Glycemic Index and Endurance Performance

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The aim of this review is to provide an up-to-date summary of the evidence surrounding glycemic index (GI) and endurance performance. Athletes are commonly instructed to consume low-GI (LGI) carbohydrate (CHO) before exercise, but this recommendation appears to be based on the results of only a few studies, whereas others have found that the GI of CHO ingested before exercise has no impact on performance. Only 1 study was designed to directly investigate the impact of the GI of CHO ingested during exercise on endurance performance. Although the results indicate that GI is not as important as consuming CHO itself, more research in this area is clearly needed. Initial research investigating the impact of GI on postexercise recovery indicated consuming high-GI (HGI) CHO increased muscle glycogen resynthesis. However, recent studies indicate an interaction between LGI CHO and fat oxidation, which may play a role in enhancing performance in subsequent exercise. Despite the fact that the relationship between GI and sporting performance has been a topic of research for more than 15 yr, there is no consensus on whether consuming CHO of differing GI improves endurance performance. Until further well-designed research is carried out, athletes are encouraged to follow standard recommendations for CHO consumption and let practical issues and individual experience dictate the use of HGI or LGI meals and supplements before, during, and after exercise.

Keywords: carbohydrate, exercise, nutrition

GI

GI was first introduced as a concept in response to research that suggested that CHO-exchange lists used by patients with diabetes did not reflect the physiological effect CHO had on actual blood glucose and insulin response (Jenkins et al., 1981). The GI classifies CHO-rich foods based on their postprandial blood glucose response compared with a reference food (usually white bread or a glucose solution; Jenkins et al., 1981). The GI is calculated by measuring the incremental area under the blood glucose response curve (IAUC) after the ingestion of a reference food containing 50 g of available CHO and a test food also containing 50 g of available CHO. The reference food is usually tested two or three times in each individual (FAO/WHO, 1998). The response to the test food is then expressed as a percentage of the mean response to the reference food in the same participant (Wolever, Jenkins, Jenkins, & Josse, 1991). The GI value for a food is based on the mean GI value tested in 10–12 individuals (FAO/WHO, 1998).

\[ \text{GI} = \frac{\text{glucose}_{\text{IAUC test food}}}{\text{glucose}_{\text{IAUC reference}}} \times 100 \]

Essentially, the GI is designed to indicate the overall rate of digestion and absorption of the CHO in a food. Foods with an HGI (>70) are generally digested and absorbed quickly, whereas foods with an LGI (<55) are digested and absorbed more slowly. For a comprehensive list of up-to-date GI values of common foods the reader is directed to Atkinson, Foster-Powell, and Brand-Miller (2008). The GI of a food can be influenced by the physical and chemical characteristics of the food (Foster-Powell, Holt, & Brand-Miller, 2002), and although an individual’s glycemic response can be highly variable (Venn & Green,
2007), most participant characteristics such as age, sex, body-mass index, and ethnicity are not believed to influence GI (Wolover et al., 2003). However, there is some evidence to suggest an interaction between GI, gender, and training status. Several studies have found a difference in GI between trained and sedentary men (Jackson, 2007; Mettler, Lamprecht-Rusca, Stoffel-Kurt, Wenk, & Colombani, 2007; Mettler, Wenk, & Colombani, 2006), whereas others have found no difference in GI using trained and sedentary women (Mettler, Vaucher, Wein-gartner, Wenk, & Colombani, 2008) or a mixed-gender group (Kim, Hertzler, Byrne, & Mattern, 2008; Trompers, Perry, Rose, & Rehrer, 2010).

If the GI of CHO influences the rate at which CHO elicits a blood glucose response, it seems plausible that feeding CHO of differing GI before, during, and after exercise will influence sport performance. However, despite the fact that the first research on GI and sport performance was carried out nearly 20 years ago (Thomas et al., 1991), there is still much indecision and a paucity of data about the benefits of consuming HGI and LGI CHO to boost performance.

### Validity of the GI

There has been discussion about the variation in published GI values for apparently similar foods (Foster-Powell et al., 2002). The glycemic response to the same food, in the same individual, tested under standardized conditions can vary (Venn & Green, 2007). Using a reference food to calculate GI reduces the between-subjects variability. Therefore, variation in the measurement of GI can be attributed to day-to-day variation and random fluctuations in individual glycemic response (Williams et al., 2008). Some variation in blood glucose can be reduced by controlling the consumption of food the day before a testing session (Granfeldt, Wu, & Björck, 2006), which, along with standardization of prior exercise, is common in sport nutrition research (Burke, Collier, & Hargreaves, 1998), and by conducting tests of both the reference food (Wolover, 2003) and the test food at least twice in each participant (Venn & Green, 2007; Williams et al., 2008). However, although duplicate testing of the reference food is common in GI research, duplicate testing of the test foods is not common practice in either GI or sport nutrition research. The large amount of variation that seems inherent in the measurement of GI limits its usefulness in some situations. However, classification of foods according to GI works well when there is a large separation in GI values between foods (Venn & Green, 2007). This is often the case in sport nutrition research, in which comparisons between effects of HGI foods (with GIs close to 100) and LGI foods (with GI values in the 30s) on performance or recovery are frequent (Burke, Collier, & Hargreaves, 1998). Only two studies have compared the effects of moderate-GI and HGI meals on exercise performance (Backhouse, Williams, Stevenson, & Nute, 2007; Kirwan, Cyr-Campbell, Campbell, Scheiber, & Evans, 2001). The small sample sizes used in most sport nutrition research may limit the ability of studies to detect any real influences GI has on performance. Investigators planning future research should give careful consideration to the repetition of trials in each participant to reduce the effects of intraindividual variation in glycemic response.

### The Effect of GI on CHO Feeding Before Exercise

It is widely accepted that CHO ingestion before, during, and after endurance exercise improves performance. However, CHO feeding before exercise remains a contentious issue, because a rapid increase in blood glucose and insulin can cause hypoglycemia in some individuals at the start of exercise (Foster, Costill, & Fink, 1979; Kuipers, Fransen, & Keizer, 1999). This observation led to the investigation into the effect of different types and structures of CHO on exercise performance (Guezennec, Satabin, Dufourez, Koziet, & Antoine, 1993; Guezennec et al., 1989; Koivisto, Karonen, & Nikkila, 1981) and to the comparison of the effects of differing GI on endurance performance. These investigations were based on the premise that consuming LGI CHO before exercise would minimize the glycemic and insulimetic response seen with HGI CHO and result in a sustained CHO supply during exercise. The studies investigating the effects of the GI of CHO fed before exercise can be divided into two categories: GI of CHO ingested 1 hr or less before exercise (Table 1) and GI of CHO fed more than 1 hr but less than 3 hr before exercise (Table 2, Download Now).

### One Hour or Less Before Exercise

In the first study designed specifically to investigate the effect of HGI and LGI foods on exercise performance, 8 trained cyclists were fed lentils (LGI), potatoes (HGI), a glucose solution, or water 1 hr before cycling at 65–70% VO2max until exhaustion (Thomas et al., 1991). The findings indicated higher blood glucose and free-fatty-acid (FFA) concentrations at the end of exercise and a 20 min longer time to exhaustion in the LGI trial than in the HGI trial. These results were widely publicized and, when combined with similar findings from other studies investigating the response to single sugars, form the basis for general advice given to athletes to choose LGI CHO for preexercise meals. However, although many other studies have found that feeding LGI foods or meals an hour or less before exercise (Table 1) results in higher blood glucose concentrations during exercise, they frequently find no difference in time to exhaustion (Febbraio et al., 2000; Garcin et al., 2001; Sparks et al., 1998; Thomas et al., 1994). Only three studies conducted since Thomas et al.’s (1991) have found an improvement in endurance performance with the consumption of LGI and moderate-GI CHO (DeMarco et al., 1999; Kirwan, O’Gorman, et al., 2001; Moore et al., in press). DeMarco et al. found that cycling time to exhaustion (at 100% VO2peak after a 2-hr ride at 70% VO2peak) after consuming an LGI meal was 72% longer and 59% longer when compared with the control and the HGI meal, respectively.
### Table 1  Studies of Glycemic Index and Preexercise CHO ingested 1 hr or Less Before Exercise

<table>
<thead>
<tr>
<th>Study</th>
<th>Participant characteristics</th>
<th>Exercise protocol</th>
<th>CHO feeding</th>
<th>Timing of feeding</th>
<th>Metabolic response</th>
<th>Performance response</th>
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<tbody>
<tr>
<td>Thomas et al., 1991</td>
<td>8 trained male cyclists</td>
<td>Cycled to exhaustion at 65–70% VO$_{2\text{max}}$</td>
<td>Lentils (LGI), potato (HGI), glucose, or water; CHO-containing foods fed to provide 1 g CHO/kg</td>
<td>60 min before exercise</td>
<td>LGI produced lower glucose and insulin response at rest but higher blood glucose concentration and higher FFA concentrations at the end of exercise.</td>
<td>Time to exhaustion longer with LGI</td>
</tr>
<tr>
<td>Thomas, Brotherhood, &amp; Miller, 1994</td>
<td>6 trained male cyclists</td>
<td>Cycled to exhaustion at 65–70% VO$_{2\text{max}}$</td>
<td>Potato flakes (HGI), rice cereal (HGI), lentil flakes (LGI), bran cereal (LGI), CHO-containing foods fed to provide 1 g CHO/kg</td>
<td>60 min before exercise</td>
<td>Both LGI foods produced lower glucose and insulin response at rest but higher blood glucose concentration and higher FFA concentration at the end of exercise.</td>
<td>No difference in time to exhaustion</td>
</tr>
<tr>
<td>Febbraio &amp; Stewart, 1996</td>
<td>6 endurance-trained men</td>
<td>Cycled at 70% VO$_{2\text{_peak}}$ for 120 min, followed by 15 min at maximum work output</td>
<td>Lentils (LGI), instant mashed potato (HGI), diet jelly (control), CHO-containing foods fed to provide 1 g CHO/kg</td>
<td>45 min before exercise</td>
<td>HGI produced higher blood glucose 15 min postingestion, but blood glucose concentration was not different at any other time point.</td>
<td>No difference in total work performed in 15-min performance trial</td>
</tr>
<tr>
<td>Sparks, Selig, &amp; Febbraio, 1998</td>
<td>8 male triathletes</td>
<td>Cycled at 70% VO$_{2\text{_peak}}$ for 50 min, followed by 15 min at maximum work output</td>
<td>Lentils (LGI), instant mashed potato (HGI), non-carbonated diet soft drink (control), CHO-containing foods fed to provide 1 g CHO/kg</td>
<td>45 min before exercise</td>
<td>HGI produced significantly higher blood glucose levels 30 and 15 min after ingestion but significantly lower blood glucose levels 10 and 20 min after the initiation of exercise.</td>
<td>No difference in total work performed in 15-min performance trial</td>
</tr>
<tr>
<td>DeMarco, Sucher, Cisar, &amp; Butterfield, 1999</td>
<td>10 trained male cyclists</td>
<td>Cycled at 70% VO$<em>{2\text{max}}$ for 2 hr followed by performance-trial cycling at 100% VO$</em>{2\text{max}}$ to exhaustion</td>
<td>Comflakes, milk, banana (HGI), All-Bran, apple and yogurt (LGI), water (control), CHO-containing meals fed to provide 1.5 g CHO/kg</td>
<td>30 min before exercise</td>
<td>HGI produced significantly higher blood glucose levels 15 min after ingestion. LGI also produced blood glucose levels higher than control at this time point. Blood glucose levels were significantly lower than control in both LGI and HGI 15 min after the initiation of exercise. After 120 min of exercise blood glucose concentrations were significantly higher in LGI.</td>
<td>Time to exhaustion in performance trial longer with LGI</td>
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(continued)
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<tr>
<td>Febbraio, Keenan, Angus, Campbell, &amp; Garnham, 2000</td>
<td>8 endurance-trained men</td>
<td>Cycled at 70% VO_{peak} for 120 min, followed by 30 min at maximum work output</td>
<td>Muesli (LGI), instant mashed potato (HGI), diet jelly (control), CHO-containing foods fed to provide 1 g CHO/kg</td>
<td>30 min before exercise</td>
<td>HGI produced significantly higher blood glucose concentration 10, 20, and 30 min after consumption and significantly lower blood glucose concentrations 15 and 30 min after the initiation of exercise.</td>
<td>No difference in total work performed in 30-min performance trial</td>
</tr>
<tr>
<td>Garcia, Bresil-Piton, &amp; Peres, 2001</td>
<td>10 endurance-trained male triathletes</td>
<td>Cycled at 80% VO_{max} for 60 min</td>
<td>Glucose (HGI), whole-wheat biscuit (LGI), water (placebo), CHO-containing foods fed to provide 0.3 g CHO/kg</td>
<td>Ingested every 30 min for 3 hr, up until 10 min before exercise</td>
<td>HGI produced a decrease in blood glucose concentration 30 min after initiation of exercise (blood glucose levels not measured before exercise).</td>
<td>Not measured</td>
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<tr>
<td>Kirwan, O’Gorman, et al., 2001</td>
<td>6 active men</td>
<td>Cycled at ~60% VO_{max} until exhaustion</td>
<td>Whole-grain rolled oats (MGI) or puffed rice (HGI) each with 300 ml of water, or water alone</td>
<td>45 min before exercise</td>
<td>HGI produced higher blood glucose concentration 15, 30, and 45 min after ingestion compared with control and 45 min after ingestion compared with MGI. MGI produced higher blood glucose than control at 15 and 30 min. At the start of exercise HGI produced higher blood glucose than control, but at 60 and 90 min MGI produced higher blood glucose than HGI or control.</td>
<td>Time to exhaustion ~23% longer in MGI trial than control and 5% longer in HGI than control; no difference between HGI and MGI</td>
</tr>
<tr>
<td>Moore, Midgley, Thurlow, Thomas, &amp; McNaughton, in press</td>
<td>10 trained cyclists</td>
<td>40-km time trial</td>
<td>Bran flakes, semiskim milk, and water (LGI) or corn flakes, semiskim milk, and water (HGI)</td>
<td>45 min before exercise</td>
<td>HGI produced higher blood glucose and insulin concentration 45 min after ingestion, but blood glucose concentrations were not different during exercise.</td>
<td>Time trial on average 3 min faster after consumption of LGI than with HGI</td>
</tr>
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Note. CHO = carbohydrate; VO_{peak} = maximal oxygen uptake; LGI = low glycemic index; HGI = high glycemic index; FFA = free fatty acids; VO_{peak} = peak oxygen uptake; MGI = medium glycemic index.
Kirwan, Cyr-Campbell, et al. (2001) found that cycling time to exhaustion (at ~60% $VO_{2\text{max}}$) after a medium-GI meal was 23% longer than that of the control but not different than with an HGI meal. Moore et al. (in press) found that cyclists completed a 40-km time trial, on average, 3 min faster when an LGI meal was fed before exercise than with an HGI meal.

**More Than 1 hr but Less Than 3 hr Before Exercise**

Study findings indicate that ingesting LGI foods or meals more than 1 hr before exercise results in higher blood glucose concentrations during exercise and higher FFA concentrations than when HGI CHO is ingested (Chen et al., 2008; Stannard et al., 2000; Stevenson et al., 2006; Stevenson, Williams, & Nute, 2005; Wee et al., 2005; Wong et al., 2008; Wu et al., 2003; Wu & Williams, 2006; Table 2). These results suggest that consuming LGI foods before exercise results in lower muscle glycogen utilization during exercise. Indeed, Wee et al. (2005) reported lower muscle glycogen utilization when an LGI meal was fed before exercise than with an HGI meal. However, most of these studies did not measure performance, instead using exercise protocols involving running at 65–70% $VO_{2\text{max}}$ for 30–60 min (Stevenson et al., 2006; Stevenson, Williams, & Nute, 2005; Stevenson et al., 2008; Stevenson, Williams, Nute, Swaile, & Tsui, 2005; Wee et al., 2005; Wu et al., 2003) or walking at 50% $VO_{2\text{max}}$ for 60 min (Stevenson, Astbury, et al., 2009). Although this protocol of steady-state exercise makes comparisons between treatments easier, it is difficult to apply the results to an athlete seeking performance enhancement.

Only 5 of the 13 studies designed to investigate the effects of GI and preexercise CHO ingestion more than an hour before exercise have measured performance (Chen et al., 2008; Stannard et al., 2000; Wee et al., 1999; Wong et al., 2008; Wu & Williams, 2006). Of these, two found a performance enhancement (Wong et al., 2008; Wu & Williams, 2006) and three found no difference in performance (Chen et al., 2008; Stannard et al., 2000; Wee et al., 1999), despite the consistent metabolic results suggesting benefits of consuming LGI CHO. However, the study that most closely resembled a competitive sporting situation found a 2.8% improvement in half-marathon times after the consumption of LGI CHO (Wong et al., 2008). The difference in time recorded in that study would have resulted in an improvement in placing in the 2007 U.S. half-marathon from 112th to 76th, a meaningful improvement for any athlete.

**Study Limitations**

A review by Burke, Collier, and Hargreaves (1998) called for the use of time trials after a period of fixed submaximal exercise as an exercise protocol. This would allow a direct comparison with athletic performance and an increase in the reliability of the measures of performance (Burke, Collier, & Hargreaves, 1998). Despite this, most studies either continued to use a time-to-exhaustion protocol (DeMarco et al., 1999; Stannard et al., 2000; Wee et al., 1999; Wu & Williams, 2006) or simply did not measure performance (Stevenson et al., 2006; Stevenson, Williams, & Nute, 2005; Stevenson et al., 2008; Stevenson, Williams, Nute, Swaile, & Tsui, 2005; Wee et al., 2005; Wu et al., 2003). Applying the results of an exercise protocol in which the aim is to maintain a set workload for as long as possible to a sporting situation in which the aim is to complete a set distance as fast as possible seems questionable. Combining the low reliability of time-to-exhaustion protocols (Burke, Collier, & Hargreaves, 1998) with the small sample sizes ($n < 10$) used in all of the studies makes the occurrence of a Type II error (failing to detect a real change) a high probability. The use of single foods, as opposed to meals, especially in the early studies, also contributes to the general lack of applicability of much of the research.

Endurance athletes typically ingest CHO during athletic events to promote CHO availability. The studies reviewed herein used protocols in which participants were not provided with CHO during exercise, again limiting the applicability of the results. Only three studies have been designed to investigate the interaction between preexercise CHO ingestion and ingestion of CHO during exercise. In a study by Burke, Claassen, et al. (1998), 6 endurance-trained male cyclists were fed either HGI potato, LGI pasta, or a low-energy jelly (control) 2 hr before completing 2 hr of cycling at 70% $VO_{2\text{max}}$ followed by a performance trial of 300 kJ. Immediately before and throughout exercise, participants ingested a total of 24 ml/kg body weight of a 10% CHO solution. Despite preexercise differences in blood glucose, insulin, and FFA concentrations between trials there were no differences in total CHO oxidation or oxidation of ingested CHO and no differences in time to complete the performance trial. In two recent studies (Chen et al., in press; Wong et al., 2009), endurance-trained male runners were fed iso- caloric meals that were either HGI or LGI or a low-energy jelly (control). Two hours after ingestion they completed a 21-km time trial, of which the first 5 km were run at 70% $VO_{2\text{max}}$. Immediately before and every 2.5 km throughout the run, participants ingested 2 ml/kg body mass (BM) of a 6.6% CHO-electrolyte solution. Despite the HGI meal’s producing a larger postprandial blood glucose IAUC, no differences were found in CHO- and fat-oxidation rates during rest or exercise. There was also no difference in 21-km time-trial performance between the HGI and LGI trials in either study (Chen et al., in press; Wong et al., 2009), although Chen et al. (in press) reported that the average time in the HGI trial was 2.1 min faster than in the control trial. Chen et al. (in press) reported that consuming an LGI meal before exercise attenuated the increase in cortisol compared with the control trial and quickened recovery to baseline of increased interleukin-6. Taken together, the results of these studies suggest that CHO ingested during exercise, in amounts currently recommended by sport nutrition guidelines, reduces the
disparity in metabolic response seen when feeding HGI and LGI CHO before exercise (Burke, Claassen, Hawley, & Noakes, 1998; Chen et al., in press; Wong et al., 2009). Further research designed to closely mimic the practices commonly used by athletes is needed to provide support for this finding and to investigate the possible link between preexercise LGI meals and accelerated recovery of immune-function parameters.

**GI and CHO Intake During Exercise**

The CHO and fluid requirements of athletes during exercise vary depending on the nature, duration, and intensity of the event or training session and the climatic conditions. Consideration also needs to be given to the practicality of consuming food or fluid during exercise, the individual athlete’s physiological characteristics, and the nutritional status of the athlete before the event. Solid foods and foods with an LGI are generally avoided by athletes, especially if the LGI is associated with a high fructose content, which has been shown to cause gastrointestinal side effects during exercise (Murray et al., 1983). Observationally, the type of event also affects CHO ingestion during exercise, with cyclists normally consuming more than runners, who often find it difficult to tolerate solid food or a large bolus of food while exercising. It is generally accepted that ingesting CHO during prolonged exercise (>90 min) at moderate to high intensities (50–80% VO$_{2\text{max}}$) improves performance (Coyle, Coggan, Hemmert, & Ivy, 1986; Coyle et al., 1983). This is largely a result of maintenance of blood glucose levels, higher glucose uptake by the working muscle (McConell, Fabris, Proietto, & Hargreaves, 1994), and an increase in CHO oxidation in the latter stages of exercise when muscle glycogen stores are low (Coyle et al., 1986).

Several studies have investigated ingestion of CHO during exercise in the forms of single sugars such as glucose, sucrose, or fructose or combinations of these (Adopo, Pernonnet, Massicotte, Brisson, & Hillaire-Marcel, 1994; Jandrain et al., 1993; Jentjens, Venables, & Jeukendrup, 2004; Jentjens, Moseley, Waring, Harding, & Jeukendrup, 2004; Massicotte, Peronnet, Brisson, Bakkouch, & Hillaire-Marcel, 1989; Murray et al., 1989). These studies suggest that when fructose (an LGI CHO) is consumed alone, the rate of CHO oxidation is unlikely to meet the ideal of 1 g/min (Adopo et al., 1994; Jandrain et al., 1993; Jentjens, Venables, & Jeukendrup, 2004; Jentjens, Moseley, & Jeukendrup, 2004; Massicotte et al., 1989). Glucose (an HGI CHO) consumed alone or in combination with sucrose easily meets the standard of 1 g/min (Jentjens, Venables, & Jeukendrup, 2004; Jentjens, Moseley, et al., 2004). When glucose and fructose are consumed together, an oxidation rate as high as 1.26 g/min has been observed (Adopo et al., 1994; Jentjens, Moseley, et al., 2004). These differences are attributable to the different routes of absorption and metabolism in the intestine for fructose compared with other CHOs, which result in less competition for oxidation when fructose and glucose are consumed together (Adopo et al., 1994; Jentjens, Moseley, et al., 2004).

Only one study (Earnest et al., 2004) has directly investigated the effects of HGI and LGI CHO consumed during exercise. In that study, 9 endurance-trained male cyclists performed a 64-km time trial on a mechanically braked cycle ergometer. During the time trial, participants were fed 15 g of either an LGI gel (honey), an HGI gel (dextrose), or an artificially flavored placebo every 16 km. There was no difference in time-trial performance between the LGI and HGI trials. However, when the GI trials were collapsed to form one CHO-supplemented trial, times were found to be significantly faster than with placebo ($p = .02$). These results may indicate that it is the consumption of CHO itself, irrespective of the GI, that is critical to improving exercise performance (Earnest et al., 2004). However, with only one published study in this area further well-designed research is clearly required. Future studies should consider the practical implication of drinking and eating while exercising, such as time lost in stopping or slowing down to ingest the food, and the potential gastrointestinal implications.

**GI and Postexercise Nutrition**

One of the most important aspects of recovery that can be influenced by nutrition is the synthesis of muscle glycogen to replace stores lost during exercise. The amount, timing, and frequency of CHO ingestion have all been shown to affect glycogen synthesis (Jentjens & Jeukendrup, 2003). Consuming CHO immediately after exercise results in higher glycogen levels 4 hr after exercise than if CHO ingestion is delayed by 2 hr (Ivy, Katz, Cutler, Sherman, & Coyle, 1988). The highest rates of muscle glycogen resynthesis have been reported when CHO is fed every 15 min to provide 1.0–1.8 g · kg BM$^{-1}$ · hr$^{-1}$ CHO over a 2- to 4-hr period immediately after exercise (Doyle, Sherman, & Strauss, 1993; Piehl Aulin, Söderlund, & Hultman, 2000; Van Hall, Shirreffs, & Calbet, 2000). This suggests that when the interval between exercise sessions is short (4–8 hr), CHO should be consumed as soon as possible after exercise to maximize recovery. However, when longer recovery times are available the consumption of CHO immediately after exercise is not as important. As long as 7–10 g/kg BM of CHO is consumed over 24 hr (at a rate of at least 50 g/hr) muscle and liver glycogen will be replaced over this time (Coyle, 1991).

Glycogen synthesis and storage are largely influenced by insulin and a rapid supply of glucose substrate. Therefore, CHO sources with a moderate to high GI may enhance postexercise recovery (Burke, Kiens, & Ivy, 2004). A study investigating the impact of long-term (30 days) consumption of HGI or LGI CHO reported that consuming LGI CHO led to a decline in muscle glycogen from baseline values, and this decline was greater than after consuming HGI CHO (Kiens & Richter, 1996).

In the 1980s, investigations focused on simple and complex CHO intakes and effects on glycogen synthesis rates (Blom, Høstmark, Vaage, Kardel, & Mehlum, 1989).

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1987; Costill et al., 1981). However, those studies produced contrasting results, which was perhaps because the investigators used a classification for CHO that was not based on glycemic response. It was not until the early 1990s that the first study reported the actual GI of postexercise CHO feedings and measured the effect this had on muscle glycogen storage (Burke, Collier, & Hargreaves, 1993). Five well-trained cyclists undertook exercise trials to deplete glycogen stores. For 24 hr after each trial, the participants rested and consumed either an HGI or LGI CHO diet. Total CHO intake over the 24-hr period was 10 g CHO/kg for each participant. The most rapid increase in muscle glycogen content occurred when HGI foods were consumed. The HGI CHO also produced greater glucose and insulin responses than the LGI CHO. However, the authors calculated that the 33% increase in glycogen storage after the consumption of HGI CHO could not be completely explained by the differences in blood glucose and insulin responses (Burke et al., 1993).

In a follow-up study Burke et al. (1996) investigated whether consuming food in a gorging pattern (four large CHO meals) or a nibbling pattern (smaller meals spread throughout the day, which simulates the flattened glucose and insulin responses after LGI meals) over a 24-hr period could not be completely explained by the differences in blood glucose and insulin responses (Burke et al., 1993).

In a similar study by Stevenson, Williams, and Biscoe (2005), 8 well-trained recreational athletes completed a 90-min run at 70% VO2max after an overnight fast. They were then provided with HGI or LGI meals at 30 min (breakfast) and 2 hr (lunch) postexercise. Blood glucose responses to the HGI and LGI meals were greater than those to the LGI CHO. Insulin responses were similar to both the HGI and LGI breakfast, leading the authors to suggest that the GI of CHO consumed immediately postexercise may not be important as long as sufficient CHO is consumed. After an HGI lunch, however, the insulin response was higher than with the LGI lunch, indicating that consuming HGI foods later in the recovery period may facilitate further muscle glycogen resynthesis (Stevenson, Williams, & Biscoe, 2005). However, muscle glycogen was not measured in that study, so this is only a speculative suggestion based on the observed metabolic responses.

Another, perhaps more meaningful, measure of the effect of GI on recovery is performance in a subsequent bout of exercise. Stevenson, Williams, McComb, and Oram (2005) investigated the effects of the GI of postexercise CHO intake on endurance capacity the following day. On Day 1 of the study 9 active male participants ran at 70% VO2max for 90 min. Thirty minutes after the completion of exercise they were given an HGI or LGI breakfast. They were then provided with HGI or LGI meals and snacks for the remainder of the day. The following day, after an overnight fast, participants were required to run to exhaustion at 70% VO2max. Consumption of an LGI CHO recovery diet resulted in 7 of the 8 participants running longer than when an HGI CHO diet was consumed. On average, time to exhaustion was 12 min longer after consumption of an LGI recovery diet (Stevenson, Williams, McComb, & Oram, 2005). The authors attributed this result to the higher rate of fat oxidation and a higher concentration of plasma FFA observed during the run to exhaustion in the LGI trial. Thus, the FFA concentrations could have been higher during recovery because of the lower glycemic and insulinenic responses to the LGI diet. This would, therefore, allow resynthesis of intramuscular triacylglycerol (IMTG) stores, as well as replenishment of muscle glycogen from the CHO intake (Stevenson, Williams, McComb, & Oram, 2005).

There is growing evidence that IMTG may provide an important substrate during endurance activity (van Loon, 2004), and IMTG concentrations have been shown to decrease during prolonged exercise (Krsak et al., 2000; van Loon et al., 2003). Furthermore, two recent studies carried out in endurance-trained participants have reported that consuming HGI meals during 24 hr of recovery leads to greater utilization of IMTG and reduced availability of nonesterified fatty acids during subsequent exercise (performed in a fasted state) than consuming LGI recovery meals (Stevenson et al., 2009b; Trell, Stevenson, Stockmann, & Brand-Miller, 2007). These results suggest that consuming an LGI diet between bouts of prolonged strenuous exercise reduces dependence on intramuscular lipid stores and increases the use of circulating plasma FFAs derived from other fat stores (Stevenson, Thelwall, et al., 2009; Trell, Stevenson, Stockmann, & Brand-Miller, 2007), thus explaining the increased fat oxidation and endurance capacity observed by Stevenson, Williams, McComb, and Oram (2005).
GI and Training Status

GI is influenced by the chemical characteristics of the food (Foster-Powell et al., 2002), but most participant characteristics such as age, sex, body-mass index, and ethnicity are not believed to influence GI (Wolever et al., 2003). Recent research has produced conflicting results as to the influence training status may have on GI. Mettler, Lamprecht-Rusca, Stoffel-Kurt, Wenk, and Colombani (2007) and Mettler, Wenk, and Colombani (2006) carried out two similar studies in which the GI of breakfast cereals was measured in endurance-trained and sedentary males. In both these studies endurance-trained participants had a lower glycemic response to the cereals than sedentary participants but had a similar response to the glucose reference solution. Because GI is calculated as a ratio of glycemic response to the glucose reference and the test food (in this case, cereal), these results led to the calculated GI being lower in endurance-trained participants than it was in sedentary participants (Mettler et al., 2007; Mettler et al., 2006). Jackson (2007) also reported a lower glycemic response to the test food but not the reference food in trained men; thus the GI was lower when measured in the trained men than in the sedentary men. However, when Mettler et al. (2007) reproduced their study using female participants, endurance-trained women produced lower glycemic responses to both the test food and the reference food, meaning that GI was not different between endurance-trained and sedentary participants (Mettler et al., 2008). Similarly, Kim et al. (2008) and Trompers et al. (2010) found no difference in the GI of raisins and snack bars when measured in mixed-gender groups of endurance-trained and sedentary participants. Women oxidize more fat and less CHO at a given exercise intensity, indicating that the results of these studies could be attributed to the different gender of participants (Horton, Pagliassotti, Hobbs, & Hill, 1998; Tarnopolsky, MacDougall, Atkinson, Tarnopolsky, & Sutton, 1990; Venables, Achten, & Jeukendrup, 2005). However, gender differences in substrate metabolism represent absolute changes in substrate utilization, not relative changes to the same substrate, making it physiologically unlikely that there is a true interaction between gender, training status, and GI. In addition, GI is reported to not differ between genders (Wolever et al., 2003). The results of all these studies consistently emphasize that endurance training improves glucose tolerance and insulin sensitivity in young, healthy individuals of normal body weight, thus reducing their risk of diabetes and heart disease. However, the collective results in terms of the relationship between GI and training status are far from conclusive, and further well-designed research is required.

Conclusions and Recommendations

Preexercise Nutrition and GI

Most studies suggest that consuming LGI CHO before exercise results in a favorable metabolic profile during exercise, but only some report an enhancement in performance. Taken together the studies suggest there may be benefits to consuming LGI CHO before exercise, but to date, no research has indicated that consuming HGI
foods before exercise negatively affects endurance performance. Recent improvements in study design to include mixed meals and CHO ingestion both before and during exercise mean that researchers are getting closer to being able to mimic real-life sporting situations. However, until methodology is developed that allows for identification of the cause of the disparity between physiology and performance, it is unlikely that a definite answer will be reached. Until that time, athletes are encouraged to follow standard recommendations in terms of the timing and amount of CHO ingested before exercise and to let practical issues and individual experience dictate their use of HGI or LGI meals before exercise.

**Nutrition During Exercise and GI**

Consumption of CHO during exercise is common practice among athletes. Intuitively, many athletes opt to consume HGI CHO during exercise, possibly because most HGI foods are less bulky and easier to consume. However, research into the effect of GI of CHO consumed during exercise is severely lacking. The one study that investigated the consumption of CHOs of differing GIs during exercise reported that the consumption of CHO itself was more important than the GI of the CHO consumed. However, this result is far from conclusive. Athletes are encouraged to let individual preference guide their selection of CHO while giving consideration to the type of training or competition and the length and intensity of each exercise session.

**Postexercise Nutrition and GI**

Initial research suggested that consuming HGI CHO during recovery increased muscle glycogen synthesis postexercise. This may be particularly important to athletes who train twice a day and thus have limited recovery time between sessions. However, when recovery periods are longer, protein (which is commonly found in commercially available LGI foods and beverages) may be included without any negative impact on glycogen resynthesis and benefits in terms of muscle protein synthesis. Recent results suggest that the interaction between increased fat oxidation and LGI CHO consumed in the first 24 hr of recovery may play an important role in enhancing subsequent performance. However, these studies are yet to be replicated in fed participants.

Between individuals of equal athletic ability, nutrition may be the key factor in success. Optimizing dietary strategies before, during, and after exercise may provide endurance athletes with the winning advantage. However, the role GI plays in the complex area of endurance-performance enhancement is inconclusive. Future research should consider the training regimens of athletes because the type of training and competition being performed often dictates dietary strategies. Acute laboratory studies investigating the influence of GI on one or two exercise bouts may not truly reflect the influence of a habitual diet of, for example, LGI foods, especially when an athlete is trying to maintain intensity through a period of high-volume training. Thought should also be given to the appropriate use of meals or supplements, in terms of the timing of the feeding in relation to the exercise bout.

Future research will need to be carefully designed to consider both individual variability in glycemic response and the importance of using measures of performance that mimic competition as closely as possible. Research should also focus on identifying causes of the currently observed disparities between physiological observations and improvements in performance. Undoubtedly, exciting challenges and opportunities lie ahead for researchers determined to unwind the complexities of GI, nutrition, and endurance performance.

**References**


Glycemic Index and Endurance Performance


