The Effects of Low– and High–Glycemic Index Meals on Time Trial Performance

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Purpose: The aim of this work was to determine whether the consumption of pre-exercise high– or low–glycemic index (GI) meals has a beneficial effect on time trial performance. Methods: Eight male cyclists were provided with either a high-GI or low-GI meal, providing 1 g·kg⁻¹ body mass of carbohydrate, 45 min before performing a 40-km time trial on a Velotron cyclePro. Results: Time trial performance was significantly improved in the low-GI trial (92.5 ± 5.2 min) compared with the high-GI trial (95.6 ± 6.0 min) (P = .009). Blood glucose concentrations at the point of exhaustion were significantly higher in the low-GI trial (5.2 ± 0.6 mmol·L⁻¹) compared with the high-GI trial (4.7 ± 0.7 mmol·L⁻¹) (P = .001). There was no significant difference in estimated carbohydrate oxidation data between the low-GI (2.51 ± 1.74 g·min⁻¹) and high-GI (2.18 ± 1.53 g·min⁻¹) meals (P = .195). No significant difference in estimated fat oxidation was observed between the low-GI (0.15 ± 0.15 g·min⁻¹) and high-GI (0.29 ± 0.18 g·min⁻¹) diets (P = .83). Conclusions: The improvement in time trial performance for the low-GI trial may be associated with an increased availability of glucose to the working muscles, contributing additional carbohydrate for oxidation and possibly sparing limited muscle and liver glycogen stores.

Keywords: endurance, nutrition, metabolism, cycling, carbohydrate

The ability to perform prolonged aerobic exercise is determined predominantly by fuel availability. Many studies have investigated the ergogenic value of consuming carbohydrate before, during, or after an exercise bout and there is a plethora of evidence to suggest that carbohydrate consumption significantly enhances endurance performance (eg, Bergstrom et al⁴). The potential mechanisms for this effect could be attributed to either a reduction in muscle glycogen utilization⁵ or maintenance of blood glucose levels⁶ during exercise.

Christensen and Hansen⁷ established a link between hypoglycemia and fatigue by showing that maintenance of euglycemia and carbohydrate oxidation late in exercise can delay fatigue. In addition, previous research has demonstrated that ingesting carbohydrate that prevents a hypoglycemic response before prolonged exercise may result in improved athletic performance by increasing blood glucose oxidation when intramuscular glycogen stores become compromised.¹⁸

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Such meals that elicit these reduced blood glucose responses have typically been found to have a reduced glycemic index (GI).

The glycemic index was first proposed by Jenkins et al.\textsuperscript{9} to describe the blood glucose responses to carbohydrate foods. Previous research into the effects of manipulating the glycemic index on exercise performance remains equivocal. Research has found consuming meals with a low-glycemic response (GI < 40) to be associated with an improvement in exercise performance compared with the consumption of high-GI meals (GI > 70; eg, studies\textsuperscript{10–14}). These observed improvements in exercise performance have typically been attributed to metabolic alterations that favor utilization of fatty acids as a fuel, and a subsequent sparing of endogenous glucose and an increased hepatic glucose production late in exercise. However, the benefits of either a low- or high-GI meal on exercise performance are inconsistent, based on studies showing no beneficial effect of these meals on time trial (TT) performance or time to exhaustion during prolonged exercise (eg, studies\textsuperscript{15–18}). This lack of agreement remains to be explained, but others have attributed it to small differences in study design, such as timing of the meal, exercise intensity, meal composition, and the specific metabolic responses to the meals, all of which may influence the metabolic and performance outcomes.\textsuperscript{12} Another important factor to consider when interpreting these studies is the issue of defining and measuring “performance.”\textsuperscript{19} Direct comparisons between studies cannot be made, as some studies\textsuperscript{2,15,16} employed a total work done in a fixed time (endurance performance) protocol, whereas others\textsuperscript{10,13,14} have employed a time to exhaustion (endurance capacity) protocol. The latter protocol can be associated with a high coefficient of variation with respect to time\textsuperscript{19} and a lack of ecological validity.

Hence, on the basis of previous work, the purpose of the current study was to investigate the influence of the GI of a pre-exercise meal on exercise performance under conditions that closely represent a sporting situation. Recently, Schenk et al.\textsuperscript{20} reported it was not the GI of a food that shows the rate at which carbohydrate is absorbed into the blood as glucose, but more by directly measuring glucose kinetics, for example, the rate of appearance of glucose (Ra_{glucose}). However, as this could not be assessed in the current study, the low- and high-GI breakfast cereals used in this study were similar to that used in the Schenk et al.\textsuperscript{20} study because they demonstrated that the lower GI of the breakfast cereal was due to an earlier increase in the rate of glucose disappearance, which subsequently reduced the increase in plasma glucose concentration.

It was hypothesized that there would be a significant improvement in TT performance after the ingestion of a low-GI CHO meal compared with a high-GI CHO meal and that this improvement would be associated with maintained blood glucose levels in the low-carbohydrate trial.

**Methods**

**Participants**

Eight well-trained, but not elite, male cyclists volunteered to participate in the study. Their mean (±SD) age, height, mass, and VO\textsubscript{2max} were, respectively, 29.4 ± 6.4 y, 182.0 ± 7.9 cm, 76.7 ± 10.9 kg, and 58.2 ± 10.1 mL·kg\textsuperscript{−1}·min\textsuperscript{−1}. Subjects
were included in the study if they cycled five or more times per week. The subjects cycled approximately ~150 km per week. Height was measured to the nearest 1.0 cm without shoes (Stadiometer, Holtain Ltd, Crymych, Dyfed). Body mass was measured to the nearest 0.1 kg with the subject wearing cycling shorts (Scales, Vogel and Halbe, Hamburg, Germany). The study was approved by the Departmental Ethics Committee, and all subjects gave their written informed consent in accordance with university guidelines for the protection of human subjects.

**Experimental Design**

Each subject participated in two 40-km time trials (TT) on a Velotron cyclePro ergometer, separated by at least 7 d. This ergometer has been previously found to have a low between-trial coefficient of variation and a highly reproducible performance in competitive cyclists. Two different carbohydrate test meals providing 1 g·kg·BM$^{-1}$ of carbohydrate were ingested 45 min before the onset of exercise. This study was carried out in a randomized, double-blind, cross-over fashion. Subjects followed the same diet and training schedule during the 2 d before each experimental trial, which was verified by a food/training diary analysis. Subjects refrained from strenuous exercise, caffeine, and alcohol consumption in the 24-h period before each experimental trial. The pre-exercise test meals were consumed while the subjects were seated in a quiet section of the laboratory. Subjects were also required to complete and sign a checklist to confirm that all of the pretest procedures had been followed. The humidity of the laboratory during testing was 48 ± 5% with mean ambient temperatures of 22 ± 2°C.

**Baseline Maximal Oxygen Uptake (VO$_{2\max}$)**

Before all experimental testing, subjects undertook a graded exercise test to determine their maximal oxygen uptake (VO$_{2\max}$). All testing took place on the same Velotron cyclePro, at the same time of day in the laboratory. Expired air was measured breath-by-breath using an automated open-circuit gas analysis system (Quark b², Cosmed Srl, Rome, Italy). Following a 5-min warm-up at 100 W, the subjects then performed an incremental maximal exercise test to exhaustion. The cycling workloads began at 100 W and increased 25 W·min$^{-1}$ until subjects reached volitional exhaustion. A respiratory exchange ratio (RER) of >1.10 and a heart rate of ±10 bpm of age-predicted maximum heart rate was taken as maximal effort.

**Experimental Protocol**

Each subject reported to the laboratory following a 6-h fast. Two days before the first trial, the subjects recorded their diet and exercise patterns to standardize carbohydrate intake and activity levels so that it could be repeated before each trial. After sitting for 5 min, each subject gave a resting fingertip blood sample taken from the right index finger, and a 5-min resting expired air sample was also collected via standard open-circuit spirometry (Cosmed b³). The subjects were then provided with a standardized meal that provided 1 g·kg·BM$^{-1}$ of carbohydrate, which was composed of either high–glycemic index (high-GI) or low–glycemic index (low-GI) carbohydrates in a randomized, double-blind, cross-over design.
The subjects had 10 min to consume the test meal and rested for the next 45 min before they commenced the prescribed exercise protocol. Subjects were provided with water ad libitum during trial 1 and this was then matched for the second trial. A 15-min postprandial fingertip blood sample was then collected, and a heart rate (HR) monitor (Polar Electro, OY, Finland) was attached to the subject. A final pre-exercise fingertip blood sample was obtained 10 min before the onset of exercise.

Following a standardized 5-min warm-up at 50 W, the subjects were required to complete the 40-km TT in as short a time as possible. Five-minute expired air samples were collected during the last 5 min of every 20-min time period throughout the TT and fingertip blood samples were collected in the last minute. The last expired air sample was collected during the last 3 km of cycling and the last fingertip blood sample was taken immediately following termination of the trial while the subjects were still seated on the Veletron cyclePro. The subjects were required to wear the mask of the Cosmed only at each sampling point throughout the trial. Heart rate and ratings of perceived exertion (RPE), using a Borg 6- to 20-point scale,23 were also recorded every 15 min. After the final seated fingertip blood sample was obtained and the subjects had rested, they were then allowed to leave the laboratory.

The subjects were not aware of their performance times, HR, or distance traveled, but they were given a verbal reminder every 15 min that they were required to continue until they reached the set distance or their limit of exercise tolerance.

Test Meals

After the collection of baseline data, test meals consisting of high-GI or low-GI foods were provided for each subject before each trial. The meals were consumed in the laboratory 45 min before the onset of exercise. The test meals contained 1 g·kg·BM⁻¹ of either high- or low–glycemic index carbohydrates and were similar in macronutrient content (Table 1). The high–glycemic index (high-GI) meal consisted of Corn Flakes (Kellogg’s Co., Manchester, UK) and semiskimmed milk (GI: 72), whereas the low–glycemic index (low-GI) meal consisted of Bran Flakes (Kellogg’s Co.) and semiskimmed milk (GI: 30). The GI of the total diets was calculated from the weighted means of the GI values for the component foods. The GI values of each test food were taken from Henry et al24 and the GI of the total meal was calculated from the weighted means of the GI values for the component foods.25 To ensure that each participant consumed a standardized volume of fluid (650 mL), each subject consumed a specific amount of water and milk with each meal.

Sample Collection and Analysis

Gas Analysis. Expired air was measured breath-by-breath using an automated open-circuit gas analysis system (Quark b²). The gas analyzers were calibrated immediately before each test using ambient air (assumed to contain 20.94% oxygen and 0.03% carbon dioxide), and certified alpha standard gases containing 16.0 ± 0.03% oxygen and 5.0 ± 0.02% carbon dioxide (Cryoservice Ltd, Worces-
Low– and High–Glycemic Index Meals

The turbine flowmeter used for the determination of minute ventilation has a resistance of <0.07 cm H₂O L·s⁻¹ at a flow rate of 12 L·s⁻¹, an accuracy of ±2%, and was calibrated with a 3-L syringe (Cosmed) immediately before each test. Using this data, substrate oxidation rates and energy expenditure were calculated from VO₂ and VCO₂ values using stoichiometric equations²⁶ and RER was also obtained.

**Blood Analysis.** Blood glucose and lactate were analyzed immediately in duplicate using a YSI 2700 Stat (Yellow Springs Instrument, Yellow Springs, USA). Serum was measured before and at the end of each exercise trial and analyzed for osmolality using a micro-osmometer, Model 3320 (Advanced Instruments Inc., Massachusetts, USA). The coefficient of variation for glucose and lactate analysis in our laboratory and on this instrument is <3.8% for both analytes.

**Statistical Analysis**

A repeated-measures ANOVA on two factors (experimental treatment and time) was used to determine metabolic and performance differences between trials. If a significant difference was determined, a post hoc test was used to locate the difference. Differences were considered statistically significant at the \( P < 0.05 \) level. All analyses were conducted using SPSS statistical software for Windows, version 14.0 (SPSS Inc., Chicago, IL, USA). All data are presented as mean ± standard deviation.

### Table 1  Characteristics of test meals for a 70-kg subject

<table>
<thead>
<tr>
<th>Description</th>
<th>Macronutrient Content</th>
<th>High-GI Breakfast</th>
<th>Low-GI Breakfast</th>
</tr>
</thead>
<tbody>
<tr>
<td>68 g of Corn Flakes</td>
<td>386 kcal</td>
<td>81 g of Bran Flakes</td>
<td>422 kcal</td>
</tr>
<tr>
<td>282 mL of semiskimmed milk</td>
<td>70 g of carbohydrate</td>
<td>337 mL of semiskimmed milk</td>
<td>70 g of carbohydrate</td>
</tr>
<tr>
<td>368 mL of water</td>
<td>6 g of fat</td>
<td>313 mL of water</td>
<td>8 g of fat</td>
</tr>
<tr>
<td></td>
<td>16 g of protein</td>
<td></td>
<td>19 g of protein</td>
</tr>
<tr>
<td></td>
<td>2 g of fiber</td>
<td></td>
<td>12 g of fiber</td>
</tr>
<tr>
<td>GI = 72*</td>
<td></td>
<td>GI = 30*</td>
<td></td>
</tr>
</tbody>
</table>

Macronutrient breakdown of high-GI and low-GI test meals provided to each subject calculated from manufacturer’s information. *Calculated by the method of Wolever and Jenkins.²⁵ Glycemic index values from Henry et al.²⁴
Results

Time Trial Performance

There was a significant improvement in 40-km TT performance following the consumption of a low-GI meal compared with a high-GI meal. The average TT time in the low-GI trial (92.5 ± 5.2 min) was significantly shorter than in the high-GI trial (95.6 ± 6.0 min; \( P = .009 \); see Table 2).

Heart Rate and RPE

There was a significant main effect for time \( (P = .001) \) but not treatment \( (P = .81) \) on heart rate between the two trials. There was no significant treatment × time interaction for heart rate \( (P = .17) \); see Table 3). There was a significant main effect for both time \( (P = .001) \) and trial \( (P = .039) \) for RPE with the values increasing over time to a maximum value of 17 and 15 for high-GI and low-GI, respectively. There was no significant treatment × time interaction though for RPE \( (P = .17) \); see Table 2

Substrate Utilization and Respiratory Exchange Ratio (RER)

The estimated CHO oxidation rates, as calculated from the VO\(_2\) and VCO\(_2\) values, indicated there was a significant main effect for both time \( (P = .001) \) and treatment \( (P = .003) \) during the TT following the consumption of a low-GI meal (2.51 ± 1.74 g·min\(^{-1}\)) compared with the consumption of a high-GI meal (2.18 ± 1.53 g·min\(^{-1}\)) (Figure 1 top). There was, however, no significant treatment × time interaction for carbohydrate oxidation \( (P = .195) \). A significant main effect for both time \( (P = .001) \) and treatment \( (P = .002) \) was observed for fat oxidation rates in the high-GI trial (0.29 ± 0.18 g·min\(^{-1}\)) compared with the low-GI trial (0.15 ±

Table 2 Performance times for each participant during the high–glycemic index (high-GI) and low–glycemic index (low-GI) CHO trials

<table>
<thead>
<tr>
<th>Participant</th>
<th>Low GI (mins)</th>
<th>High GI (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96</td>
<td>96.8</td>
</tr>
<tr>
<td>2</td>
<td>93.7</td>
<td>98.7</td>
</tr>
<tr>
<td>3</td>
<td>86.3</td>
<td>91.4</td>
</tr>
<tr>
<td>4</td>
<td>98.7</td>
<td>105</td>
</tr>
<tr>
<td>5</td>
<td>96.1</td>
<td>95.7</td>
</tr>
<tr>
<td>6</td>
<td>89.9</td>
<td>93.5</td>
</tr>
<tr>
<td>7</td>
<td>94.8</td>
<td>98.9</td>
</tr>
<tr>
<td>8</td>
<td>84.1</td>
<td>85</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>92.5 ± 5.2*</td>
<td>95.6 ± 6.0</td>
</tr>
</tbody>
</table>

*Significantly lower than the high-GI trial. Statistical significance is set at the \( P < .05 \) level.
Table 3  Heart rate (HR), respiratory exchange ratio (RER), and ratings of perceived exertion (RPE) during the high glycemic index

<table>
<thead>
<tr>
<th>Variable</th>
<th>Trial</th>
<th>Baseline</th>
<th>45 pp</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (bpm)</td>
<td>High GI</td>
<td>62 ± 14</td>
<td>64 ± 12</td>
<td>161 ± 15*</td>
<td>163 ± 16*</td>
<td>164 ± 15*</td>
<td>173 ± 14*</td>
</tr>
<tr>
<td></td>
<td>Low GI</td>
<td>59 ± 14</td>
<td>63 ± 12*</td>
<td>168 ± 8*</td>
<td>167 ± 8*</td>
<td>172 ± 7*</td>
<td>174 ± 9*</td>
</tr>
<tr>
<td>RER</td>
<td>High GI</td>
<td>0.85 ± 0.06</td>
<td>0.86 ± 0.05</td>
<td>0.93 ± 0.03*</td>
<td>0.92 ± 0.03*</td>
<td>0.89 ± 0.04*</td>
<td>0.95 ± 0.07*</td>
</tr>
<tr>
<td></td>
<td>Low GI</td>
<td>0.89 ± 0.09</td>
<td>0.92 ± 0.04</td>
<td>0.98 ± 0.03*</td>
<td>0.93 ± 0.02*</td>
<td>0.91 ± 0.03*</td>
<td>0.97 ± 0.05*</td>
</tr>
<tr>
<td>RPE</td>
<td>High GI</td>
<td>6 ± 0</td>
<td>7 ± 1</td>
<td>15 ± 2*</td>
<td>16 ± 2*</td>
<td>16 ± 2*</td>
<td>17 ± 3*</td>
</tr>
<tr>
<td></td>
<td>Low GI</td>
<td>6 ± 0</td>
<td>6 ± 0</td>
<td>13 ± 2*</td>
<td>15 ± 1*</td>
<td>15 ± 0*</td>
<td>15 ± 2*</td>
</tr>
</tbody>
</table>

High–glycemic index (high-GI) and low–glycemic index (low-GI) CHO trials. Data are presented as means ± SD of the mean. *Significantly different from baseline. Statistical significance is set at the P < .05 level.
There was no significant treatment × time interaction for fat oxidation, however ($P = .83$) (Figure 1 bottom).

There was a significant main effect for both time ($P = .001$) and treatment ($P = .001$) on RER, which shows that the RER values were higher throughout the

0.15 g·min$^{-1}$ (Figure 1 bottom).
low-GI trial (0.93 ± 0.035) compared with the high-GI trial (0.90 ± 0.04). There was no significant treatment × time interaction for RER ($P = .22$; see Table 3).

**Blood Glucose**

Following the consumption of the high-GI meals, the blood glucose concentration rose significantly from 4.5 ± 0.5 to 7.3 ± 2.4 mmol·L$^{-1}$ for the high-GI trial compared with 4.6 ± 0.4 to 5.5 ± 1.7 mmol·L$^{-1}$ for the low-GI trial ($P = .005$). During the TT, the mean blood glucose concentrations were maintained between 4 and 5 mmol·L$^{-1}$ for both the low-GI and high-GI trials. However, during both the low-GI and high-GI trials, two subjects experienced a drop in blood glucose levels below 3.5 mmol·L$^{-1}$ although no symptoms of hypoglycemia were reported. There was a significant interaction effect between time and trial ($P < .001$) for blood glucose concentration. After 20 min of exercise, blood glucose levels throughout the low GI trial remained higher than the high GI trial values at all remaining time points (NS). At the point of exhaustion blood glucose concentrations were significantly higher in the low-GI trial (5.2 ± 0.6 mmol·L$^{-1}$) compared with the high-GI trial (4.7 ± 0.7 mmol·L$^{-1}$; $P = .001$; see Figure 2a).

![Figure 2](image-url) — Mean (± SD) blood glucose concentration throughout the trial. *$P \leq 0.05$ (at 45 postprandial and exhaustion).
Blood Lactate

There was a significant main effect for time ($P = .001$) but not treatment ($P = .39$) on blood lactate concentrations between the high-GI and low-GI trials. Pre-exercise values were similar for the high-GI ($1.3 \pm 0.4 \text{ mmol·L}^{-1}$) and low-GI trials ($1.1 \pm 0.6 \text{ mmol·L}^{-1}$) but at the onset of exercise lactate levels for the high-GI and low-GI meals increased significantly to $5.1 \pm 2.2$ and $5.0 \pm 1.9 \text{ mmol·L}^{-1}$, respectively ($P = .001$). These lactate concentrations decreased gradually throughout the trial to a minimum value of $2.8$ and $2.8 \text{ mmol·L}^{-1}$ at 60 min, but increased significantly at the point of exhaustion for the high-GI ($4.7 \pm 2.4 \text{ mmol·L}^{-1}$) and low-GI trials ($4.9 \pm 1.0 \text{ mmol·L}^{-1}; P = .001$). There was no significant interaction between the trials and blood lactate ($P = .21$; see Figure 3).

Osmolality

Mean osmolality values were $295.3 \pm 4.7 \text{ mOsm·kg}^{-1}$ and $297.8 \pm 4.4 \text{ mOsm·kg}^{-1}$ for the high-GI and the high-GI and low-GI trials respectively, at the point of exhaustion.

Figure 3 — Mean ($\pm$ SD) blood lactate concentration throughout the trial. *$P \leq 0.05$ (from 45 postprandial to all other time points and at exhaustion).
Discussion

The main finding of the current study was that the ingestion of a low-GI carbohydrate meal 45 min before the onset of exercise resulted in a greater endurance performance during a 40-km TT compared with the consumption of a high-GI carbohydrate meal. The low-GI meal was associated with significantly increased blood glucose concentrations at the point of exhaustion, compared with the high-GI meal; however, there was no significant difference in substrate oxidation rates between the low- and high-GI meals, which is in contrast to most previous research.11–13 These studies did, however, assess endurance capacity and not performance as in the current study; therefore, a direct comparison cannot be made. The performance data from the current study are consistent with previous research, demonstrating that the ingestion of low-GI carbohydrate foods before exercise is associated with enhanced exercise performance.10–14 The effect of the GI of a pre-event meal on exercise performance has received considerable attention in recent years. Thomas et al14 were among the first to show that a meal with a low GI (GI = 29) extended the time to exhaustion during exercise by 20 min when compared with a meal with a high GI (GI = 98). In addition, DeMarco et al10 confirmed the advantage of a low-GI (GI = 36) meal over a high-GI (GI = ~70) meal when they found exercise time was 59% longer during a maximal effort after 2 h of submaximal cycling. Kirwan et al11 previously reported that the sweetened form of rolled oats cereal (GI = ~63) could increase exercise duration during submaximal cycling exercise by 16% (~41 min) compared with a water control. More recently, Stevenson et al13 demonstrated that the ingestion of a low-GI diet significantly improved endurance capacity compared with a high-GI diet. From these reports, it would appear that low- and/or moderate-GI meals confer a performance advantage over a high-GI meal or water. However, support for this observation has lacked consistency, and subsequent studies have shown no beneficial effect of either high-GI or low-GI meals on time trial performance at the end of steady-state cycling or in time to exhaustion during treadmill running.15,16,18

The metabolic data of the current study show that significantly greater blood glucose levels at the point of exhaustion were found after the low-GI meal (5.2 ± 0.6 mmol·L⁻¹) compared with the high-GI meal (4.7 ± 0.7 mmol·L⁻¹). In addition, the low-GI meal was associated with a longer time to exhaustion, which suggests that there was sufficient glucose to provide energy to the working muscle during the extended working time. This finding corroborates previous research in that those who demonstrated an improvement in performance had glucose levels that were significantly higher than control levels,10,12,14 whereas, when no performance improvement was observed, glucose levels were not different from control levels.15,16,18 Therefore, it appears that the improvement in exercise performance may be dependent on whether the pre-exercise meal can maintain adequate euglycemia during exercise to sustain CHO oxidation as supported in this study. In support of this observation, it has previously been shown that carbohydrate feedings that prevent a hypoglycemic response may enhance exercise performance by increasing the availability of glucose to the working muscles,1,8 contributing additional CHO for oxidation, and sparing limited muscle and liver glycogen stores.8,12 These data are consistent with the hypothesis that pre-exercise carbohydrate ingestion can spare hepatic glycogen early in exercise, sustain hepatic glucose
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output for a longer period, and increase exercise time.\textsuperscript{1,8} Our data showing an increase in hepatic glucose output at the end of 1 to 2 h of exercise add to these findings and suggest that the sparing of hepatic glycogen early in exercise allows for greater glucose output when the exercise is very prolonged. In addition, the postprandial glucose kinetics of the current study may be explained by the Schenk et al\textsuperscript{20} findings that the plasma glucose concentration is a function of both the rate of appearance of glucose (Ra\textsubscript{glucose}) into the systemic circulation and the rate of disappearance of glucose (Rd\textsubscript{glucose}) from the systemic circulation. Schenk\textsuperscript{20} showed that the more than twofold lower GI for the bran cereal compared with the high-GI Corn Flakes was more as a result of an earlier increase in Rd\textsubscript{glucose} rather than to differences in the Ra\textsubscript{glucose}. This increase in Rd\textsubscript{glucose} was associated with an earlier and significantly augmented insulin response during the initial 20-min period. This could explain the postprandial results of the current study as similar breakfast cereals were used.

The increase in carbohydrate oxidation associated with the low-GI meal compared with the high-GI meal may also offer some explanation for the observed improvement in performance. Whereas previously, when a meal causes a hyperinsulinemic state at the start of the exercise, there may be a sustained suppression of FFA and a corresponding increase in the use of carbohydrate as fuel early in exercise.\textsuperscript{11,12} This increase in carbohydrate oxidation in the initial period of exercise may stimulate greater rates of glycogenolysis and early depletion of stored glycogen, leading to hypoglycemia, which is believed to be the primary cause of fatigue during prolonged bouts of exercise.\textsuperscript{5,6,11} Some studies showing no improvement in exercise performance\textsuperscript{15,16} have suggested that this is a result of this hyperinsulinemic state at the start of the exercise and subsequent sustained suppression of FFA and corresponding increased use of carbohydrate as fuel early in exercise.\textsuperscript{11,12} However, in the current study, the RER and carbohydrate oxidation data indicate that carbohydrate oxidation was actually greater throughout the trial following the consumption of a low-GI meal compared with a high-GI meal. This greater carbohydrate oxidation observed in our low-GI trial suggests that the meal may have contributed additional carbohydrate for oxidation and subsequently spared limited muscle and liver glycogen stores as previously suggested.\textsuperscript{8,12,13} This additional carbohydrate may have also provided a greater contribution of exogenous glucose to fuel use during the exercise bout.\textsuperscript{8,12,13}

It has been reported that fatigue can also occur owing to impairment to one or more links in the chain from the central nervous system (CNS) to the contractile elements.\textsuperscript{27} Research by Nybo\textsuperscript{28} observed that when glucose levels dropped to hypoglycemic levels (~3 mmol·L\textsuperscript{−1}), the average force produced during a sustained maximal muscle contraction was reduced and this was associated with a reduced activation drive from the CNS. However, in the current study, as mean blood glucose levels did not drop below 5.0 mmol·L\textsuperscript{−1} during the high-GI trial, central fatigue may not be a cause of the reduced TT performance observed in this group. In addition, optimal sports performance is also dependent on maintaining a positive mood state.\textsuperscript{29} Welsh et al\textsuperscript{29} observed that the ingestion of a carbohydrate solution was associated with both an improved exercise-to-exhaustion time and motor skill proficiency during the latter stages of exercise. Subjects also reported feeling less fatigued at the end of the shuttle run even though they were unable to maintain running speed toward the end of the exercise. However, in the current
study, there was no significant difference in self-reported perception of fatigue as assessed by the RPE scale\(^ {22} \) between the high-GI and low-GI trial, which suggests that the CNS fatigue is not a contributory factor to the reduced TT performance observed in the high-GI trial.

There was also no significant difference observed in blood lactate concentration between the low-GI and high-GI trials. Since accumulation of lactate results in a concomitant increase in hydrogen (H\(^+ \)) ions and a subsequent reduction in pH, contributing, potentially to the development of fatigue,\(^ {30} \) the lack of difference in blood lactate observed in this study suggest that the reduced performance in the high-GI trial is unlikely to be due to increased acidity of the muscle or blood. In addition, at the point of exhaustion, the mean osmolality values for the high- and low-GI trials were within the normal ranges indicative of euhydration.\(^ {30} \)

## Practical Applications

The ingestion of a low-GI meal containing 1 g·kg·BM\(^{-1} \) of carbohydrate, 45 min before performing a 40-km TT cycling protocol, significantly improved performance compared with a high-GI meal. The possibilities of a hypoglycemic effect, increased muscle acidity, or dehydration affecting performance have been ruled out. Possibly an increase in the availability of carbohydrate and a greater carbohydrate oxidation throughout the exercise period may explain the observed improvements in TT performance in the low-GI trial. These data therefore, support the ingestion of a meal containing 1 g·kg·BM\(^{-1} \) of low-GI content before prolonged exercise.

## References

20. Schenk S, Davidson CJ, Zderic TW, Byerley LO, Coyle EF. Different glycemic indexes of breakfast cereals are not due to glucose entry into the blood but to glucose removal by tissue. *Am J Clin Nutr.* 2003;78:742–748.