International Journal of Sport Nutrition and Exercise Metabolism, 2010, 20, 122-131

An Isocaloric Glucose-Fructose Beverage's Effect on Simulated 100-km Cycling Performance Compared With a Glucose-Only Beverage

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A number of recent research studies have demonstrated that providing glucose and fructose together in a beverage consumed during exercise results in significantly higher oxidation rates of exogenous carbohydrate (CHO) than consuming glucose alone. However, there is insufficient evidence to determine whether the increased exogenous CHO oxidation improves endurance performance. The purpose of this study was to determine whether consuming a beverage containing glucose and fructose (GF) would result in improved cycling performance compared with an isocaloric glucose-only beverage (G). Nine male competitive cyclists (32.6 ± 5.8 years, peak oxygen uptake 61.5 ± 7.9 ml · kg^{-1} · min^{-1}) completed a familiarization trial and then 2 simulated 100-km cycling time trials on an electronically braked Lode cycle ergometer separated by 5–7 d. During the randomly ordered experimental trials, participants received 36 g of CHO of either G or GF in 250 ml of water every 15 min. All 9 participants completed the 100-km time trial significantly faster when they received the GF beverage than with G (204.0 ± 23.7 vs. 220.6 ± 36.6 min; $p = .023$). There was no difference at any time point between trials for blood glucose or for blood lactate. Total CHO oxidation increased significantly from rest during exercise but was not statistically significant between the GF and G trials, although there was a trend for CHO oxidation to be higher with GF in the latter stages of the time trial. Consumption of a CHO beverage containing glucose and fructose results in improved 100-km cycling performance compared with an isocaloric glucose-only beverage.

Keywords: endurance performance, carbohydrate oxidation, time trial

Carbohydrate (CHO) ingestion during prolonged (>90 min) endurance exercise has been shown to significantly improve performance compared with placebo in time-to-exhaustion protocols (Coyle, Coggan, Hemmert, & Ivy, 1986), time trials (Angus, Hargreaves, Dancey, & Febbraio, 2000), and short sprints at the end of 2 hr of exercise (Bacharach et al., 1994; Febbraio, Chiu, Angus, Arkinstall, & Hawley, 2000; Murray, Paul, Seifert, & Eddy, 1991). The mechanism behind this improvement in performance is believed to be maintenance of blood glucose concentrations and a high rate of CHO oxidation when endogenous sources become significantly reduced or depleted (Coyle et al., 1986).

Because keeping CHO oxidation high by supplementing with exogenous sources has been shown to improve performance, there has been a great deal of research to determine which exogenous CHO is oxidized at the highest rates. Until recently, most of the research focused on determining which single CHO (e.g., glucose or fructose) provided the highest exogenous oxidation rates. The bulk of the research investigating this topic has reported that the highest oxidation rates of a single CHO are approximately 1.0–1.2 g/min even when large amounts are consumed (Jeukendrup & Jentjens, 2000). However, recent research has demonstrated that combining different CHOs together (e.g., glucose and fructose) yields exogenous CHO oxidation at rates significantly higher than any single CHO.

Adopo, Péronnet, Massicotte, Brisson, and Hillaire-Marcel (1994) were the first to report that a beverage containing two CHOs was oxidized at a higher rate than a single CHO. During 2 hr of cycling at 60% VO_{2max}, significantly more CHO from a beverage containing glucose and fructose was oxidized than with a glucose-only drink when participants consumed 100 g of CHO in both beverages (74 g vs. 58 g).

More recently, Jentjens, Moseley, Waring, Harding, and Jeukendrup (2004) reported exogenous oxidation rates greater than 1.1 g/min when participants consumed a beverage containing two CHOs. Participants were given either a glucose beverage providing 1.8 g/min or a beverage providing 1.2 g/min of glucose and 0.6 g/min of fructose. The peak exogenous oxidation rate at the end of 120 min of exercise was significantly higher (1.26 g/min) for the multiple-CHO beverage than glucose only (0.80 g/min). Jentjens and Jeukendrup (2005) reported the high-

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est peak exogenous oxidation rates to date of 1.75 g/min with a beverage containing glucose and fructose given to cyclists exercising for 150 min at 60% of their VO_{2max}. The glucose-fructose beverage contained equal amounts of each CHO, and the participants received a total of 2.4 g/min CHO in both trials. The peak exogenous oxidation rate for the glucose-only beverage was 1.06 g/min.

The mechanism proposed to explain the significant difference in exogenous oxidation rates is the different intestinal transporters used to absorb glucose and fructose. Glucose uses SGLT1 (Ferraris, 2001), whereas fructose enters the small intestine via the GLUT-5 transporter (Shi et al., 1995). Therefore, combining CHOs that use different intestinal transporters may increase CHO uptake, leading to increased exogenous oxidation rates, because the transporters do not become saturated.

To date, only one study has investigated whether the difference reported in exogenous oxidation rates between single- and multiple-CHO beverages might result in improved performance. Currell and Jeukendrup (2008) designed a study in which cyclists exercised at 55% W_{max} for 120 min before completing a predetermined amount of work (~1 hr) as quickly as possible. During the trials participants were given 1.8 g/min of a glucose-only beverage or a multiple-CHO drink providing 1.2 g/min of glucose and 0.6 g/min of fructose. Performance was improved during the time trial by 8% when participants received the glucose-fructose drink.

Although the results of Currell and Jeukendrup (2008) demonstrate an ergogenic effect for a multiple-CHO beverage, the protocol used in their study may not reflect the nature of competitive cycling events. During actual races, exercise intensity varies widely, with periods of steady state, as well as low and high intensity (Jeukendrup & Van Diemen, 1998; Palmer, Hawley, Dennis, & Noakes, 1994). The stochastic nature of these events produces different physiological responses than with steady-state exercise (Foster, Green, Snyder, & Thompson, 1993; Palmer et al., 1994). Therefore, the purpose of this study was to investigate whether a sports beverage containing two CHOs (glucose and fructose) would result in improved time-trial performance using a protocol that mimics the stochastic nature of road cycling (Schabort, Hawley, Hopkins, Mujika, & Noakes, 1998). We hypothesized that a glucose-fructose beverage would improve simulated 100-km cycling performance compared with an isocaloric glucose-only beverage.

Methods

Participants

Nine endurance-trained male cyclists who regularly compete in road-cycling races participated in this study. Their physical characteristics are listed in Table 1. Before participating, they completed a health-history form to determine whether they were classified as low risk for cardiovascular disease according to the ACSM's 2000 guidelines for exercise testing and prescription. The potential risks associated with the study were explained to each participant, who then provided informed consent to participate. The study was approved by the institutional review board of Georgia State University.

Table 1 Participant Characteristics (*N* = 9)

	M ± *SEM*	Range
Age (years)	32.7 ± 1.9	24–41
Height (m)	1.75 ± 0.02	1.65–1.85
Weight (kg)	71.7 ± 2.5	61.6–87
Body fat (%)	8.5 ± 1.1	4.5–15.8
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	61.6 ± 2.6	45.2–72.2
VO_{2max} (L/min)	4.44 ± 0.28	2.8–5.62
W_{max} (W)	359 ± 14.3	285–400

Before the start of the experimental trials, all participants performed an incremental cycle-ergometer test to volitional fatigue to determine maximal workload (W_{max}) and maximal oxygen consumption (VO_{2max}). The test was performed on an electronically braked cycle ergometer (Excalibur Sport, Lode BV, Groningen, The Netherlands). On participants' arriving for the VO_{2max} test, body weight (Right-Weigh electronic scale FS-0900, Befour Inc., Saukville, WI), body fat via seven skinfold sites (C130, Lange skinfold caliper, Beta Technology Inc., Cambridge, MD; Jackson & Pollock, 1978), and height were recorded. Before participants began the VO_{2max} test, seat height, seat position, and handlebar height were measured and recorded on the cycle ergometer so they could be used on each subsequent visit. Participants then started cycling with a 5-min warm-up at 100 W. Thereafter, the test began at 150 W with incremental increases of 25 W every 2 min. Heart rate was recorded continuously using a five-lead electrocardiogram (TM Q4500 stress-test monitor, Quinton Instrument Co., Seattle, WA). Oxygen consumption and carbon dioxide production were measured using an open-circuit metabolic measurement system (Parvomedics TrueMax 2400, Salt Lake City, UT). The metabolic measurement system was calibrated before each test according to the manufacturer's specifications. Rating of perceived exertion was recorded during the final 15 s of each stage (Borg, 1970). The test was considered a valid maximal test when at least two of the three following criteria were met: a leveling off of VO_2 with increasing workload, heart rate within 10 beats/min of the participant's age-predicted maximum heart rate, and a respiratory-exchange ratio of >1.05. Peak oxygen consumption was calculated as the highest averageVO_2 during any 30 s in any given period during the test.

Familiarization Trial

Before performing the full time trials, participants undertook a familiarization trial during which they completed the first 50 km of the 100 km of the simulated time trial while receiving water only. The familiarization trial was completed on a Lode cycle ergometer.

Experimental Design

After completing the familiarization trial, participants performed two experimental trials that consisted of a simulated 100-km time trial with intermittent 1-km and 4-km sprints. This protocol has been shown to be a reliable way to test endurance performance (Schabort et al., 1998). To determine the workload required for the familiarization and experimental trials, participants were weighed on arrival. Their weight in kilograms was used to compute the total distance required. Participants were required to complete an amount of work equal to 35 kJ per kilogram of body weight, which is equivalent to the work required to complete a 100-km time trial (Angus et al., 2000). The amount of work required to complete each sprint was determined by taking the total amount of work in kJ that equated to 100 km and dividing it by 100 for the 1-km sprint workload. The 4-km sprint workload was determined by taking the workload required for the 1 km sprint and multiplying it by 4. The participants were encouraged to finish the sprints during the time trial as fast as possible. The 1-km sprints occurred at 10, 32, 52, and 72 km, and the 4-km sprints, at 20, 40, 60, and 80 km. In addition, the participants were encouraged to finish the total distance as quickly as possible. During the trials participants received an isocaloric solution containing either glucose only (G) or glucose and fructose (GF). The order of the experimental trials was randomly assigned, and trials were separated by 5–7 days.

Diet and Activity Before Testing

Participants were asked to complete a training log 7 days and a diet record 2 days before the familiarization trial. They were required to follow the same activity and diet pattern before both experimental trials. In addition, they were asked to refrain from strenuous exercise and alcohol consumption in the 24 hr before all trials.

100-km Time Trials

Participants arrived at the laboratory between 6:30 and 8:00 a.m. after an overnight fast (10–12 hr). All experimental trials were conducted at the same time of day to avoid circadian variance (Deschenes et al., 1998). On arrival participants were weighed and confirmed they had not eaten any food or drink other than water in the past 10–12 hr. The experimental trials were conducted on the same Lode cycle ergometer that was used during their initial visit to measure oxygen consumption, as well as the familiarization trial.

The only feedback given to participants during the time trial was the distance covered. All trials were performed in a thermoneutral environment (22–23 °C), and a fan was positioned nearby to minimize thermal stress.

Carbohydrate Solutions

The beverages given to participants consisted of a solution containing 36 g of glucose (G) or 18 g of glucose and 18 g of fructose (GF) in 250 ml of water. In addition, 200 mg of sodium was added to each beverage. An artificial sweetener was added to the G solution to add sweetness to ensure that it tasted similar to the GF solution. Both solutions had a similar appearance, but they were given to participants in opaque water bottles in a double-blind and randomized fashion for the two 100-km time trials. Before starting the time trial, participants were given 250 ml of either G or GF. After commencing exercise, participants were given an additional 250 ml of the solution every 15 min until completion of the time trial. The amount of CHO given to the participants each hour was approximately 144 g, or 2.4 g/min.

Heart-Rate and Gas-Exchange Measurements

Before and every 30 min during exercise, heart rate (Polar T61, Polar Electro, Kempele, Finland) was recorded and gas exchange was measured (Parvomedics TrueMax 2400, Salt Lake City, UT). Expired-gas samples were analyzed for oxygen consumption and carbon dioxide production. The analyzers were calibrated before and every hour during exercise. Whole-body CHO oxidation and fat oxidation were calculated using indirect calorimetry according to the formulas of Frayn (1983).

Blood Sampling and Analysis

Blood samples were obtained at rest, every 30 min during, and immediately after the completion of the time trial via finger stick, with 25 µl being obtained for each sample using an electronic pipette (EDP-Plus, Rainin Instrument LLC, Oakland, CA). The samples were placed in a tube containing 50 µl of lysing agent (YSI 1515 cell-lysing agent, Yellow Springs, OH). The samples were immediately analyzed for plasma glucose and lactate in an automated analyzer (YSI 2300, Yellow Springs, OH).

Statistics

A paired-samples *t* test was used to determine whether there were differences in time-trial completion time and mean power output. All other measures were compared using a two-way analysis of variance with repeated measures (using time and beverage). All values are presented as $M \pm SEM$, and all calculations were performed using SPSS (version 15, Chicago, IL). Statistical significance was set at $p < .05$.

Results

The mean time to complete the time trial was significantly faster when the GF solution was consumed than with G, 204.0 ± 7.9 versus 220.6 ± 12.2 min ($p = .023$). All 9 participants completed the time trial faster when they consumed GF.

Mean power output was also significantly higher for the duration of the 100 km when the participants con-

sumed the GF solution than with G, 206.5 ± 9.7 versus 193.2 ± 11.3 W (p = .013). Figure 1 displays the mean power output for each 20-km segment during the time trial. Mean power was higher during every segment with GF but was only statistically significant during the last 20 km (p = .023).

The mean times to complete each 20-km segment are listed in Table 2. Although the time to complete the entire trial was 8% faster during GF than G, there was no significant difference in any of the individual 20-km segments between solutions. There was, however, a main effect of time in both G and GF (p = .035), indicating that the time needed to complete each segment was longer as duration increased.

Table 3 lists the mean time and power output for each of the 1-km sprints during each trial. There was no difference in the mean time to complete the 1-km sprints between solutions. The time needed to complete each sprint increased as the time trial progressed, regardless of the solution consumed. Mean power output also declined in the 1-km sprints during both trials over time (main effect of time, p = .000). When all the 1-km power outputs were compared between treatments, there was a significant difference in mean power output during the 1-km sprints in trial GF 335.1 ± 28.1 versus G 316.2 ± 28.1 W (p = .000).

Table 4 lists the mean time and power output for each of the 4-km sprints during each trial. There was no significant difference in the mean power or time needed to complete the 4-km sprints between treatments. In both groups mean power output during these sprints declined during the duration of the time trial, and there was a significant difference between the first (p = .011), second (p = .048), and third (p = .048) compared with the final 4-km sprint. This decline in mean power output caused the time needed to complete the 4-km sprints to be significantly longer as the time trial progressed (p = .001).

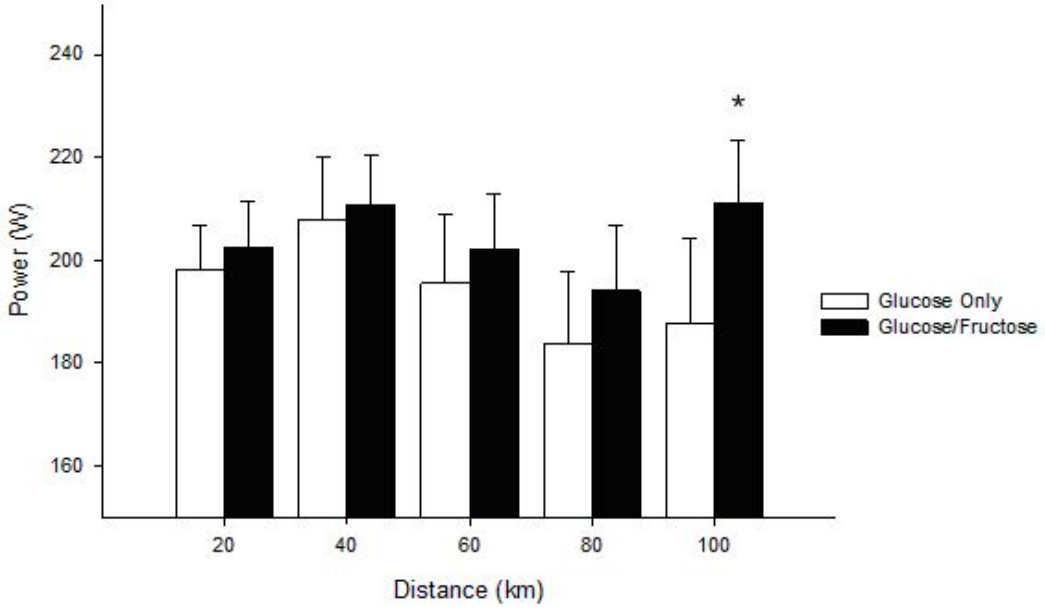

Figure 1 — Power output during each 20-km segment of the time trial, *M* ± *SE*. *Significantly different from glucose-only (p = .023).

Table 2 Segment Times Recorded at 20-km Intervals During the Entire Trial, *M* ± *SE*

	Time to Complete Segment (min)	
Segment	**Glucose only**	**Glucose-fructose**
20 km	41.72 ± 1.24	40.83 ± 0.98
40 km	40.38 ± 2.33	39.40 ± 1.66
60 km	43.42 ± 2.99	41.25 ± 1.95
80 km	46.38 ± 3.39	43.42 ± 2.54
100 km	46.58 ± 4.65	39.64 ± 2.03

Table 3 Mean Time and Power During Intermittent 1-km Sprints, *M* ± *SE*

	Glucose only	**Glucose-fructose**
Time (s)		
1st 1-km sprint	72.2 ± 3.8	72.0 ± 5.2
2nd 1-km sprint	84.7 ± 7.9	76.3 ± 5.4
3rd 1-km sprint	86.6 ± 9.5	80.4 ± 4.9
4th 1-km sprint	103.6 ± 14.6	86.6 ± 6.6
Power (W)		
1st 1-km sprint	356.0 ± 22.3	366 ± 32.6
2nd 1-km sprint	319.7 ± 32.4	344.4 ± 29.3
3rd 1-km sprint	314.2 ± 30.0	322.7 ± 23.9
4th 1-km sprint	275.0 ± 33.3	306.7 ± 29.1

Blood Metabolites

Blood glucose concentrations before exercise, during the first 150 min of exercise, and immediately postexercise are shown in Figure 2. Blood glucose was not significantly different between solutions. However, there was a significant time effect (p = .013).

Blood lactate concentrations during the first 150 min of exercise and immediately postexercise are shown in Figure 3. They were similar for both solutions, increasing in the first 30 min from 0.91 ± 0.1 to 3.24 ± 0.59 mmol/L (main effect of time, p = .000). Thereafter, mean lactate values were higher at every time point during GF but were not significantly different from G.

Table 4 Mean Time and Power During Intermittent 4-km Sprints, *M* ± *SE*

	Glucose only	Glucose-fructose
Time (s)		
1st 4-km sprint	381.7 ± 19.2	382.9 ± 17.0
2nd 4-km sprint	402.8 ± 24.1	393.6 ± 21.2
3rd 4-km sprint	413.2 ± 24.9	408 ± 24.5
4th 4-km sprint	505.3 ± 56.7	417.1 ± 23.4
Power (W)		
1st 4-km sprint	269.1 ± 17.4	266.9 ± 15.9
2nd 4-km sprint	257.4 ± 18.8	261.4 ± 16.7
3rd 4-km sprint	250.5 ± 17.5	253.5 ± 17.6
4th 4-km sprint	217.1 ± 22.3	247.0 ± 16.5

Respiratory Measurements

Oxygen consumption, respiratory-exchange ratio, and total CHO- and fat-oxidation rates are shown in Table 5. Mean VO_2 for the first 150 min of exercise was 2.80 L/min in the G trial and 2.90 L/min in GF, which was approximately 63% and 65%, respectively, of the participants' VO_{2max}. During the G trial, VO_2 remained steady through 90 min before declining by 5.1% from Minute 90 through Minute 150. Oxygen uptake was maintained between 2.89 and 2.92 L/min throughout 150 min of exercise with GF.

The mean respiratory-exchange ratio was higher at every time point with GF, but this finding was not statistically significant. Fat oxidation was not significantly different between G and GF, although it was higher at every measurement for G during the time trial.

Total CHO oxidation increased significantly during exercise in both treatments (p = .000) but was not significantly different between solutions. Heart rate increased significantly in both treatments during the time trial (p = .000) but was not different between trials.

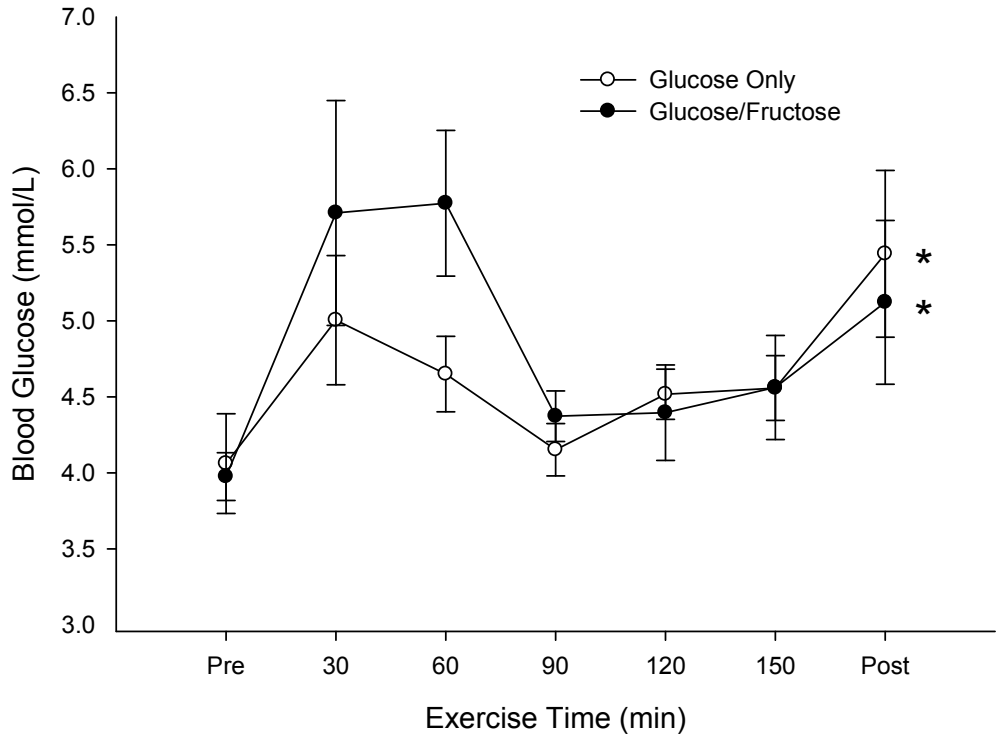

Figure 2 — Plasma glucose concentrations during the entire time trial when participants were given glucose (white circles) or glucose-fructose (black circles). *Significantly different from preexercise (p = .013).

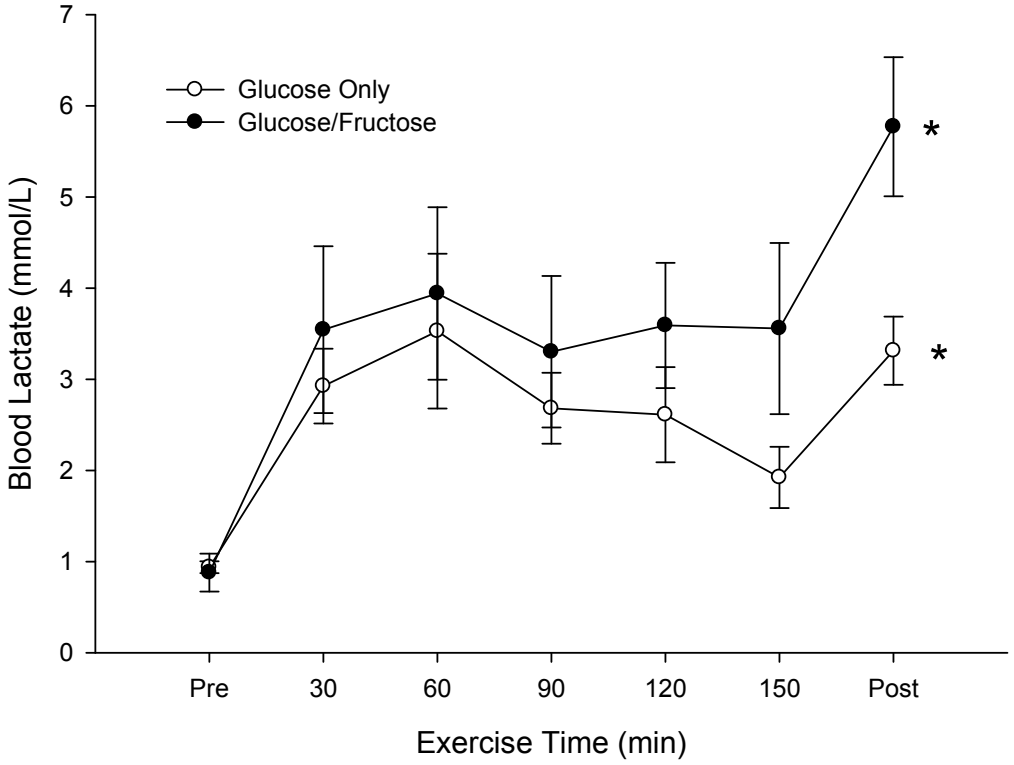

Figure 3 — Plasma lactate concentrations during the entire time trial when participants were given glucose (white circles) or glucose-fructose (black circles). *Significantly different from preexercise ($p = .00$).

Table 5 Oxygen Uptake (VO_2), Respiratory-Exchange Ratio (RER), Total Fat Oxidation (FAT), Total Carbohydrate Oxidation (CHO), and Heart Rate (HR) Before and During Exercise

Drink	Time (min)	VO_2 (L/min)	RER	FAT (g/min)	CHO (g/min)	HR (beats/min)
Glucose only	0	0.35 ± 0.02	0.84 ± 0.05	0.09 ± 0.04	0.22 ± 0.08	69 ± 5
	30	2.82 ± 0.11	0.87 ± 0.03	0.61 ± 0.14	2.18 ± 0.28	149 ± 3
	60	2.84 ± 0.12	0.86 ± 0.03	0.69 ± 0.14	2.04 ± 0.27	150 ± 3
	90	2.86 ± 0.07	0.85 ± 0.03	0.74 ± 0.14	1.86 ± 0.27	152 ± 2
	120	2.76 ± 0.08	0.84 ± 0.03	0.73 ± 0.11	1.69 ± 0.26	152 ± 3
	150	2.71 ± 0.10	0.84 ± 0.03	0.70 ± 0.10	1.79 ± 0.28	152 ± 4
Glucose-fructose	0	0.31 ± 0.06	0.92 ± 0.10	0.05 ± 0.07	0.25 ± 0.13	68 ± 6
	30	2.91 ± 0.15	0.89 ± 0.03	0.53 ± 0.17	2.41 ± 0.29	149 ± 4
	60	2.89 ± 0.08	0.88 ± 0.03	0.59 ± 0.14	2.28 ± 0.27	148 ± 5
	90	2.90 ± 0.11	0.88 ± 0.03	0.61 ± 0.16	2.18 ± 0.27	153 ± 4
	120	2.90 ± 0.14	0.88 ± 0.03	0.58 ± 0.15	2.27 ± 0.25	154 ± 5
	150	2.92 ± 0.13	0.87 ± 0.02	0.65 ± 0.13	2.11 ± 0.23	155 ± 4

Dietary Intake

There were no significant differences in the 2-day dietary intake before the G and GF trials for total energy or kcal from CHO, protein, and fat (5,569 ± 429 vs. 5,838 ± 750 kcal, 3,038 ± 237 vs. 3,209 ± 508 kcal, 937 ± 85 vs. 787 ± 48 kcal, and 1,521 ± 256 vs. 1,522 ± 341 kcal, respectively).

Gastrointestinal Distress

Gastrointestinal (GI) distress was not assessed systematically in this study, but 4 of the 9 participants experienced GI distress after the G trial. Two episodes of diarrhea, one episode of vomiting, and one incident of sour stomach were reported to the investigators after completion of the G trial. Seven of the 9 participants reported they did not

feel as if their stomachs were emptying during the G trial and they felt very full. No GI complaints were reported when participants received the GF solution.

Discussion

The main finding of the current study was that ingestion of an isocaloric CHO solution containing equal amounts of glucose and fructose significantly improved performance in a simulated 100-km cycling time trial compared with a glucose-only solution. The GF solution improved performance time by 8.1% compared with G. This improvement in performance was the result of a significantly higher average power output during the duration of the simulated time trial when participants consumed GF than with G (206.5 vs. 193.2 W). Despite the improvement in performance, no differences in CHO oxidation and blood glucose levels were seen between solutions. Respiratory-exchange ratio and VO_2 were also not significantly different between the two drinksAlthough there was a significant difference in the total time and mean power output to complete the entire time trial, there were no significant differences in the time needed to complete the individual 1- or 4-km sprints. Power output decreased during the 1- and 4-km sprints regardless of the trial, causing a corresponding increase in time to complete each sprint. These results are similar to those of other studies that used this protocol and gave participants isocaloric amounts of CHO during exercise (Burke et al., 2000; Schabort et al., 1998).

There was also no difference between the G and GF solutions for the time to complete the individual 20-km segments. However, there was a significant difference during the final 20-km segment in mean power output between G and GF. It is worth noting that mean power output during the last segment increased for both G and GF. This is contrary to what usually happens when comparing a placebo with CHO. In those instances the difference in performance is usually the result of a severe drop in performance at the end of exercise as blood glucose levels drop, causing a decrease in CHO oxidation.

Only one other study has reported improved endurance performance when participants consumed a solution containing glucose and fructose compared with glucose only. Currell and Jeukendrup (2008) designed a study in which participants exercised at a steady state for 2 hr at 55% of their W_{max} before completing a 1-hr time trial as quickly as possible. One-hour time-trial performance was improved by 8% when participants consumed GF compared with G, nearly identical to the percentage improvement found in the current study. Mean power output during the 1-hr time trial was significantly higher when participants received the multiple-CHO solution than when they received glucose alone (275 vs. 254 W). In particular, during the last half of the 1-hr time trial, power output was significantly higher when participants were given GF than with G. Gas-exchange and blood measurements were only taken during the steady-state portion of the protocol and were not different between solutions. Therefore it could not be determined what the blood glucose and CHO oxidation responses were during the time-trial portion of the study.

In the current study, total CHO oxidation was not significantly different between GF and G. These findings are similar to those of several studies that investigated the metabolic responses during prolonged steady-state exercise when consuming a multiple-CHO solution compared with glucose only. Jentjens and Jeukendrup (2005) reported consumption of a glucose and fructose solution containing 1.2 g/min of both CHOs in a single solution resulted in peak exogenous oxidation rates of 1.75 g/min at the end of 150 min of cycle-ergometry exercise at 60% VO_{2max}. An isocaloric, glucose-only drink was oxidized at rates of 1.06 g/min. However, despite the large difference between the exogenous oxidation rates, total CHO oxidation was not different. Similar results have been published in other studies in which a glucose and fructose solution was compared with a glucose-only solution (Currell & Jeukendrup, 2008; Jentjens, Achten, & Jeukendrup, 2004; Wallis, Rowlands, Shaw, Jentjens, & Jeukendrup, 2005).

The explanation behind the significant differences in exogenous oxidation rates of a glucose-fructose drink compared with glucose only is most likely a result of the different transporters the CHOs use to enter the bloodstream. The intestinal transporter for glucose is SGLT-1 (Ferraris, 2001), whereas fructose uses GLUT-5 (Shi et al., 1995). When large amounts of either glucose or fructose are consumed, the individual transporter becomes saturated, which can limit the total amount of individual CHO that enters the bloodstream. Research studies have demonstrated the peak exogenous oxidation rates of glucose to be approximately 1.0 g/min even when large amounts of glucose are consumed (Wagenmakers, Brouns, Saris, & Halliday, 1993). Combining multiple carbohydrates such as glucose and fructose in a sports drink takes advantage of the different transporters for glucose and fructose, thereby reducing the possibility of saturating the individual transporters or maximizing the transport capacities of two transporters instead of one.

The potential benefit to the athlete who consumes a solution containing glucose and fructose compared with a single CHO is that it might spare endogenous CHO early in exercise so that it is available for use as duration increases. Research studies that measured muscle glycogen utilization using steady-state and time-trial protocols have concluded that ingesting CHO does not spare muscle glycogen in cycling (Bosch, Dennis, & Noakes, 1994; Hawley, Bosch, Weltan, Dennis, & Noakes, 1994). However, there is evidence to suggest that consuming CHO during cycling does spare liver glycogen (Bosch et al., 1994; Jeukendrup et al., 1999). Even though several recent studies have reported higher exogenous oxidation rates with consumption of glucose and fructose solutions than with glucose-only drinks, total CHO oxidation rates have been similar between the two. Therefore, if total CHO oxidation is the same regardless of which beverage is being consumed despite a significant

difference in exogenous oxidation, the difference in total CHO oxidation must be accounted for by endogenous sources. In addition, because muscle glycogen depletion occurs at the same rates regardless of the beverage consumed, the difference is likely accounted for by liver glycogenolysis. This potential scenario is an area that warrants further study.

In addition to CHO oxidation's being similar between treatments, blood glucose concentrations were also maintained at similar levels with G and GF. In the study by Currell and Jeukendrup (2008), blood glucose measurements were not taken during the time-trial portion of the protocol. Therefore, it is not possible to determine whether the improvement in performance noted in that study was caused by maintenance of euglycemia. However, during the steady-state portion of the protocol, plasma glucose was maintained when the participants consumed glucose only or glucose and fructose. This is consistent with the research, which has only investigated the metabolic responses between a glucose-fructose and a glucose-only solution during steady-state exercise. There have been no reported differences in blood glucose response during steady-state exercise of moderate intensity (58–63% VO_{2max}) ranging from 120 to 300 min (Jentjens & Jeukendrup, 2005; Jentjens, Achten, & Jeukendrup, 2004; Jeukendrup et al., 2006).

A possible explanation for the blood glucose results obtained in the current study may be related to an increased muscle glucose uptake when participants received GF. The rate of glucose uptake by exercising muscle is positively related to exercise intensity and increases curvilinearly (Katz, Broberg, Sahlin, & Wahren, 1986; Wahren, Felig, Ahlborg, & Jorfeldt, 1971). During the simulated time trials, power output was significantly higher when participants received GF than with G. The higher output recorded with GF indicates that a higher sustained workload was achieved during this trial. Solutions containing glucose and fructose have demonstrated a higher exogenous oxidation rate than glucose only (Adopo et al. 1994; Jentjens, Moseley, et al. 2004; Jentjens & Jeukendrup, 2005). This difference in exogenous CHO metabolism is most likely a result of the different transporters that glucose (SGLT-1) and fructose (GLUT-5) use. Having two transporters available to move CHO out of the small intestine and into the bloodstream could make more glucose available for muscle uptake. With a glucose-only beverage, the SGLT-1 transporter is more likely to become saturated and limit the amount of CHO that can be delivered to the bloodstream and the exercising muscle. This most likely accounts for the higher rates of exogenous oxidation rates demonstrated in the research (Adopo et al. 1994; Jentjens, Moseley, et al. 2004; Jentjens & Jeukendrup, 2005). Therefore, in the current study during the GF trial, muscle glucose uptake was likely higher than in G because of a higher exercise intensity and more available substrate.

GI distress was not measured directly during the current study. However, 4 of the 9 participants reported experiencing GI distress after the G trial after leaving the laboratory. Seven of the 9 participants commented during the G trial that their stomachs were not emptying and that they felt the solution was not exiting the stomach. Prior research has demonstrated that consuming large amounts of CHO during exercise can cause GI distress (Wagenmakers et al., 1993). Recent studies that have investigated the effects of combining glucose and fructose in a solution in comparison with glucose only have used feeding protocols that gave participants large amounts of CHO during steady-state exercise. Jentjens, Achten, and Jeukendrup (2004) gave participants 2.4 g/min of a glucose-only solution and a multiple-CHO solution containing 1.2 g of glucose, 0.6 g of fructose, and 0.6 of sucrose during 150 min of cycling at ~60% VO_{2max}. There were no severe GI complaints when the participants received the mixed-CHO solution. However, during the glucose-only trial, more participants reported severe GI discomfort (nausea, bloated feeling, and urge to vomit and vomiting) than in the mixed-CHO trial. In the glucose trial, 1 participant vomited after 120 min of exercise. Furthermore, 2 participants were not able to completely finish the last glucose drink because they felt that this "would make them sick" (p. 1557). The primary goal of the study by Jentjens, Achten, and Jeukendrup was to investigate the metabolic effects of CHO on steady-state exercise, so performance was not affected.

However, in a study that investigated the impact of several CHO solutions on endurance capacity, Maughan, Fenn, and Leiper (1989) found that consuming large amounts of a single CHO limited performance. The protocol used in that study required the participants to cycle at 70% VO_{2max} until exhaustion. One of four CHO solutions was given to the participants before exercise and every 10 min during exercise. In three of the trials, the CHO solutions contained glucose syrup, fructose syrup, or glucose and fructose syrup. Each of the syrup CHO solutions contained 36 g of CHO and was given to the participants in 100 ml of water. The amount of CHO consumed per hour during these trials was 216 g. The fourth solution was a CHO-electrolyte drink that contained 4 g of CHO per 100 ml of water. The participants were able to cycle significantly longer when they received the CHO-electrolyte beverage than with the syrup solutions. The investigators reported that none of the CHO syrup solutions were well tolerated and that in the case of the fructose-only beverage some of the GI complaints were severe. In one case, nausea caused one of the participants to stop exercising. Total CHO oxidation was higher with the syrup solutions but not significantly so. Therefore, it can be concluded that CHO oxidation did not limit performance in that study.

Murray, Paul, Seifert, Eddy, and Halaby (1989) were able to demonstrate that a 6% glucose or sucrose beverage was superior to a 6% fructose beverage during a short time trial at the end of 115 min of cycling during which the participants exercised at varying intensities. CHO oxidation was not significantly different between beverages, nor was blood glucose before the short time trial at the end of the protocol. However, the investigators did

measure how well the three beverages were tolerated, and fructose was significantly less well tolerated than glucose or sucrose. Based on these results, CHO oxidation and maintenance of blood glucose levels did not positively affect performance. Rather, it was GI distress associated with fructose ingestion that explains the difference in performance.

In the current study, the participants were given a large amount (~144 g/hr) of CHO in both endurance-exercise trials. Despite finishing significantly faster with GF than with G, CHO oxidation was not different between solutions. It is possible that the large amounts of glucose consumed during the G trial overloaded the SGLT-1 transporter, causing the mild and severe GI distress displayed in this study. This GI distress may be associated with a slower finishing time with G.

The common explanation for how CHO ingestion improves performance is maintenance of euglycemia, which provides exogenous glucose for CHO metabolism when endogenous sources become depleted (Coyle et al., 1986). This explanation for CHO's ergogenic effect is relevant for comparing it with placebo. However, to date there have been few published studies that have compared two different CHOs and concluded that the difference in performance was caused by a maintenance of blood glucose that kept CHO oxidation high as duration increased.

The current guidelines for CHO ingestion during exercise recommend that athletes ingest 30–60 g/hr (Coyle, 2004). These recommendations are based on studies that have investigated the consumption of single CHOs during prolonged exercise. Ingesting large amounts of single CHOs can reduce gastric emptying and lead to GI distress. More research needs to be done in this area, with the focus being on multiple-CHO solutions to determine whether reduced gastric emptying or GI distress will occur when consuming larger amounts of CHO in a multiple-CHO solution.

In summary, the current study demonstrates that a CHO solution containing glucose and fructose improves simulated 100-km time-trial performance by 8% compared with an isocaloric glucose-only solution. The improvement in performance was a result of higher maintenance of power output during exercise. The faster finishing times occurred in this study despite no significant difference in CHO oxidation and blood glucose, which in the past has been postulated as the reason for ingesting CHO during exercise. There is some evidence in prior research and in the current study that when consuming large amounts of a single CHO, GI problems can potentially limit performance. More research needs to be conducted in this area to determine what physiological factors improve performance when multiple-CHO solutions are consumed.

Acknowledgments

We would like to thank Dr. Mindy Millard-Stafford at the Georgia Institute of Technology for loaning us a Lode cycle ergometer during data collection. We would also like to thank Ben Corona and Michael Green for their assistance with data and blood metabolite collection. Finally, we would like to thank all the cyclists who participated, without whose efforts this study would not have been possible.

References

Adopo, E., Péronnet, F., Massicotte, D., Brisson, G.R., & Hillaire-Marcel, C. (1994). Respective oxidation of exogenous glucose and fructose given in the same drink during exercise. *Journal of Applied Physiology, 76*(3), 1014–1019.

Angus, D.J., Hargreaves, M., Dancey, J., & Febbraio, M.A. (2000). Effect of carbohydrate or carbohydrate plus medium-chain triglyceride ingestion on cycling time trial performance. *Journal of Applied Physiology, 88*(1), 113–119.

Bacharach, D.W., von Duvillard, S.P., Rundell, K.W., Meng, J., Cring, M.R., Szmedra, L., & Castle, J.M. (1994). Carbohydrate drinks and cycling performance. *Journal of Sports Medicine and Physical Fitness, 34*(2), 161–168.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine, 2*(2), 92–98.

Bosch, A.N., Dennis, S.C., & Noakes, T.D. (1994). Influence of carbohydrate ingestion on fuel substrate turnover and oxidation during prolonged exercise. *Journal of Applied Physiology, 76*(6), 2364–2372.

Burke, L.M., Hawley, J.A, Schabort, E.J., St. Clair Gibson, A., & Noakes, T.D. (2000). Carbohydrate loading failed to improve 100-km cycling performance in a placebo-controlled trial. *Journal of Applied Physiology, 88*(4), 1284–1290.

Coyle, E.F. (2004). Fluid and fuel intake during exercise. *Journal of Sports Sciences, 22*(1), 39–55.

Coyle, E.F., Coggan, A.R., Hemmert, M.K., & Ivy, J.L. (1986). Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *Journal of Applied Physiology, 61*(1), 165–172.

Currell, K., & Jeukendrup, A.E. (2008). Superior endurance performance with ingestion of multiple transportable carbohydrates. *Medicine and Science in Sports and Exercise, 40*(2), 275–281.

Deschenes, M.R., Sharma, J.V., Brittingham, K.T., Casa, D.J., Armstrong, L.E., & Maresh, C.M. (1998). Chronobiological effects on exercise performance and selected physiological responses. *European Journal of Applied Physiology and Occupational Physiology, 77*(3), 249–256.

Febbraio, M.A., Chiu, A., Angus, D.J., Arkinstall, M.J., & Hawley, J.A. (2000). Effects of carbohydrate ingestion before and during exercise on glucose kinetics and performance. *Journal of Applied Physiology, 89*(6), 2220–2226.

Ferraris, R.P. (2001). Dietary and developmental regulation of intestinal sugar transport. *The Biochemical Journal, 360*(Pt. 2), 265.

Foster, C., Green, M.A., Snyder, A.C., & Thompson, N.N. (1993). Physiological responses during simulated competition. *Medicine and Science in Sports and Exercise, 25*(7), 877–882.

Frayn, K.N. (1983). Calculation of substrate oxidation rates in vivo from gaseous exchange. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology, 55*(2), 628–634.

Hawley, J.A., Bosch, A.N., Weltan, S.M., Dennis, S.C., & Noakes, T.D. (1994). Glucose kinetics during prolonged exercise in euglycaemic and hyperglycaemic subjects. *European Journal of Applied Physiology, 426*(5), 378–386.

Jackson, A.S., & Pollock, M.L. (1978). Generalized equations for predicting body density of men. *The British Journal of Nutrition, 40,* 497–504.

Jentjens, R.L., Achten, J., & Jeukendrup, A.E. (2004). High oxidation rates from combined carbohydrates ingested during exercise. *Medicine and Science in Sports and Exercise, 36*(9), 1551–1558.

Jentjens, R.L., & Jeukendrup, A.E. (2005). High rates of exogenous carbohydrate oxidation from a mixture of glucose and fructose ingested during prolonged cycling exercise. *The British Journal of Nutrition, 93*(4), 485–492.

Jentjens, R.L., Moseley, L., Waring, R.H., Harding, L.K., & Jeukendrup, A.E. (2004). Oxidation of combined ingestion of glucose and fructose during exercise. *Journal of Applied Physiology, 96*(4), 1277–1284.

Jeukendrup, A.E., & Jentjens, R.L. (2000). Oxidation of carbohydrate feedings during prolonged exercise: Current thoughts, guidelines and directions for future research. *Sports Medicine (Auckland, N.Z.), 29*(6), 407–424.

Jeukendrup, A.E., Moseley, L., Mainwaring, G.I., Samuels, S., Perry, S., & Mann, C.H. (2006). Exogenous carbohydrate oxidation during ultraendurance exercise. *Journal of Applied Physiology, 100*(4), 1134–1141.

Jeukendrup, A.E., & Van Diemen, A. (1998). Heart rate monitoring during training and competition in cyclists. *Journal of Sports Sciences, 16,* 91–99.

Jeukendrup, A.E., Wagenmakers, A.J., Stegen, J.H., Gijsen, A.P., Brouns, F., & Saris, W.H. (1999). Carbohydrate ingestion can completely suppress endogenous glucose production during exercise. *The American Journal of Physiology, 276*(4 Pt 1), E672–E683.

Katz, A., Broberg, S., Sahlin, K., & Wahren, J. (1986). Leg glucose uptake during maximal dynamic exercise in humans. *The American Journal of Physiology, 251*(1 Pt. 1), 70.

Maughan, R.J., Fenn, C.E., & Leiper, J.B. (1989). Effects of fluid, electrolyte and substrate ingestion on endurance capacity. *European Journal of Applied Physiology and Occupational Physiology, 58*(5), 481–486.

Murray, R., Paul, G.L., Seifert, J.G., & Eddy, D.E. (1991). Responses to varying rates of carbohydrate ingestion during exercise. *Medicine and Science in Sports and Exercise, 23*(6), 713–718.

Murray, R., Paul, G.L., Seifert, J.G., Eddy, D.E., & Halaby, G.A. (1989). The effects of glucose, fructose, and sucrose ingestion during exercise. *Medicine and Science in Sports and Exercise, 21*(3), 275–282.Palmer, G.S., Hawley, J.A., Dennis, S.C., & Noakes, T.D. (1994). Heart rate responses during a 4-d cycle stage race. *Medicine and Science in Sports and Exercise, 26*(10), 1278–1283.

Schabort, E.J., Hawley, J.A., Hopkins, W.G., Mujika, I., & Noakes, T.D. (1998). A new reliable laboratory test of endurance performance for road cyclists. *Medicine and Science in Sports and Exercise, 30*(12), 1744–1750.

Shi, X., Summers, R.W., Schedl, H.P., Flanagan, S.W., Chang, R., & Gisolfi, C.V. (1995). Effects of carbohydrate type and concentration and solution osmolality on water absorption. *Medicine and Science in Sports and Exercise, 27*(12), 1607–1615.

Wagenmakers, A.J., Brouns, F., Saris, W.H., & Halliday, D. (1993). Oxidation rates of orally ingested carbohydrates during prolonged exercise in men. *Journal of Applied Physiology, 75*(6), 2774–2780.

Wahren, J., Felig, P., Ahlborg, G., & Jorfeldt, L. (1971). Glucose metabolism during leg exercise in man. *The Journal of Clinical Investigation, 50*(12), 2715–2725.

Wallis, G.A., Rowlands, D.S., Shaw, C., Jentjens, R.L., & Jeukendrup, A.E. (2005). Oxidation of combined ingestion of maltodextrins and fructose during exercise. *Medicine and Science in Sports and Exercise, 37*(3), 426–432.