Physiological Impact of a Single Serving Slow Absorption Carbohydrate on Metabolic, Hemodynamic, and Performance Markers in Endurance Athletes During a Bout of Exercise

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Abstract

Davitt, PM, Saenz, C, Hartman, T, Barone, P, and Estremera, S. Physiological impact of a single serving slow absorption carbohydrate on metabolic, hemodynamic, and performance markers in endurance athletes during a bout of exercise. *J Strength Cond Res* 35(5): 1262–1272, 2021—The purpose of this study was to determine how a slow-absorbing carbohydrate affected markers of metabolism, hemodynamics, and performance in well-trained endurance athletes. We examined total and exogenous carbohydrate oxidation (CHO ox), glucose, and performance after consuming different glucose beverages, before a treadmill run. Ten male runners (32.4 years; $\dot{V}O_2$max, 55.9 ml·kg^{-1}·min^{-1}) participated on 3 occasions: slow digestion CHO (S), fast digestion CHO (F), and water (W). Subjects consumed a 50 g dose of either S or F before a 3-hour treadmill run at 57% $\dot{V}O_2$max. Variables were assessed at −15, 0, 30, 60, 90, 135, and 180 minutes. Immediately postrun, subjects completed a time-to-fatigue test at 110% $\dot{V}O_2$max. There was a significant difference in CHO ox for W vs. F and S (C,1.14; S,1.52; F,1.66 ± 0.2 g·min^{-1}, $p < 0.05$). Fat ox was significantly higher in S vs. F (S,0.54; F,0.47 ± 0.08 g·min^{-1}, $p < 0.05$). Exogenous CHO ox was significantly higher in F vs. S (F,0.26; S,0.19 + 0.04 g·min^{-1}, $p < 0.05$). There was a significant difference in average blood glucose for trial (F,94.5; S,97.1 vs. W,88.4 + 2.1 mg·dl^{-1}) and time × trial for F vs. S (0 minutes, $p < 0.05$). There were no significant performance differences. Consumption of a single bolus of CHO beverage before a 3-hour run elicits significant alterations in energy metabolism compared with just water, with S CHO oxidizing significantly more fat than a rapidly digested carbohydrate. These findings suggest that slow-digesting modified starch provides a consistent blood glucose level and sustained exogenous energy supply during a sustained, 3-hour endurance run. Significance was set at $p < 0.05$.

Key Words: carbohydrate oxidation, starch, glucose, exogenous, running, ultraendurance

Introduction

Energy demands for endurance exercise vary depending on the acute program variables such as the duration and intensity of the exercise. These acute program variables also directly affect substrate utilization and thus the diet considerations before and during exercise. The demands of varying physical exercise require different types and amounts of fuel to sustain the working muscle (33,34,39). This becomes extremely important within endurance exercise because of the specific intensities that are sustained, and also because the duration of the activity will change the contribution of energy over time (8). As exercise intensity increases, so does the contribution of carbohydrate toward total energy utilization (33,39). Maintaining blood glucose is pivotal to endurance exercise performance (7), especially at higher intensities, because the working muscle continually draws down the glucose concentrations within the muscle (i.e., glycogen) and from the blood (i.e., blood glucose). Frequent consumption of rapid-absorbing carbohydrate supplementation before and during exercise has been used for many years to augment a supply of glucose to the working muscle and allowing the athlete to maintain a euglycemic state.

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Endurance athletes, who practice or compete for durations greater than 60 minutes, especially at moderate-to-higher intensities, are told they need to rely on the continual consumption of dietary carbohydrates (CHOs). The reasoning primarily centers on the finite levels of muscle glycogen as a limiting factor in performance (3,4). The current dogma suggests that the continual consumption of a carbohydrate source throughout the entire endurance bout is necessary to help maintain blood sugar, prolong the onset of fatigue and optimize performance. Modern recommendations from top associations suggest the consumption (in 15–30 minutes doses) of 30–60 g of CHO per hour (20,23,30,37), with others suggesting 90 g per hour in endurance bouts lasting more than 3 hours (20,23,30,37). In longer endurance events, a higher CHO consumption has been correlated with slightly better performance times, but also greater gastrointestinal distress (29). Conventional wisdom seems to accept the sacrifice of gastrointestinal (GI) comfort in exchange for performance, by requiring an individual to consume copious amounts of costly and cumbersome CHO sources in repeated amounts during a sustained exercise bout. There is also legitimate concern regarding the effects repeated and chronic consumption of high glycemic CHO may have on exacerbating insulin resistance and its secondary manifestations (e.g., obesity, metabolic syndrome, and CVD), particularly for those athletes who are not at the "elite" level (i.e., most athletes) (25,27).

Another modality that maintains performance while relieving an individual from constantly purchasing, carrying, and consuming the CHO sources is to use stored body fat. Becoming a high fat burner allows an endurance athlete to maintain fitness level (i.e., aerobic capacity), fuel performance at race paces from a higher proportion of endogenous fat (i.e., fatty acids and intramuscular TG triglyceride) and decrease the glucose and insulin burden on the body, all the while decreasing the reliance on continual exogenous carbohydrate-based dietary supplements. Endurance athletes may still benefit from some level of carbohydrate but may not need to rely as heavily on this source of energy if they are also more efficient at mobilizing endogenous fat stores for energy. Whether running a marathon or a 100-mile trail race, even individuals who are fat adapted and running at competitive paces still rely on carbohydrate sources of energy at higher intensity and explosive bursts during competition.

The ability to provide a constant supply of glucose while promoting and not inhibiting an individual's fat burning capabilities will help sustain exercise performance and alleviate the rapid insulin and glucose burden on the body. A more traditional, high-CHO sports drink will force the body to shift fuel utilization toward CHO and subsequently causes a removal of blood glucose. This requires the individual to continually supply dietary CHO to maintain blood glucose and sustain the exercise, which has been reported to cause significant GI distress. Glycogen depletes after prolonged, moderate-to-high-intensity exercise therefore reducing subsequent performance by decreasing intensity and explosive actions (e.g., chasing down an opponent, final kick, and maintaining a higher intensity). Consuming glucose every 15–30 minutes during exercise ensures a continuous supply of performance maintaining glucose availability.

A low glycemic starch (derived from hydrothermally processed corn starch) is a product that can be taken before endurance exercise, in a single dose, and achieve all of the previous benefits toward promoting fat burning, while maintaining blood glucose, thereby reducing the need for repeated high-glycemic CHO sources while exercising. Exogenous carbohydrate ingestion, including the use of a modified starch, is exercise dependent. Shorter, high-intensity exercises benefit more from higher levels of resting muscle glycogen but not as much from exogenous sources mid-exercise. Hetrick et al. (15) found that glucose was not impacted by modified starch during a short, high-intensity protocol. However, there is still interest in continuous carbohydrate ingestion during exercise lasting greater than 60 minutes. There is still a lack of understanding of the time course comparison of low-glycemic, low-osmolarity carbohydrate sources vs. traditional high-glycemic carbohydrate sources during sustained endurance exercise when consumed in a single dose. Therefore, we investigated the metabolic, hemodynamic, and performance effects of a single bolus, pre-exercise slow-digesting carbohydrate in comparison with a fast-absorbing carbohydrate and water-only group throughout a 3-hour treadmill run.

The primary aim was to compare the absorption and oxidation rate of a slowly digested and absorbed, modified corn starch carbohydrate source during a steady-state submaximal endurance exercise bout to a typical glucose carbohydrate beverage and water in a male endurance-trained population. A single bolus, pre-exercise dose protocol was chosen to directly compare the effects of the fast vs. slow digestion CHO when testing the theorized protocol of the slow digestion CHO. It was hypothesized that the modified starch would result in slower absorption, attenuating the excursion of blood glucose and providing a more consistent concentration of glucose compared with the maltodextrin and water. The secondary aim was to compare the performance, in each condition, in a supramaximal time-to-fatigue test (TTF) after a sustained endurance bout. It was hypothesized that the slow release of the modified starch would result in a more prolonged availability and oxidation of exogenous glucose compared with maltodextrin. It was also hypothesized that the modified starch would result in a superior high-intensity TTF performance after a 3-hour treadmill run through the maintenance of blood glucose.

Methods

Experimental Approach to the Problem

A repeated measures study design was used to test the differences of a single bolus of a slow-absorbing vs. a fast-absorbing carbohydrate, in comparison with a water-only control, on physiological metrics throughout a sustained endurance run. The order of the 3 trials was randomized, and subjects completed all the trials, with approximately 7 days in between sessions. We collected data on each trial in a single day, with indirect calorimetry assessed at each time point to identify energy expenditure and substrate utilization. In addition, we collected heart rate (HR), ratings of perceived exertion (RPE), and blood finger sticks at each time point to assess physiological and subjective effort changes throughout the treadmill run.

Subjects were instructed to replicate their 24-hour diet from the familiarization period and refrain from alcohol consumption and any structured exercise for 24 hour before experimental trials. They were also instructed to follow their normal diet and training schedule throughout the duration of the research study. On the morning of each experimental trial, subjects were instructed to consume either no calories at all or a very small snack (100–250 calories) at least 2 hour before arrival to the laboratory. The subject's choice was documented, as was the specific food/drink consumed to have them replicate the pre-exercise conditions and keep them the same. This was performed based on personal preference of each subject to simulate their real-world choices before a serious run or race. Subjects were instructed to refrain from any foods that contain corn because of the natural abundance of ^{13}C found in corn-derived products.

Subjects

Ten male, (24-43 years) experienced endurance athletes were recruited from the local community using flyers and word of mouth. Eligible subjects were required to be actively endurance training (i.e., running) and had completed a running race of at least the marathon distance. Many of the study subjects had completed an ultramarathon distance of 50 km up to 100 mi within the past 3 years, and all were actively still racing. Subject characteristics and exercise trial data are presented in Table 1. Study subjects had the purpose of the study explained to them, as well as the risks and benefits of participation before signing a written informed consent that was approved by the institutional review board (protocol 16-1) of Marcy College, NY.

PreParticipation Screening. All study subjects were screened for the following inclusion criteria: men, ages 18–45 years, completed >marathon distance (26.2 miles), free from injury that would affect performance, not taking any medications or having any conditions known to alter energy metabolism or performance, and not allergic to corn. Study subjects had the purpose of the study explained to them, as well as the risks and benefits of participation before signing a written informed consent that was approved by the institutional review board (protocol 16-1) of Marcy College, NY.

Table 1
Subject Characteristics and Trial Averages for the experimental trials.*

Age: 32.4 ± 6.02 y	Speed: 9.8 ± 0.3 km·h^{-1} at 1% grade (min: 8.4; max: 11.3)
Height: 172.7 ± 3.9 cm	Intensity: 57.2 ± 4.7% $\dot{V}O_2$max
Body mass: 73.5 ± 9.8 kg	kcal total: 2,031.5 ± 21.4 kcal
BMI: 24.6 ± 3.4	Distance at 3 h: 29.4 ± 0.9 km
Body fat%: 15.3 ± 6.5	Temp: 21.7 ± 1.4 C
$\dot{V}O_2$max: 55.9 ± 4.8 ml·kg^{-1}·min^{-1}	Humidity: 54 ± 15%
Sleep: 6.1 ± 0.3 h	

*Values are presented as mean ± *SE*.

Procedures

Familiarization Testing. Before collection of data in the experimental trials, subjects completed baseline assessments. Subjects were instructed to not engage in any vigorous or prolonged activity the day before coming to the laboratory and also to refrain from alcoholic beverages. In addition, subjects were questioned on and instructed to maintain their current training schedule while engaged in the research study, and no specific races were allowed to take place within a week before the trials. Caffeine beverages were allowed the day before but were instructed to be replicated the same for the subsequent trials. Height and body mass were collected using a stadiometer and body composition using BOD POD (Cosmed USA, Chicago, IL). Aerobic capacity ($\dot{V}O_2$max) was determined using indirect calorimetry (Parvo Medics TrueOne 2400, Salt Lake City, UT), using the Maksud and Coutts protocol (26) on a high-speed treadmill (Trackmaster; JAS Fitness Systems, Carrollton, TX). This $\dot{V}O_2$max was used to set up the speed for the experimental trials.

Experimental Design. Subjects were studied under each of the 3 conditions, on separate occasions, assigned in a random order. Subjects arrived at the laboratory in the morning hours (each subject arrived to each of their trials within ~1 hour of each other) and had height, body mass, urine specific gravity (USG), and resting baseline measurements taken and then completed 180 minutes of a steady-state treadmill bout. Hydration status (USG) was confirmed to be below 1.020 before the initiation of the exercise bout, otherwise they had to consume 8 oz of water and wait 10–15 minutes. Fifteen minutes before the treadmill bout, subjects consumed one of 3 different beverages containing either carbohydrate or plain water. Carbohydrate drinks were originally plain and both were "flavored" with the same lemon-lime electrolyte powder to help blind the subjects to the study drink and keep the flavor profile similar. The single bolus, pre-exercise dose protocol was chosen to isolate the effects of what happens when only one dose is consumed, over the course of a sustained endurance bout. This allows a direct comparison to test the proposed understanding of the time course of the modified corn starch in comparison with a fast-acting CHO.

The endurance trial consisted of a steady-state run set at 57% $\dot{V}O_2$max, for a duration of 180 minute. Running speed was calculated from individual $\dot{V}O_2$max results and using the American College of Sports Medicine (ACSM) equation for running (38). Periodic finger stick, HR, RPE whole body (RPE_{WB}), RPE legs (RPE_L), GI distress, and breath measurements were taken throughout the entire run. Respiratory gases were collected through indirect calorimetry for a period of 10 minute at each measurement point. The experimental day layout is shown in Figure 1.

Time-to-Fatigue Test (TTF). On completion of the 180-minute run, the treadmill was stopped and the subjects had ~2 minute before beginning the TTF test, which was predetermined by the investigators and set at 110% $\dot{V}O_2$max. Because of some subject's estimated treadmill speed required to elicit this intensity and limits of the treadmill, the investigators included a slight incline for some of the subjects. The subjects were not able to change the speed of the treadmill and were blinded to the speed and grade. Immediately on volitional termination of the TTF test, a finger stick was collected, as well as RPE, HR, and body mass. The subjects were then free to go and were instructed on subsequent follow-up trials.

Drink Administration. In a blind and randomized order, subjects were assigned to the following beverage groups: a fast-absorbing maltodextrin (F), slow-absorbing, hydrothermally modified starch (S), or water (W). All drinks were prepared ahead of time and consisted of 16 oz of water, with the carbohydrate beverages containing 50 g of dissolved glucose, making them a 10.6% solution. The drinks were carefully prepared, and the dosage was based on the respective nutritional labels, with the quantities being measured out on a scientific scale. Each trial was randomized for the first 2 sessions for all subjects. Water was provided ad libitum throughout the entire run.

Both of the carbohydrate drinks used were corn derived and their glucose molecules contained naturally abundant ^{13}C. Confirmation of drink ^{13}C isotopic enrichment (IE) was determined with the analysis of S and F 50 g doses and pilot breath testing for ^{13}C enrichment (Metabolic Solutions, Nashua, NH). At each breath-sampling time point, pulmonary gas exchange was determined for the assessment of metabolic rate and energy substrate partitioning (i.e., fat vs. carbohydrate oxidation), and an aliquot of expired breath was collected in evacuated Exetainer tubes for subsequent determination of $^{13}CO_2$ IE by isotope ratio mass spectrometry (IRMS) (Metabolic Solutions, Nashua, NH). The concentration (i.e., percentage) of ^{13}C in the test drinks (ING) was determined so that the specific oxidation rates could be calculated.

Baseline breath sampling was performed, before ingestion of test drinks, to determine background ^{13}C, which was used to compare the differences in $^{13}CO_2$, to calculate oxidation rates of the exogenous beverage. Comparing the ^{13}C abundance of an international standard, Pee Dee Belemnite (PDB), to the measured ^{13}C of the breath sample, one is able to calculate the atom percent excess (APE) of ^{13}C in each breath. Subtracting out the baseline APE for each breath time point provides a corrected ^{13}C APE. Using $\dot{V}CO_2$ from indirect calorimetry, the concentration of drink tracer, and the percent excess ^{13}C in each breath, we are able to calculate exogenous oxidation rates of the drink. This calculation was performed using the following formula, similar to previously reported (19).

$$\text{Exogenous glucose oxidation} = \dot{V}_2 \times \{([APE_{EXP} - APE_{BKG}]/[ING - APE_{BKG}]) \times (1/k)\}$$

where APE_{EXP} is the ^{13}C IE of expired air during each exercise time point, APE_{BKG} is the ^{13}C IE of expired air before ingestion of carbohydrate drink (background), and $k = CO_2$, in liters, produced by the oxidation of 1 g of glucose ($k = 0.7467$).

Blood Metabolites. All blood samples were measured using finger stick (Figure 1 shows time points). Blood glucose and ketones were measured using their own meters using the Abbott Precision Xtra meter (Abbott, Alameda, CA). Lactate was measured using the Lactate Plus (Nova Biomedical, Waltham, MA).

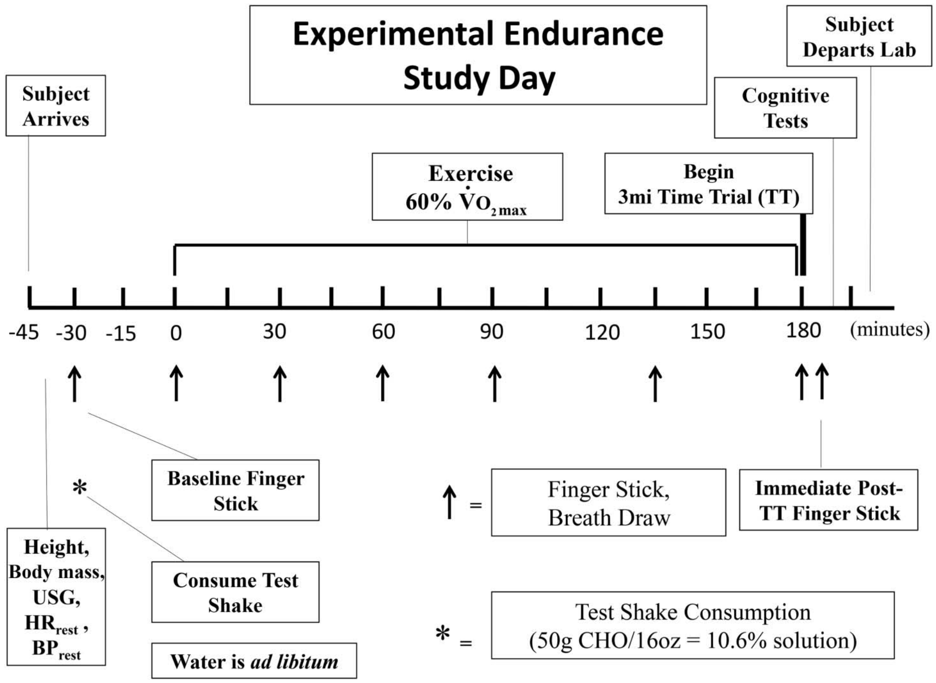

Figure 1. Experimental study day timeline.

Statistical Analyses

Data are presented as mean + *SE*. The average time point measurements and statistical analyses were calculated using 0–180 minutes (during exercise), whereas area under the curve (AUC) concentrations were calculated using all measurements (−15 to 180 minutes). Two-way comparisons among trials and across time points were made by analysis of variance (ANOVA) with repeated measures (RM-ANOVA) with post hoc comparisons using Tukey's HSD (honestly significant difference) test. In addition, one-way RM-ANOVA was used to compare the average values among trials. Cohen's *d* was used to calculate effect sizes (ESs), with 0.2, 0.5, and 0.8 considered an indication of small, medium, and large effects, respectively. Effect sizes and 95% confidence intervals (CIs) were calculated between the trials (F vs. S). Statistical analyses were performed using JMP 9.0 software (SAS Institute, Cary, NC). Statistical significance was set at 0.05.

Results

Metabolic Rate, Heart Rate, and Perception of Effort

Data are represented from the 180-minute exercise bout. There was no significant difference in trial for $\dot{V}O_2$, RPE_{WB}, or RPE_L, $p > 0.05$ (Table 2 shows the results). There was no significant difference in trial-by-time for $\dot{V}O_2$, EE, HR, RPE_{WB}, or RPE_L, $p > 0.05$ (Table 2 shows the results). There was a significant difference in the RER Trial for F vs. S vs. W, $p < 0.0001$ (Table 2 shows the results).

Metabolites

Blood Glucose. There was a significant difference in the average glucose concentration for the trial (F = 94.5 ± 1.5 and S = 97.1 ± 2.1 vs. W = 88.4 ± 2.7 $mg\cdot dl^{-1}$, $p = 0.024$; ES, −0.38; 95% CI, 90.1–96.6) but no significant difference between F and S, Figure 2A. There was a significant trial-by-time difference with F greater than S and W at 0 minute ($p < 0.05$), Figure 2B.

Individual glucose concentrations were reported for F and S, Figure 3.

Lactate and Ketones

There were no significant differences between trials in blood lactate concentration (F = 1.3 ± 0.1, S = 1.2 ± 0.1, W = 1.2 ± 0.1 $mmol\cdot L^{-1}$, $p > 0.05$; ES, 0.22; 95% CI, 1.1–1.4). There were no significant differences between trials in blood ketone concentrations (F = 0.16 ± 0.03, S = 0.21 ± 0.02, W = 0.26 ± 0.05 $mmol\cdot L^{-1}$, $p > 0.05$; ES, 0.83; 95% CI, 0.2–0.3).

Substrate Oxidation

Carbohydrate oxidation was significantly higher in F and S vs. W, but not significantly different from each other (F = 1.66 ± 0.3, S = 1.52 ± 0.2, W = 1.14 ± 0.1 $g\cdot min^{-1}$, $p = 0.0003$; ES, 0.30; 95% CI, 1.25–1.59). There were no significant trial-by-time differences among any groups for total carbohydrate oxidation, $p > 0.05$.

Fat oxidation was significantly lower in F vs. S and both F and S vs. W groups (F = 0.47 ± 0.08, S = 0.54 ± 0.08, W = 0.68 ± 0.07 $g\cdot min^{-1}$, $p = 0.0005$; ES, −0.14; 95% CI, 0.50–0.66). There were no significant trial-by-time differences between the groups, $p > 0.05$, (Figure 4).

Exogenous carbohydrate oxidation was significantly higher in F vs. S (F = 0.26 ± 0.04, S = 0.19 ± 0.03 $g\cdot min^{-1}$, $p = 0.0093$; ES, 0.68; 95% CI, 0.18–0.27). There was a significant trial-by-time difference, at time points 30 and 60 minutes, with F significantly greater than S, $p < 0.05$. The W trial was used for confirmation of negligible breath tracer (Figure 5).

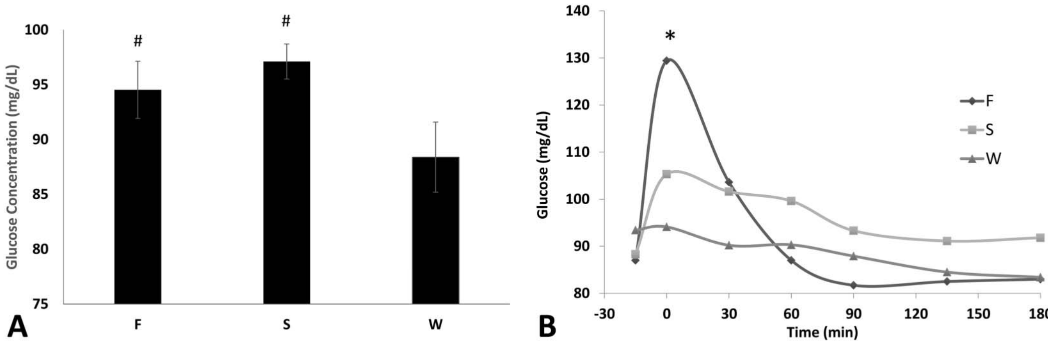

Figure 2. Glucose concentration. Values are presented as mean ± *SE*; $n = 10$. A, average glucose concentration for 180-minute run. B, glucose concentration across the entire trial. F = fast absorption carbohydrate trial; S = slow absorption carbohydrate trial; W = water-only trial; #Significantly different than W. *Significantly different from S and W trials at time 0 minutes ($p < 0.05$).

AUC Concentrations

Total carbohydrate oxidized (AUC) was significantly higher in F and S vs. W, but not significantly different from each other (F = 310.1 ± 25.3, S = 283.8 ± 26.0, W = 212.4 ± 23.1 g, $p < 0.0001$; ES, 0.32; 95% CI, 236.4–301.1), Figure 6A. Total exogenous carbohydrate oxidized (AUC) was significantly higher in F vs. S (F = 49.4 ± 2.1, S = 38.5 ± 1.7, $p = 0.023$; ES, 0.58; 95% CI, 29.0–44.0) Figure 6B. Total fat oxidation (AUC) was significantly lower in F and S vs. W (F = 89.6 ± 11.5, S = 102.6 ± 13.0, W = 129.4 ± 11.8, $p = 0.0002$; ES, −0.34; 95% CI, 92.0–122.4), Figure 6C. There were no significant differences in total kilocalorie expended (AUC) across the entire 180-minute treadmill run (F = 2,120.7 ± 64.6, S = 2,146.3 ± 78.7, W = 2,111.0 ± 79.6 kcal, $p = 0.54$; ES, −0.11; 95% CI, 2,040.8–2,211.3), Figure 6D.

Gastrointestinal Distress

There were very few GI complaints throughout the entire run. There were zero severe occurrences of any GI symptoms and only 2 single occurrences of anything in the moderate level. Gastrointestinal distress results are presented in Table 3.

Time-To-Fatigue Test

The TTF took place immediately after the 180-minute run. TTF average speed was 15.7 ± 0.3 km·h^{-1} (range 14.8–16.4) at a 2.6 ± 0.3% grade. There were no significant differences between the trials for the TTF at 110% $\dot{V}O_2$max (F = 156.1 ± 35.5, S = 223.7 ± 42.9, W = 161.1 ± 21.4 seconds, $p = 0.18$; ES, −0.54; 95% CI, 139.4–221.2).

Discussion

The ability to provide a sustained source of glucose is paramount to maintaining blood glucose concentrations and a continued source of fuel during prolonged endurance events. There are a multitude of options when it comes to providing this sustained source of glucose, and most are rapidly absorbing and require frequent, continued dosing to provide the desired effect. The aim of this study was to compare 2 different types of carbohydrate sources provided in a single bolus pre-exercise dose on carbohydrate and fat oxidation, blood metabolites, and performance during a 3-hour treadmill run. Although there were no differences in oxygen consumption, energy expenditure, HR, or RPE between the F and S groups, the S group had a significantly attenuated glucose excursion

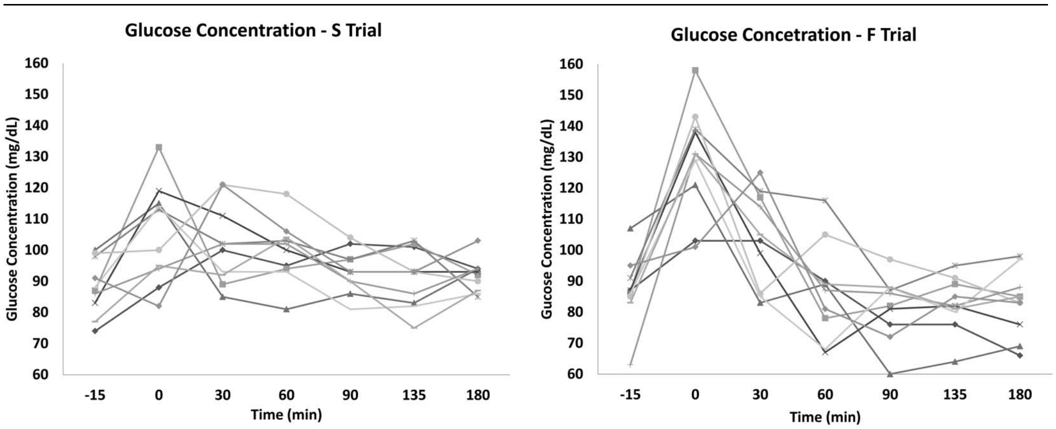

Figure 3. Individual glucose concentrations. Values are means; $n = 10$. F = fast absorption carbohydrate trial; S = slow absorption carbohydrate trial.

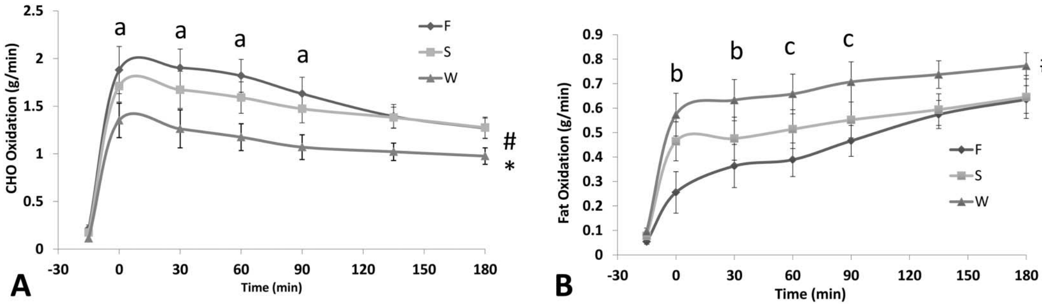

Figure 4. A, Carbohydrate oxidation and (B) fat oxidation. Values are presented as mean ± *SE*; $n = 10$. #F trial significantly different than S and W trials; *F trial significantly different than S and W trials; #S trial significantly different than F and W trials, $p < 0.05$. a = W significantly different than F and S trials at time points 0, 30, 60, and 90 minutes; b = F significantly different than S and W trials at time points 0 and 30 minutes; c = W significantly different than S and W trials at time points 60 and 90 minutes. CHO = carbohydrate; F = fast absorption carbohydrate trial; S = slow absorption carbohydrate trial; W = water-only trial.

right after the consumption of the carbohydrate drink (Figure 2), compared with the F group, which supports the hypothesis. This attenuated glucose excursion in the S group provided a more sustained and stable glucose concentration over the course of the entire 180-minute run.

These findings are in support of previous findings documenting both the rapid surge of glucose into the bloodstream after consuming maltodextrin (32,35) and a blunted glucose response shortly after consuming a similar low-glycemic type starch (9,13,32,35). The rapid increase in blood glucose, in the F group, is followed by a similar surge in exogenous glucose oxidation likely because of the increased flux of glucose to the working muscle (Figure 5). In a similar fashion, the attenuated glucose response in the S group resulted in a blunted but more sustained exogenous carbohydrate oxidation rate throughout the entire run. The use of stable isotope tracers allows the quantification of dietary carbohydrate oxidized over time, and the current study reported just about all of the exogenous carbohydrate recovered (49.4 g) for the F group, whereas the S group only had 77% (38.5 g) recovered, indicating the ability of the starch carbohydrate to provide a sustained supply of glucose into the blood, and therefore working muscle for a period longer than 180 minute. It can be seen in Figures 2B and 5 that the blood glucose and exogenous carbohydrate oxidation profile mirror each other, eluding to a cause and effect with glucose supply dictating exogenous oxidation rates (i.e., glucose-fatty acid cycle) (40).

Continuous carbohydrate consumption during exercise emphasizes the importance of exogenous carbohydrates to offset limited skeletal muscle glycogen stores. However, current evidence on the role of exogenous carbohydrate during exercise is inconclusive and does not clearly demonstrate that higher carbohydrate consumption actually spare skeletal muscle glycogen (8,12,14). The scarce reports that do suggest a possible skeletal muscle glycogen sparing indicate it may only spare some muscle glycogen in the first hour but then actually compensates for that glycogen sparing by using more glycogen in the subsequent hours. The ultimate result, as previously demonstrated, is no difference in glycogen utilization between carbohydrate consumption and water-only consumption during a 3-hour bout of exercise (36). Instead, research indicates that frequent, high amounts of exogenous carbohydrate, in comparison to water alone, spare the use of total fat for fuel, rather than glycogen. Our study found similar results. In the current study, we see that when an isocaloric large dose of carbohydrate is given, the slower absorption starch resulted in a significantly higher fat oxidation than the fast-absorbing carbohydrate. Supporting mechanisms for this finding are found in previous literature indicating there is an enhanced breakdown of fat in comparing the modified starch with

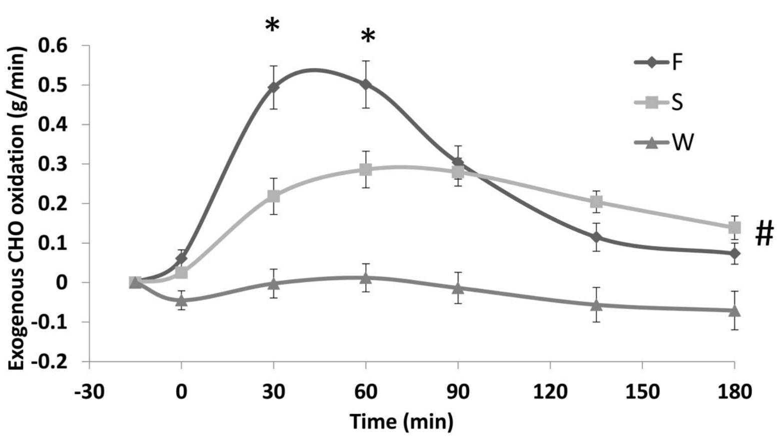

Figure 5. Exogenous carbohydrate oxidation. Values are presented as mean ± *SE*; $n = 10$. #F trial significantly different from the S trial, $p < 0.05$. *Significantly different from the S trial at time points 30 and 60 minutes, $p < 0.05$. CHO = carbohydrate; F = fast absorption carbohydrate trial; S = slow absorption carbohydrate trial; W = water-only trial.

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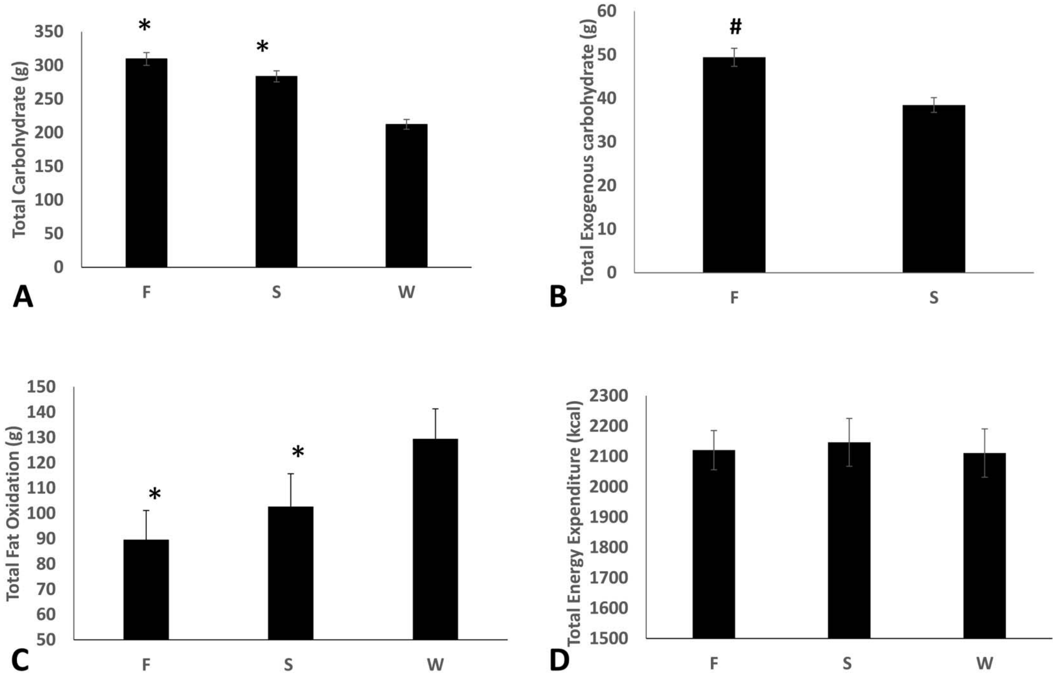

Figure 6. AUC. A, total carbohydrate oxidation AUC; (B) total exogenous carbohydrate oxidation AUC; (C) total fat oxidation AUC; and (D) total energy expenditure AUC. Values are presented as mean ± *SE*; $n = 10$. #F trial significantly higher than the S trial, $p < 0.05$. *Significantly different from W, $p < 0.05$.

maltodextrin, with glycerol and fatty acid concentrations significantly higher during exercise in the starch group (32). This can also be explained by the "glucose-fatty acid cycle reversed," whereby an attenuation in carbohydrate excursion leads to a decrease in carbohydrate oxidation and dictates a concomitant increase in fat oxidation (40).

The decision to provide only a single dose of a 50 g carbohydrate drink before the initiation of exercise and to not provide any additional calories during the run was based on the research question regarding the absorption and oxidation of a single bolus throughout the sustained endurance bout. This provides a better understanding of the individual time course that each respective carbohydrate type has when consumed in isolation before a sustained endurance run, especially given the proposed nature of the hydrothermally processed starch to have a slower absorption. In addition, it also showcases the continued reliance that endurance athletes have when consuming the fast-absorbing carbohydrate fuels. Reliance on rapid, continued dosing can be supported by looking at the frequent dosing strategies used in many of the carbohydrate supporting research studies, with many using 15–20 minutes doses (16–18,21,22,31), using carbohydrate intake rates as high as 100 $g \cdot h^{-1}$ (31). The more frequent dosing would blunt the fat oxidation rates even more than the current study saw in the F group. This frequency of dosing seen in many of the studies may seem less than ideal, considering an athlete playing soccer, tennis, or other sports lasting several hours may not have access to refueling at such a frequent recurrence, let alone longer distance endurance runners who do not have aid stations that close together, and therefore would need to carry with them whatever carbohydrates they need for the frequent dosing between aid stations. Although the current study did not test variations in the glucose response at different times of day, there would likely be differences if the study was repeated later in the day (late afternoon and early evening), as both resting glucose concentrations and postprandial glucose responses are demonstrated to be diurnal in their variation (1,5).

The current data support this more frequent fast-acting carbohydrate dosing requirement, given the rapid rise and fall of blood glucose within the period of 60 minute for the F group (Figure 2B). This necessity of frequency dosing can be alleviated by consuming such products that provide a more gradual and sustained glucose response, similar to the starch-type carbohydrates and those consumed in the current study (S group). Oftentimes nutritional intake, specifically carbohydrates, can cause GI distress and actually limit endurance performance (10,11,24,29), with typical sports drinks having a high osmolarity. However, the modified corn starch used in the current study had a low osmolarity. The current study collected a 12-item, 4-point scale GI distress questionnaire at each time point, but did not see any severe and only 2 moderate GI occurrence across all time points and trials (Table 3) likely because of the single bolus given pre-exercise. This can elude to an important point because the single bolus of fast-absorbing carbohydrate in the current study is more likely to be replaced with more numerous and frequent doses, which are those that are more associated with GI symptoms. The dosing strategy for the S group used in the current study, however, does support real-world practical dosing strategies, particularly for a similar moderate intensity, reducing the potential for GI distress out in the field.

Results from the current study reported no significant difference in the 110% $\dot{V}O_2max$ TT, immediately after the 180-minute run. There are similar previous reports comparing a fast-absorbing maltodextrin or glucose to a starch carbohydrate with no difference in exercise performance (2,13,32). This supports the use of a modified starch for endurance exercise with bursts of supramaximal intensity, in comparison with a fast-absorbing glucose, with no difference in performance.

Table 2
Values are mean ± *SE*; *n* = 10.*†

		Time (min)								
	Trial	−15	0	30	60	90	135	180	Averages	*p* (trial) ES, (95% CI)
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	F	4.0 ± 0.1	32.0 ± 2.5	32.0 ± 2.7	31.8 ± 2.6	31.8 ± 2.9	32.1 ± 2.8	32.4 ± 3.0	32.0 ± 0.6	0.47 (−0.16, 31.1–32.7)
	S	4.1 ± 0.4	32.2 ± 2.4	32.1 ± 2.2	32.2 ± 2.4	31.9 ± 2.6	32.1 ± 2.5	32.3 ± 2.7	32.1 ± 0.7	
	W	3.9 ± 0.3	31.3 ± 2.2	32.0 ± 2.5	31.3 ± 3.3	31.8 ± 2.8	32.1 ± 2.8	32.6 ± 3.0	31.9 ± 0.8	
RER	F	0.88 ± 0.03	0.91 ± 0.03	0.91 ± 0.02	0.90 ± 0.02	0.88 ± 0.02	0.85 ± 0.01	0.84 ± 0.01	0.88 ± 0.01‡	<0.0001‡ vs. S,W§ vs. F (0.22, 0.84–0.87)
	S	0.85 ± 0.02	0.88 ± 0.02	0.88 ± 0.02	0.87 ± 0.02	0.86 ± 0.01	0.85 ± 0.01	0.84 ± 0.01	0.87 ± 0.01§	
	W	0.80 ± 0.02§	0.85 ± 0.02	0.84 ± 0.02	0.83 ± 0.01	0.82 ± 0.01	0.81 ± 0.01	0.81 ± 0.01	0.83 ± 0.01	
EE (kcal·min^{-1})	F	1.3 ± 0.3	9.8 ± 1.9	10.9 ± 1.6	10.8 ± 1.4	10.7 ± 1.4	10.7 ± 1.0	10.8 ± 0.9	10.88 ± 0.3	0.02‖ vs. W (0.04, 10.4–11.3)
	S	1.4 ± 0.2	11.0 ± 1.4	11.0 ± 1.6	11.0 ± 1.4	10.9 ± 1.2	10.9 ± 1.0	10.9 ± 1.0	10.94 ± 0.4‖	
	W	1.3 ± 0.2	10.6 ± 1.5	10.7 ± 1.6	10.6 ± 1.2	10.6 ± 1.1	10.7 ± 0.9	10.9 ± 0.9	10.69 ± 0.4	
HR (BPM)	F	54 ± 1.5	130 ± 3.4	132 ± 4.1	136 ± 4.4	138 ± 4.1	141 ± 4.3	147 ± 4.0	137 ± 4.1	0.02‖ vs. W (−0.12, 133.0–141.5)
	S	56 ± 2.0	131 ± 3.8	134 ± 3.6	136 ± 4.5	138 ± 4.0	143 ± 3.6	150 ± 4.2	139 ± 3.8‖	
	W	54 ± 1.8	130 ± 3.4	132 ± 3.5	132 ± 3.6	133 ± 3.6	141 ± 3.7	148 ± 3.8	136 ± 3.4	
RPE (whole body)	F	6.1 ± 0.1	7.6 ± 0.5	8.9 ± 0.6	9.8 ± 0.5	11.2 ± 0.4	12.4 ± 0.4	13.3 ± 0.7	10.5 ± 1.1	0.43 (−0.31, 10.4–11.4)
	S	6.4 ± 0.3	8.1 ± 0.5	9.6 ± 0.6	10.7 ± 0.6	11.6 ± 0.6	12.4 ± 0.6	13.5 ± 0.8	11.0 ± 0.8	
	W	6.1 ± 0.1	8.1 ± 0.6	9.4 ± 0.4	10.7 ± 0.4	11.5 ± 0.4	12.8 ± 0.6	14.0 ± 0.8	11.1 ± 0.9	
RPE (legs)	F	6.1 ± 0.1	7.7 ± 0.4	8.7 ± 0.3	9.7 ± 0.4	10.7 ± 0.6	12.1 ± 0.6	13.5 ± 0.9	10.4 ± 1.1	0.60 (−0.24, 10.1–11.1)
	S	6.4 ± 0.3	8.3 ± 0.6	9.3 ± 0.5	10.2 ± 0.7	11.5 ± 0.7	12.0 ± 0.7	13.3 ± 0.9	10.8 ± 0.8	
	W	6.3 ± 0.2	8.2 ± 0.5	9.2 ± 0.4	10.0 ± 0.4	10.7 ± 0.4	12.3 ± 0.6	13.5 ± 0.8	10.7 ± 1.1	

*CI = confidence interval; ES = effect size; F = fast absorption carbohydrate trial; S = slow absorption carbohydrate trial; W = water-only trial; $\dot{V}O_2$ = oxygen consumption; RER = respiratory exchange ratio; EE = energy expenditure; HR = heart rate; RPE = ratings of perceived exertion.
†Metabolic, hemodynamic, and perception of effort.
‡Significantly different from the S and W trial.
§Significantly different than the F trial.
‖Significantly different than the W trial ($p < 0.05$).

Table 3
Gastrointestinal Distress.*

Question	Not at all						A little						Moderately						Very much					
	0	30	60	90	135	180	0	30	60	90	135	180	0	30	60	90	135	180	0	30	60	90	135	180
1 Nausea																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
2 Regurgitation or belching																								
F	10	9	10	10	10	10								1										
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
3 Heartburn																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
4 Feeling of fullness																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
5 Vomiting																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
6 Side ache																								
F	10	10	10	10	10	10																		
S	10	10	9	10	10	10			1															
W	10	10	10	10	10	10																		
7 Bloating																								
F	10	9	10	10	10	10		1																
S	10	9	9	9	9	10		1	1	1	1													
W	10	10	10	10	10	10																		
8 Abdominal cramps																								
F	10	10	10	9	9	10				1	1													
S	10	10	8	10	10	10			1															
W	10	10	10	10	9	10					1													
9 Flatulence																								
F	10	8	9	9	9	9		2	1	1	1							1						
S	10	10	10	9	9	9				1	1	1												
W	10	10	9	10	10	10			1															
10 Urge to defecate																								
F	10	10	10	10	10	10																		
S	10	10	10	10	9	9					1	1												
W	10	10	9	9	10	10			1	1														
11 Diarrhea																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		
12 Constipation																								
F	10	10	10	10	10	10																		
S	10	10	10	10	10	10																		
W	10	10	10	10	10	10																		

*n = 10. Total count of occurrence of each item, at each time point, for each trial.

Practical Applications

When running at a moderate intensity for a sustained period, our findings suggest there is a more stable glucose concentration and sustained exogenous glucose supply to the working muscle when consuming a commercially available modified corn starch in comparison with a fast-acting glucose source. This slower absorption in the S group starch may prevent any unwanted hyperglycemic and hypoglycemic responses. Future work may want to look at longer exercise durations that mimic ultraendurance events given the incomplete recovery of the slow absorption starch in the S group. Few studies have studied the metabolic shifts in fuel during ultraendurance events (5+ hours) in a laboratory setting (22). The slow absorption starch promoted a significantly higher fat oxidation than the fast-absorbing maltodextrin, which may provide to be useful for both maximizing total fat oxidation and decreasing the reliance on needed exogenous glucose sources during sustained endurance exercise. This can alleviate the fuel supplies needed to be carried or had during a prolonged endurance bout. Future work should also look at fat oxidation differences over the more sustained period but at higher intensities to more closely resemble "race paces" for endurance and ultraendurance distances. This could see the use of even higher single bolus doses of the slow absorption modified starch, given its low osmolarity and extremely prolonged supply into the bloodstream. For the practitioner, the results of this study demonstrate the possibility of athletes in competition or practice lasting 60–180 minutes who may benefit from the single dose, slow absorption carbohydrate strategy, given the demonstrated slow, but continual release up to at least 180 minute. This becomes even more evident in the latest endeavors of the "train low," fat adaptation strategies commonly being used today for training, whereas still providing some dietary carbohydrate (6,28). A modified starch provides a more stable absorption and blood glucose concentration over time while promoting fat oxidation.

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References

1. Aparicio NJ, Puchulu FE, Gagliardino JJ, et al. Circadian variation of the blood glucose, plasma insulin and human growth hormone levels in response to an oral glucose load in normal subjects. *Diabetes* 23: 132–137, 1974.
2. Bell R. Effect of Pre-exercise Ingestion of Modified Amylomaize Starch on Endurance Performance *Thesis* Ames. IA: Iowa State University, 2011. Available at: https://pdfs.semanticscholar.org/9a92/3343324cd1cb782e81445913d4bf28cf9c84.pdf?_ga=2.180381607.188773318.1612353000-984169165.1612353000.
3. Bergstrom J, Hermansen L, Hultman E, Saltin B. Diet, muscle glycogen and physical performance. *Acta Physiol Scand* 71: 140–150, 1967.
4. Bergstrom J, Hultman E. A study of the glycogen metabolism during exercise in man. *Scand J Clin Lab Invest* 19: 218–228, 1967.
5. Biston P, Van Cauter E, Ofek G, et al. Diurnal variations in cardiovascular function and glucose regulation in normotensive humans. *Hypertension* 28: 863–871, 1996.
6. Burke L. Ketogenic low CHO, high fat diet: The future of elite endurance sport?. *J Physiol* 599: 819–843, 2021.
7. Coggan AR, Coyle EF. Reversal of fatigue during prolonged exercise by carbohydrate infusion or ingestion. *J Appl Physiol* 63: 2388–2395, 1987.
8. Coyle EF, Coggan AR, Hemmert MK, Ivy JL. Muscle glycogen utilization during prolonged strenuous exercise when fed carbohydrate. *J Appl Physiol* 61: 165–172, 1986.
9. Daly ME, Vale C, Walker M, et al. Acute fuel selection in response to high-sucrose and high-starch meals in healthy men. *Am J Clin Nutr* 71: 1516–1524, 2000.
10. de Oliveira EP, Burini RC. Carbohydrate-dependent, exercise-induced gastrointestinal distress. *Nutrients* 6: 4191–4199, 2014.
11. de Oliveira EP, Burini RC, Jeukendrup A. Gastrointestinal complaints during exercise: Prevalence, etiology, and nutritional recommendations. *Sports Med* 44(suppl 1): S79–S85, 2014.
12. Fielding RA, Costill DL, Fink WJ, et al. Effect of carbohydrate feeding frequencies and dosage on muscle glycogen use during exercise. *Med Sci Sports Exerc* 17: 472–476, 1985.
13. Goodpaster BH, Costill DL, Fink WJ, et al. The effects of pre-exercise starch ingestion on endurance performance. *Int J Sports Med* 17: 366–372, 1996.
14. Hargreaves M, Briggs CA. Effect of carbohydrate ingestion on exercise metabolism. *J Appl Physiol* 65: 1553–1555, 1988.
15. Hetrick MM, Naquin MR, Gillan WW, Williams BM, Kraemer RR. A hydrothermally processed maize starch and its effects on blood glucose levels during high-intensity interval exercise. *J Strength Cond Res* 32: 3–12, 2018.
16. Hulston CJ, Jeukendrup AE. No placebo effect from carbohydrate intake during prolonged exercise. *Int J Sport Nutr Exerc Metab* 19: 275–284, 2009.
17. Jentjens RL, Jeukendrup AE. High rates of exogenous carbohydrate oxidation from a mixture of glucose and fructose ingested during prolonged cycling exercise. *Br J Nutr* 93: 485–492, 2005.
18. Jentjens RL, Moseley L, Waring RH, Harding LK, Jeukendrup AE. Oxidation of combined ingestion of glucose and fructose during exercise. *J Appl Physiol* 96: 1277–1284, 2004.
19. Jentjens RL, Venables MC, Jeukendrup AE. Oxidation of exogenous glucose, sucrose, and maltose during prolonged cycling exercise. *J Appl Physiol* 96: 1285–1291, 2004.
20. Jeukendrup A. A step towards personalized sports nutrition: Carbohydrate intake during exercise. *Sports Med* 44(suppl 1): S25–S33, 2014.
21. Jeukendrup AE, Borghouts LB, Saris WH, Wagenmakers AJ. Reduced oxidation rates of ingested glucose during prolonged exercise with low endogenous CHO availability. *J Appl Physiol* 81: 1952–1957, 1996.
22. Jeukendrup AE, Moseley L, Mainwaring GI, et al. Exogenous carbohydrate oxidation during ultraendurance exercise. *J Appl Physiol* 100: 1134–1141, 2006.
23. Kerksick CM, Wilborn CD, Roberts MD, et al. ISSN exercise & sports nutrition review update: Research & recommendations. *J Int Soc Sports Nutr* 15: 38, 2018.
24. Lavoue C, Siracusa J, Chalchat E, Bourrilhon C, Charlot K. Analysis of food and fluid intake in elite ultra-endurance runners during a 24-h world championship. *J Int Soc Sports Nutr* 17: 36, 2020.
25. Ma J, Jacques PF, Meigs JB, et al. Sugar-sweetened beverage but not diet soda consumption is positively associated with progression of insulin resistance and prediabetes. *J Nutr* 146: 2544–2550, 2016.
26. Maksud MG, Coutts KD. Comparison of a continuous and discontinuous graded treadmill test for maximal oxygen uptake. *Med Sci Sports* 3: 63–65, 1971.
27. Malik VS, Li Y, Pan A, et al. Long-term consumption of sugar-sweetened and artificially sweetened beverages and risk of mortality in US adults. *Circulation* 139: 2113–2125, 2019.
28. Melby CL. High-fat versus high-carbohydrate diets for optimal higher intensity endurance exercise performance: And the winner is. *J Physiol* 599:727-728, 2021.

29. Pfeiffer B, Stellingwerff T, Hodgson AB, et al. Nutritional intake and gastrointestinal problems during competitive endurance events. *Med Sci Sports Exerc* 44: 344–351, 2012.
30. Potgieter S. Sport nutrition: A review of the latest guidelines for exercise and sport nutrition from the American College of Sport Nutrition, the International Olympic Committee and the International Society for Sports Nutrition. *South Afr J Clin Nutr* 26: 6–16, 2013.
31. Roberts JD, Tarpey MD, Kass LS, Tarpey RJ, Roberts MG. Assessing a commercially available sports drink on exogenous carbohydrate oxidation, fluid delivery and sustained exercise performance. *J Int Soc Sports Nutr* 11: 8, 2014.
32. Roberts MD, Lockwood C, Dalbo VJ, Volek J, Kerksick CM. Ingestion of a high-molecular-weight hydrothermally modified waxy maize starch alters metabolic responses to prolonged exercise in trained cyclists. *Nutrition* 27: 659–665, 2011.
33. Romijn JA, Coyle EF, Sidossis LS, et al. Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *Am J Physiol* 265: E380–E391, 1993.
34. Romijn JA, Coyle EF, Sidossis LS, Rosenblatt J, Wolfe RR. Substrate metabolism during different exercise intensities in endurance-trained women. *J Appl Physiol* 88: 1707–1714, 2000.
35. Sands AL, Leidy HJ, Hamaker BR, Maguire P, Campbell WW. Consumption of the slow-digesting waxy maize starch leads to blunted plasma glucose and insulin response but does not influence energy expenditure or appetite in humans. *Nutr Res* 29: 383–390, 2009.
36. Stellingwerff T, Boon H, Gijsen AP, et al. Carbohydrate supplementation during prolonged cycling exercise spares muscle glycogen but does not affect intramyocellular lipid use. *Pflugers Arch* 454: 635–647, 2007.
37. Thomas DT, Erdman KA, Burke LM. American College of Sports Medicine joint position statement. Nutrition and athletic performance. *Med Sci Sports Exerc* 48: 543–568, 2016.
38. Thompson PD, Arena R, Riebe D, Pescatello LS; American College of Sports M. ACSM's new preparticipation health screening recommendations from ACSM's guidelines for exercise testing and prescription, ninth edition. *Curr Sports Med Rep* 12: 215–217, 2013.
39. van Loon LJ, Greenhaff PL, Constantin-Teodosiu D, Saris WH, Wagenmakers AJ. The effects of increasing exercise intensity on muscle fuel utilisation in humans. *J Physiol* 536: 295–304, 2001.
40. Wolfe RR. Metabolic interactions between glucose and fatty acids in humans. *Am J Clin Nutr* 67: 519S–526S, 1998.