogenous CHO stores (e.g. muscle glycogen), both of which are associated with impaired performance (Triplett et al. 2010; Rowlands et al. 2012; Roberts et al. 2014; Wilson and Ingraham 2015; King et al. 2019). Thus, these comparison beverages may have had ergolytic effects, which exaggerated performance benefits when compared to MTC. Conversely, studies utilizing moderate CHO intake rates (1.30–1.55 g·min^{-1}) that more closely approximate maximal maltodextrin/glucose oxidation capacity, have reported more modest benefits (0.5–3.0%) among cyclists, triathletes, and runners in laboratory and field studies (Rowlands et al. 2012; Baur et al. 2014; Wilson and Ingraham 2015; Rowlands and Houltham 2017). Only one study has compared an MTC beverage (~1.0 g·min^{-1} glucose + ~0.5 g·min^{-1} fructose) to a beverage containing glucose (~1.0 g·min^{-1}) at rates currently recommended (Thomas et al. 2016) and within maximal oxidation capacity limits for maltodextrin/glucose (1.0–1.2 g·min^{-1}) (Baur et al. 2014). This study found that average power in a 30-km time trial following a 2-h preload (55% W_{max}) was similar between MTC and glucose. This outcome is supported by our finding of no differences in average sprint power with CHO ingestion at only marginally higher ingestion rates (1.3 g·min^{-1}). In addition, it is worth noting that our observed effects of MF/MF-H on late-exercise sprint power (ES = 0.21–0.22; 3.9–4.2% higher power versus MD), although not statistically significant, were also consistent with aforementioned prior studies in which MTC were compared with maltodextrin at moderate intake rates. Taken together, it seems clear that performance benefits with MTC versus maltodextrin/glucose are small, and benefits are attenuated (and possibility nullified) as comparison beverage ingestion rates approach the maltodextrin/glucose oxidation maximum limit of ~ 1.0–1.2 g·min^{1}.

Ergogenic effects of MTC relative to isocaloric glucose/maltodextrin are typically attributed to two mechanisms: (1) enhanced exogenous CHO oxidation rates resulting in endogenous CHO sparing and/or enhanced late-exercise CHO availability (Jentjens and Jeukendrup 2005; Wallis et al. 2005; King et al. 2018), and (2) attenuated CHO-induced GI distress (Rowlands et al. 2012; Wilson and Ingraham 2015). Both mechanisms likely stem from enhanced intestinal CHO absorption with MTC versus maltodextrin/glucose-alone. Maltodextrin/glucose absorption from the intestinal lumen occurs via the apical enterocyte sodium-dependent glucose co-transporter 1 (SGLT1) at maximal rates roughly equal to maximal exogenous oxidation rates (~1.0–1.2 g·min^{1}) (Rowlands et al. 2015). When fructose is ingested in addition to maltodextrin/glucose (i.e. MTC), it is absorbed separately and non-competitively via GLUT5 at a maximal rate of ~ 0.6 g·min^{1}, permitting maximal exogenous CHO oxidation rates to rise as high as ~ 1.75 g·min^{1} (Shi et al. 1997; Jentjens and Jeukendrup 2005). Thus, when CHO is ingested at rates exceeding the maximum oxidation limit for maltodextrin/glucose alone, MTC are absorbed/oxidized at higher absolute rates and with greater efficiency likely resulting in reduced CHO malabsorption and GI distress relative to maltodextrin/glucose alone (Rowlands et al. 2015).

As discussed above, it seems likely that any ergogenic effects stemming from enhanced exogenous CHO oxidation and/or GI comfort were likely minimized due to the CHO ingestion rate chosen in the present study. All treatments in the present study were ingested at 1.3 g·CHO·min^{-1}. This rate was chosen based on manufacturers recommendations for MF-H consumption, but also aligns with dose–response evidence reporting optimal performance with MTC ingestion versus placebo at that rate (Smith et al. 2013). Importantly, when MTC are ingested at rates below the maximal oxidation rate for maltodextrin/glucose (1.0–1.2 g·min^{-1}), exogenous oxidation rates do not differ from isocaloric maltodextrin/glucose (Hulston et al. 2009). This suggests that absorption kinetics and GI comfort are also likely similar at these rates. As the prescribed CHO ingestion rate for all treatments in the present study was only marginally higher than 1.2 g·min^{-1}, differences in CHO absorption and oxidation were possibly negligible. In support, despite some evidence for small, but non-significant, differences in late-exercise blood glucose, we found no differences in total CHO or fat oxidation rates. Additionally, we found little evidence of any systematic benefit for GI comfort with MF-H or MF versus MD.

The lack of any meaningful difference in GI comfort across treatments may have also been related to the CHO types and their associated osmolalities utilized in the present study. Prior studies reporting CHO-induced GI distress typically utilize comparison beverages containing high concentrations of glucose, which can have osmolalities ≥ 700 mOsmol·kg^{-1} (Triplett et al. 2010). Beverages with such high osmolalities may osmotically pull water into the intestinal lumen causing gastric distension (Rehrer et al. 1994). In studies (such as the present one) utilizing treatment beverages containing maltodextrin, a high molecular weight glucose polymer, GI distress symptoms rarely exceed the mild range, possibly as a result of lower beverage osmolality (~300–400 mOsmol·kg^{-1}) attenuating osmotic drag (Rowlands et al. 2012; Guillochon and Rowlands 2017). In agreement with this concept, we found few (≤ 3) incidences of severe GI distress across all treatments with most ratings remaining in the mild range or below.

MF-H did not enhance cycling performance or GI comfort relative to MF. These findings align with those of McCubbin et al. (2019) who found no differences in GI comfort or performance between a hydrogel supplement and energy/CHO-matched control during ~ 3.25 h running (3 h at 60% VO_{2max} followed by an incremental performance test to exhaustion). Anecdotal reports and product information suggest that potential performance benefits stemming from ingestion of MF-H are due to enhanced GI tolerance/comfort relative to traditional CHO beverages. CHO-induced GI distress during exercise is not well understood, but thought to be multi-factorial in nature and likely triggered by gut ischemia (particularly at higher intensities), CHO malabsorption, and gastric distension stemming from duodenal receptor inhibition of gastric emptying and water secretion into the intestinal lumen (de Oliveira and Burini 2014). MF-H would seemingly be an ideal supplement to consume to attenuate these factors as it contains MTC, which are absorbed more efficiently and induce less GI distress than any single CHO type when ingested at high rates (Triplett et al. 2010; Rowlands et al. 2012, 2015; Wilson and Ingraham 2015). Moreover, the ability of MF-H to form gels at pH levels found in the stomach seem to contribute to enhanced gastric emptying relative to non-hydrogel CHO beverages, at least when consumed at rest (Sutehall et al. 2019). Nevertheless, we found no evidence of any benefit from consuming MF-H on GI comfort relative to MF or MD. Moreover, we actually found some evidence, albeit non-significant, suggesting that MF-H increases feelings of fullness relative to MF and MD. Prior studies have reported that the form of CHO ingested (e.g. solid, liquid, gel) can impact GI comfort (Sareban et al. 2016; Guillochon and Rowlands 2017). It is possible that when MF-H forms a hydrogel in the stomach, the change in form increases stretch of the stomach lining causing increased feelings of fullness. However, this is purely speculative. Clearly more research is warranted to determine the true impact of MF-H on gastric emptying, CHO absorption, and GI comfort during exercise.

It is somewhat surprising that we found no differences in GI distress across treatments and that GI distress ratings generally remained in the mild-moderate range or below. Indeed, the exercise protocol in the present study was designed to replicate the high intensities experienced in cycling races. This both increased external validity, but also increased the likelihood of gut-ischemia-induced GI distress with CHO consumption (de Oliveira and Burini 2014). However, it is possible that GI distress during laboratory cycling, particularly of a severity that impacts performance, is simply rare unless CHO is consumed either at excessively high rates, or in forms that limit absorption (Triplett et al. 2010; Baur et al. 2016). Neither occurred in the present study. Environmental conditions also seem to mediate GI comfort during exercise (Rehrer et al. 1994; Peters et al. 1999). Specifically, hot ambient temperatures are associated with CHO-induced GI distress likely as a result of increased blood flow to the skin (i.e. increased gut ischemia) (Peters et al. 1999; de Oliveira and Burini 2014). Perhaps future studies utilizing field conditions might elicit sufficient GI distress to detect meaningful differences between these treatments. Alternatively, perhaps the true ergogenic potential of MF-H can only be realized at much higher CHO intake rates that cannot be tolerated when consumed as traditional CHO beverages. Prior research has established a curvilinear dose response to CHO ingestion with a performance optimum at ~ 1.3 g·min^{-1} with decrements in performance at higher rates presumably due to CHO malabsorption/GI distress (Smith et al. 2013). As anecdotal reports have reported ingestion of exceedingly concentrated MF-H solutions (30% CHO) to be well-tolerated during high intensity running, it is possible that MF-H may permit the presumed CHO ingestion rate optimum and performance to be pushed to higher levels than previously established (i.e. > 1.3 g·min^{-1}) (Sutehall et al. 2018). Thus, future studies should assess the impacts of MF-H ingestion at rates higher than in the present study.

A limitation of the current study is a lack of a non-caloric flavor-matched placebo beverage treatment. The decision to utilize energy and CHO-matched controls in place of a placebo was made because the primary focus of this study was the practical application of this novel supplement relative to current recommendations for CHO intake during exercise. Moreover, the addition of a placebo trial would have increased subject time and energy requirements, likely potentiating dropout, lack of motivation, etc. Nevertheless, without a placebo trial it is impossible to determine whether performance in the exercise protocol was truly exogenous-carbohydrate-limited. As such, it is possible that similarities in performance between treatments were more the result of methodological limitations than a lack of ergogenic effects. Nevertheless, it is well-established that CHO enhances performances across most durations of exercise (Stellingwerff and Cox 2014). Thus, we are confident that the current study design was appropriate for detecting any metabolically mediated ergogenic effects. It is also worth noting that the present study did not assess differences in exogenous/endogenous fuel utilization across treatments. While beyond the scope of this study, it is possible that future analyses of these variables may provide valuable insight as to the mechanism of any performance improvements or lack thereof.

In conclusion, we observed no differences in cycling performance between MF-H, MF, and MD. There were also no differences in GI symptoms across treatments. Therefore, our findings refute anecdotal reports that MF-H beverages reduce GI discomfort and improve endurance performance. It remains to be seen if carbohydrate hydrogels influence exercise performance or GI comfort when consumed: a) during exercise conditions that elicit more severe levels of GI distress or b) at higher dosages (≥ 1.3 g·min^{-1}).

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Compliance with ethical standards

Conflict of interest The authors report no conflicts of interest.

Ethical approval This study was approved by the institutional review boards of the participating institutions.

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