Timing Carbohydrate Beverage Intake During Prolonged Moderate Intensity Exercise Does Not Affect Cycling Performance

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ABSTRACT

Int J Exerc Sci 2(1) : 4-18, 2009. Carbohydrate beverages consumed during long-term exercise have been shown to attenuate fatigue and improve performance; however, the optimal timing of ingestion is unclear. Therefore, the purpose of this study was to determine if timing the carbohydrate ingestion (continual loading (CL), front-loading (FL), and end-loading (EL)) during prolonged exercise influenced exercise performance in competitive cyclists. Ten well-trained cyclists completed three separate exercise bouts on a bicycle ergometer, each lasting 2 hours at an intensity of ~67% VO_2 max, followed by a 15-minute "all out" time trial. In the CL trial, a carbohydrate beverage was ingested throughout the trial. In the FL trial, participants ingested a carbohydrate beverage during the first hour and a placebo beverage during the second hour. In the EL trial, a carbohydrate beverage was ingested during the second hour and a placebo during the first hour. The amount of carbohydrate consumed (75 g) was the same among conditions. The order of conditions was single-blinded, counterbalanced, and determined randomly. Performance was measured by the work output during the 15-minute performance ride. There were no differences in work output among the three conditions during the final time trial. In the first hour of exercise, peak venous blood glucose was highest in the FL condition. In the second hour, peak venous blood glucose was highest in the EL condition. Following the time trial, venous blood glucose levels were similar among CL, FL, and EL. Overall, the timing of carbohydrate beverage consumption during prolonged moderate intensity cycling did not alter cycling performance.

KEY WORDS: Carbohydrate oxidation, supplementation, rate of perceived exertion, heart rate, power

INTRODUCTION

Interest in endurance activity has increased dramatically in recent years. In 2007, over 407,000 people in the United States completed an official marathon, which represents a 27% increase from the 299,000 finishers in 2000 (27). Triathlon participation also increased by 63% (121,000 to 323,000) from 2000 to 2007 based on race-day insurance licensing and annual membership in USA Triathlon (29). With the steep rise in participation for these endurance events, there is a growing need for endurance athletes to use proper nutrition for maximum performance.

Dietary carbohydrate intake is important for physical performance and is generally considered more important than the consumption of protein or fat during exercise (2, 10, 13). Studies in exercisers indicate that increasing carbohydrate consumption prior to long-term exercise may increase glycogen stores leading to improved endurance capacity and increased time to exhaustion (8, 10, 28). Further, carbohydrate ingestion during exercise has been shown to delay fatigue, improve performance, and increase sprint capacity (3, 4, 6, 7, 20, 28). During exercise, general carbohydrate ingestion recommendations are 30-60 grams per hour depending on the intensity and duration of the exercise (9, 14, 16, 18). However, it is unclear whether or not the timing of ingestion of carbohydrate impacts exercise performance during prolonged moderate intensity exercise (60-75% of VO_2 max) (6, 20, 28). For example, it is unclear whether to consume the recommended dosages of carbohydrate upon initiation of exercise, throughout the exercise session, or toward the end. A better timing strategy could result in improved performance during prolonged exercise.

Furthermore, only one known study has examined carbohydrate timing during exercise and its effects on performance. McConell et al. showed that carbohydrate ingestion towards the end of moderate intensity exercise did not improve performance compared to carbohydrate ingested throughout the exercise session (21). The performance effects are difficult to interpret since this study used a quantity (78.25 grams per hour) of carbohydrate above the 30-60 grams per hour recommended range using a 21% carbohydrate beverage solution which is far above the 6-8% maximally effective absorptive range in which commercially available carbohydrate sports drink are available (9, 13). Additionally, McConell et al. did not investigate the effects of consuming carbohydrate towards the beginning of an exercise session as opposed to other time points. The present study sought to include this timing strategy by investigating the effects of front-loading carbohydrate to see if performance differences existed between end-loading and/or continual loading.

Additionally, carbohydrate beverages are often consumed during endurance competition, but the most effective timing of carbohydrate consumption during this period is generalized without supporting scientific evidence. If a particular timing strategy elicited improvements in performance, the carbohydrate ingestion protocol would represent a safe and legal performance enhancer for endurance athletes.

Thus, the purpose of this study was to determine if the timing of carbohydrate ingestion during prolonged moderate intensity exercise influenced exercise performance in competitive cyclists. It was hypothesized that continual loading (CL) of carbohydrate would result in a greater performance in cycling time compared to front-loading (FL) or end-loading (EL) of carbohydrate during prolonged moderate intensity exercise.

METHOD

Participants and Pre-Trial Assessments
Ten well-trained cyclists (30.1 ± 1.9 y, mean ± SEM) were recruited for this study, which was approved by the Southern Illinois University Edwardsville Institutional Review Board. All subjects were currently undergoing regular cycle training, which included at least five hours of cycling per week. Prior to participation, subjects signed an informed consent and completed a general medical questionnaire and physical activity readiness questionnaire (PAR-Q). Participants were excluded if they were under the age of 18 years, used medications that could affect metabolism (including birth control for women), were habitual smokers or tobacco users, were pregnant, likely to become pregnant, or lactating, and if they were involved in a major athletic event within the span of the study that significantly altered their regular diet (i.e. carbohydrate loading) or caused extreme deviations from a regular training protocol. Additionally, participants underwent pre-trial (baseline) assessments that included body composition, heart rate, maximal oxygen consumption (VO_2 max), and lactate threshold assessment.

Body Composition
Body composition was assessed using whole body plethysmography via the BOD POD (Life Measurement, Inc., Concord, California). Participants followed standard procedure for the BOD POD, which included wearing skin-tight bike shorts or a swimsuit and fitted head cap to ensure an accurate assessment. Body composition was calculated using the subject's body volume measurement obtained from the BOD POD and corrected for thoracic volume and surface area artifact as previously described (11, 12). The mass of the subject is then divided by this adjusted body volume to obtain the density of this subject. This density value is placed into a formula to calculate body fat percentage based on the two-compartment model as proposed by Siri (26). Since the Siri equation is used for Caucasian participants, and all participants in this study were Caucasian, the same equations were used for all participants.

Maximal Oxygen Consumption, Heart Rate, and Lactate Threshold
Exercise testing was performed on a Velotron cycle ergometer using the Velotron Coaching (version 1.5) software (Racermate, Inc., Seattle, Washington). A Polar heart-rate monitor (Polar Electro, Finland) was interfaced with a TrueOne 2400 metabolic measurement system (ParvoMedics, Sandy Lake, Utah), which was used to calculate oxygen consumption from expired gases. The metabolic measurement system was warmed up for 30 minutes and calibrated according to manufacturer's specifications using 16% oxygen and 4% carbon dioxide gases. The flowmeter was calibrated using a known volume of air from a 3-Liter syringe. Participants were then fitted with a face mask connected to a one-way valve that fed expired air through flexible tubing to a mixing chamber. Expired air was then analyzed for oxygen and carbon dioxide and averaged every 15 seconds. Maximal oxygen consumption was elicited using a modified protocol from Roels et al. (23), which was terminated when participants reached volitional failure. The modified protocol consisted of the participants' cycling resistance (work load) being increased by 25 watts (as opposed to

previous 50-watt increases in earlier stages) once 300 watts of resistance was achieved for men and 200 watts achieved for women. Roels et al., used 25-watt increases (as opposed to 50-watt increases in earlier stages) once a respiratory exchange ratio of 1.0 was achieved (23). Lactate threshold was estimated simultaneously with VO_2 max using a portable Accutrend® lactate analyzer (Accutrend, Hawthorne, NY) via finger-prick blood collection every 3 minutes into each stage. Before each blood collection, the finger tip was cleaned with a 70% isopropyl alcohol pad and wiped dry. The finger was pricked using an autolet lancet device and a capillary tube collected the venous blood, which was then transferred to a lactate strip and presented to the analyzer. Lactate threshold was estimated to be the point at which venous blood lactate levels increased significantly (approximately 1 mmol) above the resting level (17). Following a 15-minute recovery after the VO_2 max test, participants completed a 15-minute "all-out" time trial to familiarize themselves with the performance phase of the following three experimental trials. From this pre-trial, 67 ± 1% VO_2 max was calculated and the associated heart rate, lactate, and work load levels were extrapolated for the subsequent 3 experimental sessions.

Experimental Protocol

Following pre-trial assessments, each participant completed three separate single-blinded, counter balanced exercise sessions. These sessions were randomly assigned and each differed only in the timing of carbohydrate ingestion (CL, FL, and EL). Prior to each of the three experimental trials, participants completed a 3-day dietary wash-in that consisted of their typical "pre-competition" diet. Coinciding with the wash-in, participants kept food records on Days -3, -2, and -1 so that actual dietary intake could be quantified. Food type and amount from the 3-day food records were entered into a food database and analyzed using the Food Processor nutritional software (ESHA Research, 2006). Additionally, each participant recorded their food intake on the day of the trial (Day 0), avoided a large meal three hours before each trial, and completed the same type and volume of exercise they normally undergo in the two days prior to a competition (with the exception of an abstention from exercise 12 hours prior to the experimental trial). Participants began each of their three trials at the same time of day to maintain consistency in the exercise and dietary wash-in. The volume of exercise was identical for each exercise session (5-minute warm-up, 5-minutes at steady state of ~67% of their VO_2 max, 2 hours of cycling at ~67% VO_2 max, followed by an additional 15-minute "all out" time trial); however, the timing of carbohydrate ingestion differed during each trial (see below). To allow adequate time for recovery, each exercise session was spaced at least one week apart but no more than two weeks a part.

Timing of Carbohydrate Ingestion

In all three experimental cycling trials, participants consumed ~75 g of carbohydrate over the course of two hours with the only difference among the trials being the timing of the consumption. In the FL trial, participants ingested a 6% carbohydrate-electrolyte (Gatorade ®) beverage at 15-minute intervals during the first hour (0, 15, 30, 45 minutes) and a placebo beverage, containing minimal carbohydrate or electrolytes (1%) and an artificial sweetener, at 15-minute intervals during the second hour (60, 75, 90, 105 minutes). In the CL trial, a 3.5% carbohydrate beverage was ingested at 15-minute intervals throughout the entire 2-hour trial to ensure that participants received the same total quantity of carbohydrate (~75 grams) in the same total volume of solution. In other words, half of a 6% carbohydrate beverage plus 1% placebo (7% total) equaled 3.5% solution. In the EL trial, participants ingested the placebo beverage, containing minimal carbohydrate or electrolytes (1%) at 15-minute intervals during the first hour (0, 15, 30, 45 minutes) and the 6% carbohydrate-electrolyte beverage at 15-minute intervals during the second hour.

To disguise the nature of the study, all solutions were given in single-blind fashion. Participants were unaware which of the experimental trials they were undergoing or that a difference existed in the carbohydrate beverages among trials. In order to help blind participants to the differences among the carbohydrate and placebo beverages, multiple flavors of the same solution were also given randomly.

Prior to each exercise trial, participants were instructed to void if needed. The participants were then fitted with a heart rate monitor and face mask interfaced with the metabolic cart, which was calibrated in the same manner as described above. Next, pre-exercise heart rates and VO_2 levels were assessed for 5 minutes and participants were allowed to warm-up on the cycle ergometer for five minutes at a self-selected intensity. During this time, the participants adjusted their fit on the cycle ergometer for appropriate comfort. A fan was present to alleviate thermal stress for all participants. After the warm-up, participants were instructed to steadily increase their resistance and effort until they were informed by the investigator that they had reached ~67% of their VO_2 max. At this point, participants pedaled for five additional minutes to confirm steady-state. Just before the five minutes was completed, a finger-prick blood sample was taken as described above and analyzed for venous blood glucose and lactate. Blood glucose was assessed using a glucometer (Contour®) with test strips (Bayer HealthCare, Mishawaka, IN) and lactate was determined, as at baseline, using the portable lactate analyzer.

Once initial blood glucose and lactate assessments were completed, the mask was removed for the cyclists comfort, and the official start of the two hours of cycling at ~67% VO_2 max began. Each 2 hour session was broken into 15 minute intervals. Twelve minutes into each interval, the mask and hose were again fitted on the participant and allowed to equilibrate for 3 minutes. At each 15-minute interval (0, 15, 30, 45, 60, 75, 90, 105, 120 minute time points), venous blood glucose, venous blood lactate, heart rate, rating of perceived exertion (RPE, Borg's 6-20 scale), and oxygen uptake rate were assessed and recorded immediately prior to ingestion of glucose. If a change in the VO_2 had occurred at each 15 minute interval, the workload was adjusted to bring the VO_2 back to ~67% VO_2 max. To facilitate maintenance of a steady VO_2, participants were able to constantly view their real-time heart rate on a watch receiver and were instructed to keep their heart rate within a certain range based upon ~67% of their VO_2 max.

Performance Stage/Time Trial

Once the prescribed data collection was completed at the end of the 2-hour cycling trial, participants immediately transitioned to the 15-minute "all-out" time trial with continuous collection of expired gases and heart rate. Participants were told that they should treat the next 15 minutes as a race. The amount of work generated (kJ), the distance traveled (km), and the average speed ($km \cdot hr^{-1}$) from this cycling output was recorded with Velotron 3D (version 1.0) software (RacerMate, Inc., Seattle, Washington). The participants were able to manually adjust the resistance to various fixed workloads at their discretion in a manner equivalent to riding a racing bike with a 53 or 39 front chain ring and a standard 9-sprocket 12 to 25 rear chain ring. The work output and speed data was determined using the software's programming code and collected at 5-second intervals. The 15-minute average work output and speed were then calculated from the averages of the intervals. The participants were not able to view their work output, distance, or speed. Immediately following the completion of the performance stage, participant venous blood glucose, lactate, and RPE were again collected and participants were allowed to cool-down. Participants were then reminded of their next appointment (if applicable) and thanked for their time.

Statistical Analyses

This study employed two separate designs and analyses. The first was a randomized group design in which the independent variable was carbohydrate group with three levels (FL, CL, and EL). The dependent variable was the total work, distance, and speed on the 15-minute "all-out" time trial and this was measured using One-Way ANOVAs. The significance level was set at $P<0.05$ for all trials.

The second was a pretest-posttest randomized-group design. These measurements were taken in three separate between-treatment conditions. The 10 (time points) x 3 (treatments) factorial design with repeated measures and dependent variables (venous blood glucose, venous blood lactate, heart rate, and VO_2) were analyzed using ANOVAs with repeated measures on the first factor and a Tukey post hoc test was used to identify the source of significant variance.

Additionally, the area under the curve for blood glucose and blood lactate was assessed among the three experimental trials and measured using One-Way ANOVA.

Statistical analysis was conducted using SPSS for Windows (SPSS, Inc., 2007). The significance level was set at $P<0.05$ for the tests and was controlled for any main effects of the treatment condition and repeated measures as well as pair wise comparisons using the Bonferroni technique. Upon data analysis, it was discovered that the assumptions for parametric tests were met and therefore transformation of the data was not required.

RESULTS

Participants were ten (eight male; two female) healthy, well-trained cyclists. All participants were Caucasian and the females were premenopausal. Physical characteristics are shown in Table 1.

Table 1. Participant Characteristics

Gender (m,f)	8, 2
Age (y)	30.1 ± 1.9
Height (cm)	173.0 ± 2.1
Weight (kg)	72.2 ± 2.6
BMI (kg·m²)	24.2 ± 0.6
Body Fat (%)	13.0 ± 1.4
VO_2 max (L·min^{-1})	4.15 ± 0.27

Values are mean ± SEM (N = 10).

Dietary Intake

Participants consumed a self-selected pre-competition diet during the three days prior to each trial and on the day of each trial (Table 2). As all participants were highly motivated athletes, all food records were completed and turned in. These records indicated that the participants consumed the same type of foods and number of calories prior to each of their trials. There was no difference among experimental conditions for energy, carbohydrate, fat, or protein intake. Participants generally consumed a high carbohydrate and low fat diet leading up to the experimental exercise bout but tended to eat a much higher percentage of carbohydrate on the day of the exercise session.

VO_2 max, RPE, and Heart Rate

VO_2 held steady at an average of 38.0 ± 0.3 ml·kg^{-1}·min^{-1} (2.75 ± 0.2 L·min^{-1}) among all three trials during 2-hour carbohydrate feeding stage before spiking to an average of 48.6 ± 0.2 ml·kg^{-1}·min^{-1} (3.54 ± 0.1 L·min^{-1}) during the time trial (mean ± SEM). As shown in Figure 1, RPE increased steadily (12 ± 0 to 15 ± 0) during the carbohydrate feeding stage but was not significantly different among experimental trials. During the 15-minute time trial, RPE spiked to 19 ± 0 but the degree of increase was not significantly different among all three trials. As shown in Figure 2, heart rate responded without significant variation among the three trials, ranging from an average of 142 ± 2 beats per minute (bpm) at the start and drifting to 150 ± 3 bpm by the end of the 2-hour carbohydrate feeding stage. The heart rate spiked to 173 ± 4 bpm at the conclusion

Table 2. Macronutrient and Energy Intake Three Days Prior to and the Day of Cycling Protocols

	Energy (kcal)	CHO %	FAT %	PRO %
3-Days Prior to Trial*†				
Continual	2617 ± 101	56.6 ± 1.9	26.8 ± 2.8	17.6 ± 1.1
Front	2631 ± 111	57.0 ± 2.1	25.8 ± 2.2	16.8 ± 0.8
End	2495 ± 119	54.6 ± 2.5	27.4 ± 1.9	17.5 ± 1.4
Day of Trial				
Continual	1046 ± 167	73.7 ± 5.0	15.6 ± 4.2	13.8 ± 1.8
Front	1076 ± 174	71.9 ± 5.2	17.0 ± 4.4	13.8 ± 1.5
End	1061 ± 186	72.0 ± 4.8	16.3 ± 3.3	13.9 ± 1.5

Values are mean ± SEM (N = 10). *Each value indicates the average of the 3-days for the 10 subjects. †Macronutrient percentages of "3-Days Prior to Trial" do not add up to 100% due to rounding as well as exclusion of the macronutrient, alcohol. No significant differences (P<0.05) exist among the conditions.

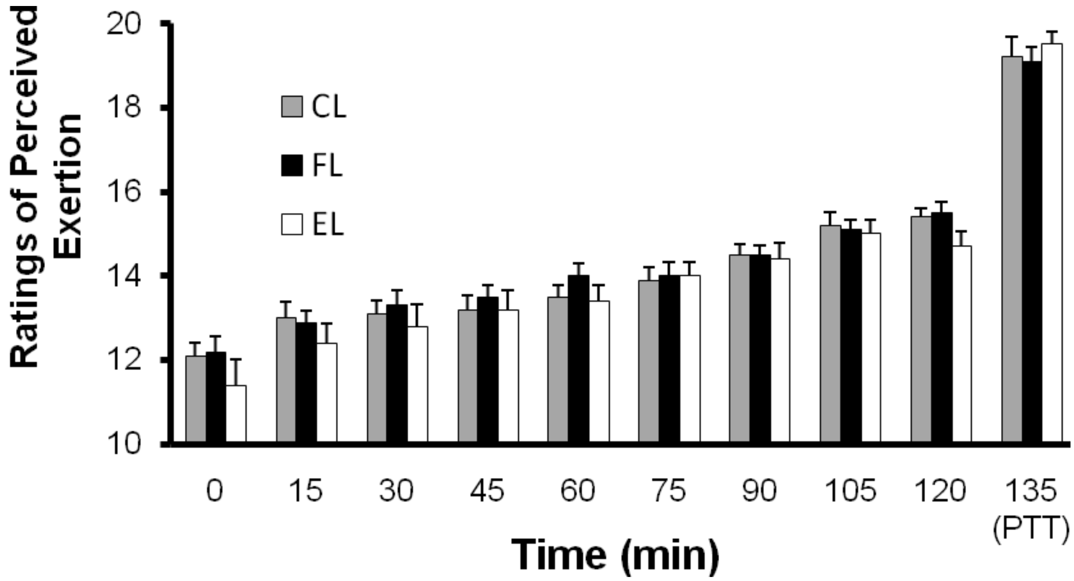

Figure 1. RPE was not significantly different (P<0.05) among the three conditions at all time points during the trials and after the time trial (PTT). CL: Continual load, FL: Front load, EL: End load, PTT: Post-time trial. Values are mean ± SEM (N=10).

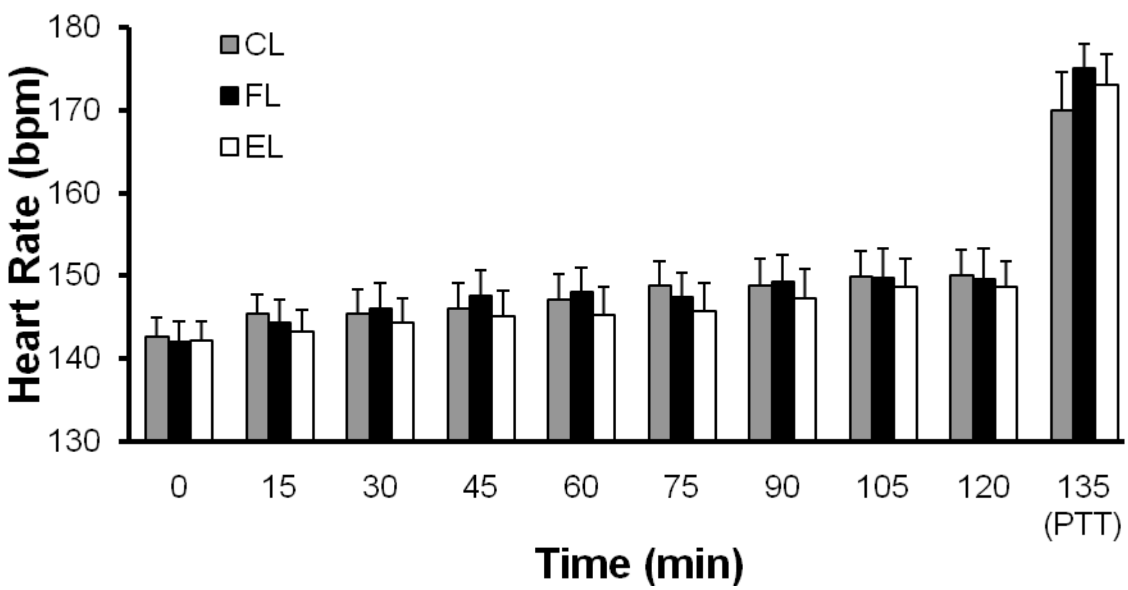

Figure 2: Heart rate at 135 (PTT) minutes was significantly greater (P < 0.05) than previous time points for each given condition. CL: Continual load, FL: Front load, EL: End load, PTT: Post-time trial. Values are mean ± SEM (N=10).

of the time trial. VO_2 max, RPE, and heart rate were all significantly greater at the conclusion of the time trial compared to previous time points.

Table 3. Venous Blood Lactate During Experimental Trials

	Time (min)			
	0	60	120	135 (PTT)
Lactate (mmol $\cdot L^{-1}$)				
Continual	3.5 ± 0.3	3.6 ± 0.5	3.4 ± 0.4	7.3 ± 0.9*
Front	3.1 ± 0.3	3.1 ± 0.2	4.1 ± 0.6	7.0 ± 1.0*
End	3.5 ± 0.4	3.6 ± 0.3	3.8 ± 0.4	7.8 ± 0.5*

Values are mean ± SEM (N = 10). No significant differences (P<0.05) exist among the conditions. * denotes that lactate at 135 (PTT) minutes was significantly greater (P<0.05) than 0, 60, and 120 minutes for each given condition. PTT: post time-trial.

Venous Blood Lactate

As shown in Table 3, venous blood lactate held steady and without significant variation among the three trials at an average of 3.5 ± 0.1 mmol$\cdot L^{-1}$ during 2-hour carbohydrate feeding stage before spiking to 7.4 ± 0.4 mmol$\cdot L^{-1}$ at the conclusion of the time trial. There was also no difference in the area under the blood lactate curve among the three experimental conditions. The venous blood lactate concentration during the 2-hour stage was an average of 0.1 mmol$\cdot L^{-1}$ above the participants' estimated lactate threshold.

Venous Blood Glucose

As shown in Figure 3, pre-exercise venous blood glucose was not significantly different between all three conditions. During the carbohydrate feeding stage, the FL condition was associated with higher venous blood glucose in the first hour and lower levels during the second hour, CL was associated with slightly elevated venous blood glucose levels throughout the trial, and EL was associated with lower venous blood glucose during the first hour and higher levels during the second hour. Venous blood glucose was significantly different in FL compared to EL (P< 0.05) at all time points except 0 and 135 (post-time trial). FL was significantly different than CL (P<0.05) at the 30, 60, and 90 minute time points. CL was significantly different than EL (P< 0.05) at all time points between and including 45 and 120 minutes. Following the 15-minute time trial (at 135 minutes), venous blood glucose reached the same endpoint in all three conditions. Additionally, there was also no difference in the area under the blood glucose curve among the three experimental conditions.

Cycling Performance

Speed, distance, and work output were all measured during the 15-minute time trial following the 2-hour carbohydrate loading phase of the experimental trials (Table 4). The FL condition led to a significant increase (P<0.05) in speed and distance compared to the CL condition, but not in work output. All other comparisons of conditions showed no significant difference in speed, distance, and work output among the three different carbohydrate loading conditions.

DISCUSSION

Contrary to the hypothesis, there was no clear performance advantage with any single carbohydrate timing strategy.

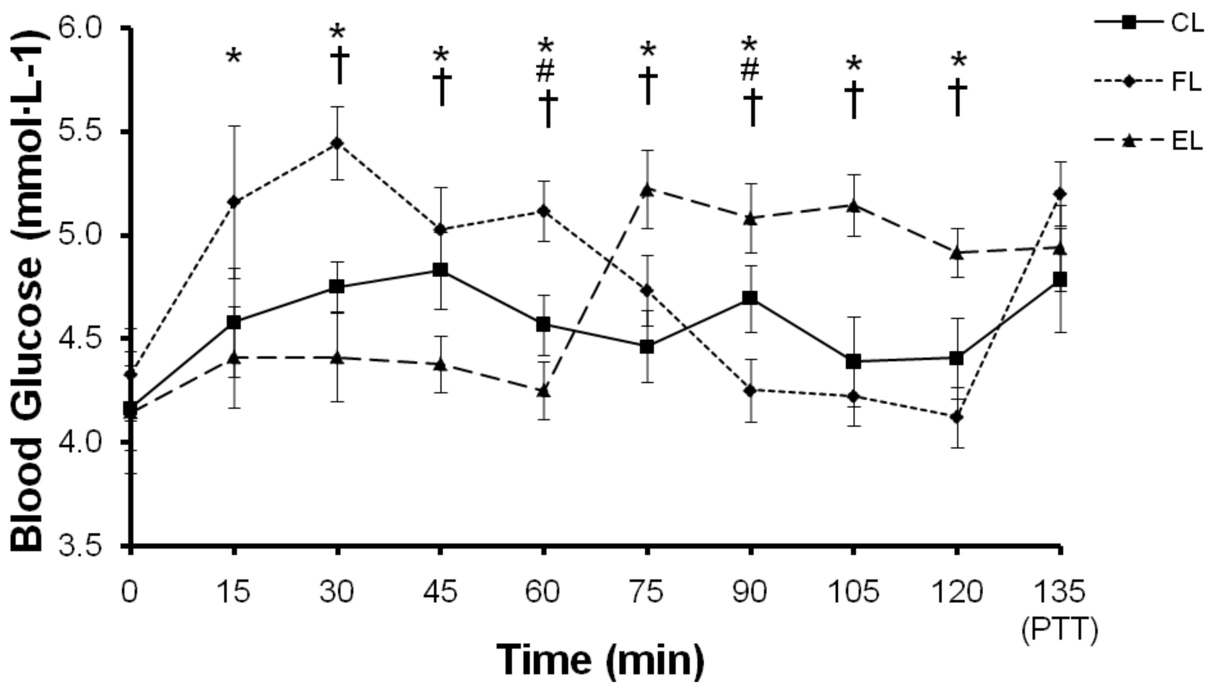

Figure 3. CL: Continual load, FL: Front load, EL: End load, PTT: Post-time trial. * denotes FL different from EL ($P<0.05$). # denotes FL different from CL ($P<0.05$). † denotes EL different from CL ($P<0.05$). Values are mean ± SEM (N=10).

However, FL led to a slight significant advantage over CL when comparing speed and distance traveled during the 15-minute time-trial. Nevertheless, in terms of work output, this performance advantage of FL, while present, was not significantly higher than CL.

This slight discrepancy between work output and speed/distance was likely due to inherent limitations of the cycle ergometer equipment and software regarding the non-linear nature between work output and speed as postulated by Allen and Coggan (1). To summarize their conclusion, they conclude that cycling trainers with power meters, including Velotron cycle ergometers, generate rolling resistances that account for a fraction of the flywheel's power demand. Therefore, it is difficult to "get the power down" when the rotational speed of the flywheel is high. In other words, when the wheel is spinning rapidly (as in a sprint finish), distance is being accumulated although there is an inequivalent amount of direct work input by the cyclist. Recording on 1-second intervals or quicker, unlike the 5-second intervals used in this study, might have minimized the work output & speed/distance discrepancy. Regardless, the primary standard on which to measure performance of a cyclist in a laboratory setting is work output since speed is effected by many conditions set forth by the experimenter and setting. Because the work output was not different between the three trials, it can be safely assumed that there are no differences in performance among the three carbohydrate timing protocols.

Table 4. Post-Time Trial Physiological and Performance Measures

	CL	FL	EL
Total Work (kJ)	216 ± 15	229 ± 14	228 ± 15
Speed ($km \cdot hr^{-1}$)	35.24 ± 1.00	36.26 ± 0.92*	35.92 ± 0.93
Distance (km)	8.80 ± 0.25	9.05 ± 0.23*	8.98 ± 0.24
HR (bpm)	170 ± 5	175 ± 3	173 ± 4
VO_2 max ($L \cdot min^{-1}$)	3.55 ± 0.24	3.49 ± 0.27	3.57 ± 0.25
% VO_2 max	85.3 ± 3.5	83.9 ± 4.8	86.0 ± 4.3
Lactate ($mmol \cdot L^{-1}$)	7.3 ± 0.9	7.0 ± 1.0	7.8 ± 0.5

Values are mean ± SEM (N = 10); * denotes different from CL (P<0.05).
FL: ingestion of a 6% CHO beverage in the first hour and 1% CHO beverage in the second hour; CL: ingestion of a 3.5% CHO beverage in the first and second hour; EL: ingestion of a 1% CHO beverage in the first hour and 6% CHO beverage in the second hour.

In spite of the great amount of studies that examines timing of carbohydrate pre- and post-exercise and the resulting performance effects, there is almost an absence of literature on timing of carbohydrate during exercise. There is only one similar study in the literature with which to compare the present study (21). Although differing in the type of carbohydrate beverage and concentrations used, McConell et al. compared end loading, continual loading, and no loading (different operational definitions were used by that group). No-loading was a placebo beverage throughout the two hours. Those researchers found a performance difference only when comparing continual loading to no loading (placebo). However, McConell et al. used an end loaded solution of 21%, which is much higher than any solution commercially available and outside recommended ranges of carbohydrate from other studies and reviews (9, 13). In addition, the total amount of carbohydrate consumed (157.5 grams in two hours) was in excess of 30-60g/hr recommendation established by the literature (9, 14, 16, 18). The present study sought to use practical carbohydrate beverage concentrations following guidelines within present dosage recommendations (~75 grams over the course of two hours) and is, therefore, more applicable to athletes. The present study showed no carbohydrate timing strategy was superior for performance when recommended carbohydrate beverage solutions were used.

Venous blood glucose changed with the three trials as expected during the carbohydrate loading stage. However, in the 15 minutes of the time trial, the FL venous blood glucose level increased from the 120-minute time point to the 135-minute (post-time trial) time point to levels the same as the CL and EL conditions. These data suggest that carbohydrate came from a source other than blood glucose since it was lower prior to the time trial. A likely source is liver or muscle glycogen since these tissues contribute to venous blood glucose levels during moderate exercise (10). Additionally, other studies have shown that carbohydrate feeding spares liver glycogen during exercise (5, 14). This leads to the possibility that participants did not reach glycogen depletion during the exercise bout prior to the 15-minute "all-out" time trial.

However, given the limitations of the measurements in the study, it is impossible to determine from where this glucose originated. Regardless, there is clearly an emergence of glucose in the bloodstream that was not present immediately prior to the time-trial.

In the FL condition, liver glycogen was likely spared from use since glucose from the carbohydrate beverage was available during the first hour. Interestingly, this lower glycemia had no effect on subsequent cycling performance. During the EL condition, glucose was readily present and available for oxidation, hence the lack of significant increase from 120 to 135 minutes. The CL condition showed a modest, but non-significant increase in venous blood glucose levels. Obviously lacking is a "no load," negative control condition. The carbohydrate timing study of McConell et al. expectedly revealed a post-time trial blood glucose profile significantly lower than the other carbohydrate loaded conditions (21). With no reason to assume differences in this result, repeating this portion of the McConell et al. experiment for the present study was secondary to gathering information from a positive control, the CL condition.

This study incorporated a time trial rather than a time to exhaustion to measure performance for several reasons. First, there was the desire to keep this study's conditions similar to McConell et al. in order to compare findings. Second, there could be a conflict of experimental interest in allowing the researcher to gauge and determine "exhaustion." Third, a moderate intensity endurance ride followed by a time trial better represents a situation experienced in competition. Finally, there are reports that the use of time trials has been shown to be a more reliable method of assessing performance than time until fatigue since the reproducibility of time trials is higher (15).

One potential limitation in our study design is that the different concentrations of carbohydrate beverage used may affect gastric emptying. To our knowledge, there is no way to adjust the quantity of carbohydrate in the same volume without changing the carbohydrate concentration. To maintain a consistent carbohydrate concentration of 6%, would have a required a change in volume for the CL condition, which could reveal the nature of our study to the participants. However, there is evidence from studies examining gastric emptying and subsequent carbohydrate oxidation at the intestines. These studies concluded that 32% to 48% of carbohydrate sent to the intestines were oxidized and therefore gastric emptying does not limit carbohydrate oxidation (22, 25). Additionally, a recent moderate intensity endurance cycling study showed that the effect of lowering carbohydrate concentration from 6% to 3% does not enhance gastric emptying or time trial performance (24).

Another potential limitation is the carbohydrate beverage provided in the study were different flavors of Gatorade ® powder composed of a mixture of glucose, fructose, and sucrose sugars. The exact quantities of these sugars are proprietary and therefore unavailable, however the total grams of carbohydrate given to the participants is known as indicated on the product's nutrition labeling. The type of carbohydrate and various combinations of these types has been shown to have differential effects in terms of performance (13). However, as this study used the mix of carbohydrates (i.e. Gatorade ®) during each of the three experimental trials, there is no carbohydrate-type difference between the trials, only a timing difference.

Other limitations of this study included the measurement error of the cycle ergometer producing the differential speed/distance and work output results as described above. Second, muscle biopsy equipment or use of clamps and tracer-labeled glucose infusion would have allowed the determination of the source and the extent of endogenous and exogenous carbohydrate oxidation during the trials. Third, a "no-load" control group would have helped highlight the differences in performance of feeding verses not feeding during exercise. Finally, providing standardized pre-competition meals to the participants and having overnight observation prior to testing would have allowed for a more controlled wash-in period prior to the trials.

Assessing exercise performance measures associated with the timing of carbohydrate ingestion may provide valuable insights for the development of a proper protocol that can be used by the many exercisers and endurance athletes. This project sought to produce a practical strategy for timing carbohydrate ingestion to maximize exercise performance. Based on the results of this study it appears that timing carbohydrate ingestion during exercise does not effect performance in a cycling time trial. In addition, this study raises the possibility that front-loading may contribute to glucose sparing better than other timing strategies. Future work should use a similar study design and increase the duration of the time trial and/or adjust the time spent in the carbohydrate loading zone.

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