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REVIEW ARTICLE

The Use of Carbohydrates During Exercise as an Ergogenic Aid

Naomi M. Cermak · Luc J. C. van Loon

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Abstract Carbohydrate and fat are the two primary fuel sources oxidized by skeletal muscle tissue during prolonged (endurance-type) exercise. The relative contribution of these fuel sources largely depends on the exercise intensity and duration, with a greater contribution from carbohydrate as exercise intensity is increased. Consequently, endurance performance and endurance capacity are largely dictated by endogenous carbohydrate availability. As such, improving carbohydrate availability during prolonged exercise through carbohydrate ingestion has dominated the field of sports nutrition research. As a result, it has been well-established that carbohydrate ingestion during prolonged (>2 h) moderate-to-high intensity exercise can significantly improve endurance performance. Although the precise mechanism(s) responsible for the ergogenic effects are still unclear, they are likely related to the sparing of skeletal muscle glycogen, prevention of liver glycogen depletion and subsequent development of hypoglycemia, and/or allowing high rates of carbohydrate oxidation. Currently, for prolonged exercise lasting 2–3 h, athletes are advised to ingest carbohydrates at a rate of 60 $g \cdot h^{-1}$ ($\sim$1.0–1.1 $g \cdot min^{-1}$) to allow for maximal exogenous glucose oxidation rates. However, well-trained endurance athletes competing longer than 2.5 h can metabolize carbohydrate up to 90 $g \cdot h^{-1}$ ($\sim$1.5–1.8 $g \cdot min^{-1}$) provided that multiple transportable carbohydrates are ingested (e.g. 1.2 $g \cdot min^{-1}$ glucose plus 0.6 $g \cdot min^{-1}$ of fructose). Surprisingly, small amounts of carbohydrate ingestion during exercise may also enhance the performance of shorter (45–60 min), more intense (>75 % peak oxygen uptake; VO_{2peak}) exercise bouts, despite the fact that endogenous carbohydrate stores are unlikely to be limiting. The mechanism(s) responsible for such ergogenic properties of carbohydrate ingestion during short, more intense exercise bouts has been suggested to reside in the central nervous system. Carbohydrate ingestion during exercise also benefits athletes involved in intermittent/team sports. These athletes are advised to follow similar carbohydrate feeding strategies as the endurance athletes, but need to modify exogenous carbohydrate intake based upon the intensity and duration of the game and the available endogenous carbohydrate stores. Ample carbohydrate intake is also important for those athletes who need to compete twice within 24 h, when rapid repletion of endogenous glycogen stores is required to prevent a decline in performance. To support rapid post-exercise glycogen repletion, large amounts of exogenous carbohydrate (1.2 $g \cdot kg^{-1} \cdot h^{-1}$) should be provided during the acute recovery phase from exhaustive exercise. For those athletes with a lower gastrointestinal threshold for carbohydrate ingestion immediately post-exercise, and/or to support muscle re-conditioning, co-ingesting a small amount of protein (0.2–0.4 $g \cdot kg^{-1} \cdot h^{-1}$) with less carbohydrate (0.8 $g \cdot kg^{-1} \cdot h^{-1}$) may provide a feasible option to achieve similar muscle glycogen repletion rates.

1 Introduction

Carbohydrate and fat are the two primary fuel sources oxidized by skeletal muscle tissue during prolonged, endurance-type exercise. The relative contribution of these fuel sources largely depends on the exercise intensity and duration [1, 2] as well as the athlete's training status [3].

N. M. Cermak · L. J. C. van Loon (✉)
Department of Human Movement Sciences, Faculty of Health, Medicine and Life Sciences, NUTRIM School for Nutrition, Toxicology and Metabolism, Maastricht University Medical Centre+, P.O. Box 616, 6200 MD Maastricht, The Netherlands
e-mail: l.vanloon@maastrichtuniversity.nl

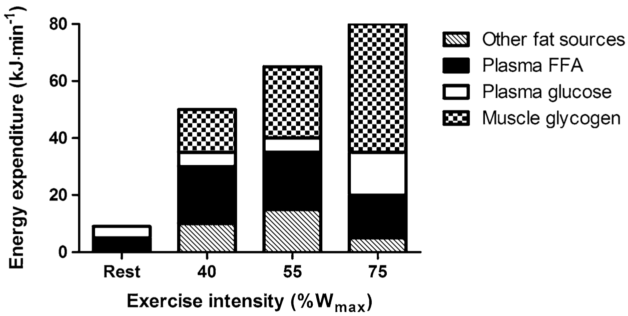

Fig. 1 Energy expenditure (expressed in kJ·min^{-1}) as a function of exercise intensity [expressed in percentage of maximal workload capacity (%W_{max})]. The relative contribution of plasma glucose, muscle glycogen, plasma free fatty acids (FFA) and other fat sources (sum of intramuscular plus lipoprotein-derived triglycerides) to energy expenditure are illustrated as described in the legend

During low- to moderate-intensity exercise (30–65 % of peak oxygen uptake; VO_{2peak}), fat dominates as the preferred fuel source. However, as depicted in Fig. 1, with an increase in exercise intensity, the contribution of carbohydrate oxidation to total energy expenditure becomes greater, with muscle glycogen becoming the most important substrate source [1]. Carbohydrate is stored in the human body as liver (~100 g) and skeletal muscle glycogen (~350–700 g; depending on training status and diet). These endogenous carbohydrate stores are relatively small, representing less than 5 % of the total energy storage [4]. However, muscle glycogen represents an essential fuel source during prolonged moderate- to high-intensity exercise [5, 6] by contributing more than 50 % of the total energy requirements [1, 2]. Therefore, endogenous carbohydrate availability may become compromised when carbohydrate requirements of training or competition exceed endogenous carbohydrate stores. Consequently, fatigue during prolonged exercise is most often associated with muscle glycogen depletion and reduced blood glucose concentrations [7]. As such, to achieve optimal performance during prolonged (>2 h) moderate- to high-intensity exercise, the exogenous provision of carbohydrates during exercise is generally required.

2 Historical Perspective on the Use of Carbohydrates as an Ergogenic Aid

Research on the ergogenic properties of carbohydrate supplementation has been accumulating since the beginning of the 20th century. Two of the first scientists to recognize the importance of carbohydrate availability during prolonged exercise were Krogh and Lindhard [8] who manipulated the total amount of carbohydrate consumed in their subjects' diet. Subjects reported that it was easier to exercise after consuming a carbohydrate-rich diet when compared with a high-fat diet [8]. However, measurable performance-enhancing effects of exogenous carbohydrate provision were observed during the 1924 Boston Marathon. One year prior, Levine and colleagues [9] measured blood glucose concentrations following the marathon and noted that at the end of the race, most participants showed very low concentrations of blood glucose. Based on this observation, Levine and colleagues hypothesized that low blood glucose concentrations may cause fatigue [9, 10]. To test their hypothesis, Levine and colleagues [9, 10] had several of the athletes consume carbohydrates during the same marathon 1 year later. Carbohydrate supplementation prevented the drop in blood glucose concentration and running performance substantially increased [9].

In 1932, Christensen [11] confirmed a positive relationship between increasing exercise intensity and the amount of carbohydrate utilization. A few decades later, Bergstrom and Hultman furthered Christensen's observations with the development of the skeletal muscle biopsy technique [6, 12]. For the first time, skeletal muscle glycogen was recognized for its critical role during exercise, laying the groundwork for future sports nutrition research. Bergstrom and colleagues [13] discovered that the concentration of skeletal muscle glycogen could be manipulated by modulating the carbohydrate content of the diet [13]. In line, they reported that feeding a high-carbohydrate diet improved exercise performance. Therefore, it was concluded that skeletal muscle glycogen content is closely related to the capacity to perform prolonged moderate- to high-intensity exercise [13]. Following this discovery, the next few decades were host to multiple studies examining the effects of high-carbohydrate diets. As such, super-compensated muscle glycogen levels have been reported to improve the performance of prolonged exercise events (>90 min) by 2–3 % compared with low-to-normal concentrations of muscle glycogen [14]. An extensive discussion on dietary strategies to augment pre-exercise glycogen stores (i.e. carbohydrate loading) and the impact of carbohydrate consumption prior to exercise on subsequent performance would be beyond the scope of the present review. For an elegant review on carbohydrate loading prior to exercise, please refer to Hawley and colleagues [14].

Additional contributions from Bergstrom and Hultman [6] stimulated numerous research papers examining the metabolic effects of carbohydrate feeding *during* exercise [15–24]. As a consequence, the last few decades have provided a plethora of evidence supporting the ergogenic effects of carbohydrate ingestion during prolonged, endurance-type exercise [18–22, 25–33]. Presently, carbohydrate ingestion during exercise has become general practice by athletes in many different sports of varying exercise duration and intensity. The common practice of consuming carbohydrates during exercise has resulted in the development and production of sports-specific carbohydrate-containing supplements that provide carbohydrate in various forms (solid, gel, or liquid), types (e.g. glucose, maltodextrin, and fructose), and concentrations. This review describes the scientific rationale leading up to the use of carbohydrates during prolonged (>2 h) exercise. More specifically, this review discusses the preferred type(s), amount, and form of carbohydrate that can be used to improve endurance exercise performance, and highlights the potential benefits of carbohydrate use during shorter (45–60 min), more intense (>75 % VO_{2peak}) exercise activities. Consequently, this review will provide comprehensive guidelines for proper carbohydrate ingestion during prolonged endurance, high-intensity, and intermittent/team sports exercise. In addition, we will briefly address the impact of carbohydrate ingestion during immediate post-exercise recovery for those athletes involved in multi-day competition. The literature cited in this review was retrieved online using PubMed. Key search terms used included 'carbohydrate' with 'performance' or 'glycogen' or 'glucose' or 'exercise' or 'mouth rinse' or 'intermittent' and/or 'recovery'.

3 Carbohydrate Ingestion During Endurance-Type Exercise

The ergogenic effects of carbohydrate feeding during prolonged moderate- to high-intensity exercise have been consistently demonstrated in numerous studies [17–21, 23, 24]. In agreement, a recent meta-analysis pooled 88 randomized crossover studies investigating the ergogenic properties of carbohydrate ingestion on exercise performance. Approximately 83 % of the included studies used cycling exercise and measured either exercise capacity by using a time-to-exhaustion protocol (mean test duration of 106 min) or exercise performance using a time-trial study design (mean test duration 47 min). From the mixed model meta-analysis, performance benefits of the carbohydrate supplement ranged from substantial 6 % improvements to moderate 2 % impairments. The range from −2 to 6 % is not very surprising given the numerous differences in exercise protocols, carbohydrate feeding strategies, subjects' characteristics and other experimental conditions between studies. The largest effect inferred from the meta-analysis was an increase of 6.5 % when the supplement consisted of a 3–10 % carbohydrate plus protein drink providing $\sim 0.7\ g \cdot kg^{-1} \cdot h^{-1}$ glucose polymers, $\sim 0.2\ g \cdot kg^{-1} \cdot h^{-1}$ fructose and $\sim 0.2\ g \cdot kg^{-1} \cdot h^{-1}$ protein [34]. Overall, the meta-analysis concluded that the use of carbohydrate supplements with an appropriate composition and administration regimen can have large ergogenic properties [34].

Nevertheless, the performance improvements with carbohydrate ingestion during endurance exercise have been questioned as to whether they are only due to a placebo effect, rather than a true performance-enhancing effect. The placebo effect is a favorable outcome arising purely from a belief that a subject has received the beneficial treatment. Hulston and Jeukendrup [35] tested the placebo effect by recruiting ten male cyclists to perform three exercise trials consisting of 120 min of steady-state cycling (61 % VO_{2peak}) followed by an approximate 60-min time trial. During the 120 min of steady-state cycling, subjects ingested water, a carbohydrate solution or a non-caloric placebo solution matched for the same color and taste as the carbohydrate solution. To investigate any possibility of a placebo effect, subjects were informed that both solutions (carbohydrate and placebo) contained carbohydrate and the purpose of the study was to compare different carbohydrate drinks with water [35]. Time-trial performance times were 11.3 % faster in the carbohydrate trial compared with water and 10.6 % faster when compared with the placebo trial. These results suggest that there is no placebo effect from carbohydrate ingestion during prolonged cycling exercise.

Although research has identified a range of potential mechanisms by which exogenous carbohydrate consumption may improve exercise performance, these mechanisms may contribute differently to the ergogenic benefits of carbohydrate ingestion observed during short ($\sim$1 h) high-intensity (>75 % VO_{2peak}) exercise as opposed to more prolonged (>2 h) low- to moderate-intensity (60–75 % VO_{2peak}) exercise. The following subsection discusses the leading potential mechanisms suggested to be responsible for the ergogenic effects of carbohydrate ingestion during prolonged exercise, including the sparing of skeletal muscle glycogen and maintaining proper blood glucose concentrations (euglycemia) and high rates of carbohydrate oxidation.

3.1 Potential Mechanism(s) Underlying the Ergogenic Properties of Carbohydrate Ingestion During Endurance Exercise

Fatigue following prolonged, endurance-type exercise generally coincides with the depletion of skeletal muscle glycogen stores. Although still under considerable debate, exogenous carbohydrate consumption during prolonged exercise may attenuate the rate of glycogenolysis, thereby sparing muscle glycogen stores and ultimately delaying the onset of fatigue. This theory was first demonstrated by Bergstrom and Hultman [6] who reported that intravenous glucose infusion reduced muscle glycogen degradation by $\sim$20 % during 60 min of cycling exercise. Since then, many studies have confirmed a 20–28 % lower muscle glycogen loss when carbohydrate is ingested during prolonged exercise [5, 21, 25, 36–39]; however, others have failed to confirm these findings [18, 40–42]. Hargreaves and colleagues [21] reported a 26 % decrease in muscle glycogen use when subjects ingested 172 g of carbohydrate during 4 h of prolonged, moderate-intensity cycling. In a subsequent study, however, Hargreaves and Briggs [42] found no glycogen-sparing effect when subjects ingested 120 g of carbohydrate during 2 h of cycling at 70 % VO_{2peak}. In line, Coyle and colleagues [18] had subjects cycle at a similar intensity (71 % VO_{2peak}) until fatigued while being fed carbohydrate or a placebo. Although subjects were able to ride 1 h longer in the carbohydrate trial when compared with the placebo trial, no differences were observed in the net decline in muscle glycogen content between treatments [18].

While there is no obvious explanation for the apparent discrepancy between studies, muscle glycogen sparing may occur in a time-dependent and/or fiber-type-dependent manner. Stellingwerff and colleagues [38] demonstrated a time-dependent change in muscle glycogen use during prolonged cycling exercise. Mixed-muscle glycogen use was lower during the initial hour of exercise when carbohydrate was ingested as opposed to the placebo trial. As such, there was a greater dependence on muscle glycogen as a substrate source during the early stages of exercise in the placebo trial [38]. Moreover, Tsintzas and colleagues [36] demonstrated a fiber-type-specific change in muscle glycogen content following treadmill running. Fiber-type-specific glycogen content was determined prior to and after 60 min of treadmill running (70 % VO_{2peak}) while ingesting a carbohydrate or placebo solution [36]. Overall, mixed muscle glycogen declined 28 % less when carbohydrate was ingested compared with a placebo during 60 min of running exercise [36]. However, when fiber-type-specific glycogen content was analyzed, it became evident that only type I muscle fibers displayed evidence of glycogen sparing [36]. In contrast, when carbohydrate was ingested during more prolonged, moderate-intensity cycling exercise (3 h at 63 % VO_{2peak}) glycogen sparing was reported in type II muscle fibers only [38]. The difference in fiber-type specificity may be attributed to the type of exercise (running vs cycling) as well as to the duration (1 vs 3 h) of the exercise bout, as muscle fiber-type recruitment shifts to include more type II fibers during the latter stages of more prolonged exercise [43]. At any rate, if muscle fiber-type-specific differences in glycogen sparing exist during prolonged exercise, measurements of mixed-muscle glycogen content may be unable to detect glycogen sparing as a mechanism responsible for the ergogenic properties of carbohydrate ingestion during prolonged exercise. Regardless, skeletal muscle glycogen sparing still remains one of the major mechanisms to explain the ergogenic properties of carbohydrate consumption during prolonged, moderate- to high-intensity exercise.

Early research suggests that exogenous carbohydrate provision during prolonged exercise improves exercise capacity and/or exercise performance by maintaining blood glucose concentrations, and thus enabling high rates of carbohydrate oxidation. Coyle and colleagues [18] reported that carbohydrate ingestion prevented a decline in blood glucose concentration and attenuated the decline in carbohydrate oxidation rates during prolonged exercise to exhaustion (71 % VO_{2peak}). In a subsequent study, cyclists exercised on three separate occasions at 70 % VO_{2peak} until exhaustion ($\sim$170 min), which resulted in a significant drop in blood glucose concentration [26]. Upon exhaustion, subjects were given 20 min of rest after which they were required to continue cycling after (i) ingesting glucose polymers (3 $g \cdot kg^{-1}$); (ii) receiving a glucose infusion; or (iii) ingesting a placebo. Blood glucose levels initially increased in both glucose trials; however, only the glucose infusion trial was able to maintain euglycemia. In line, although time to fatigue was significantly increased in both glucose trials when compared with placebo ingestion, time to fatigue was significantly longer in the glucose infusion when compared with the glucose ingestion trial. Therefore, the authors concluded that the decline in blood glucose concentration significantly contributed to fatigue by limiting glucose oxidation rates, a condition that can be reversed by glucose infusion [26]. Further evidence to support the idea that exogenous carbohydrate provision improves exercise performance by maintaining blood glucose concentration came from Nybo [44]. Three hours of exercise at 60 % VO_{2peak} in endurance-trained subjects lowered blood glucose concentrations and decreased voluntary force production from pre- to post-exercise as measured during a 2 min sustained maximal knee extension. However, when euglycemia (4.5 $mmol \cdot L^{-1}$) was maintained by ingesting 200 g of carbohydrate during exercise, the attenuation in maximal voluntary force production from pre- to post-exercise was avoided [44]. Maintaining euglycemia and high rates of carbohydrate oxidation through carbohydrate feeding may also spare liver glycogen [45, 46]. Although hepatic glucose is tightly regulated to ensure a constant rate of glucose output in the presence or absence of carbohydrate feeding, high rates of carbohydrate intake have been shown to reduce liver glucose production to basal levels [47] or completely block hepatic glucose output [46]. This sparing of liver glycogen allows for greater carbohydrate availability in the liver towards the end stages of competitive exercise, when exercise intensity is strongly increased.

In contrast, other research [16, 48] has found that maintaining blood glucose levels did not appear to consistently improve exercise performance when compared with hypoglycemic conditions. Claassen and colleagues [48] demonstrated a high degree of variability with respect to hypoglycemia and its effects on exercise performance after 48 h on a low-carbohydrate diet. When subjects were provided with a glucose infusion following the completion of a 48 h low-carbohydrate diet, less than 50 % of the subjects were able to complete the 150 min of exercise at 70 % VO_{2peak}, despite maintaining euglycemia. Moreover, 22 % of the subjects in the placebo group were able to finish the 150 min of cycling exercise despite being hypoglycemic [48].

As such, studies exploring the mechanisms behind the ergogenic properties of carbohydrate ingestion during exercise do not lead to one specific mechanism per se. Instead, there may be a combination of mechanisms by which carbohydrate ingestion during exercise improves performance and these may depend on a host of variables, including (but not limited to) the type, duration, and intensity of the exercise, training status of the athletes, as well as the applied carbohydrate feeding schedule.

3.2 Type and Amount of Carbohydrate

Different types of carbohydrates may be oxidized at various rates during prolonged exercise [49]. Exogenous carbohydrate oxidation rates have been assessed following the ingestion of fructose, galactose, sucrose, maltose, starch and glucose polymers and compared with glucose [50]. Whereas most carbohydrate sources showed similar oxidation rates to glucose, exogenous fructose was shown to be oxidized at a slightly lower rate than glucose [50, 51], while exogenous galactose was shown to be oxidized at a rate almost 50 % lower than glucose [50–52]. The lower exogenous oxidation of these two carbohydrates is likely explained by differences in intestinal absorption and the need for the liver to first convert these monosaccharides into substrates (glucose and lactate) before they can be used by skeletal muscle tissue. Moreover, there does not seem to be a difference in the oxidation rates between high-molecular-weight glucose polymers which may help to maintain the osmolality of a beverage, compared with low-molecular-weight glucose polymers [53]. To summarize, carbohydrates can be divided into two categories according to the rate at which they are oxidized. One group containing glucose and glucose polymers is oxidized at relatively high rates of up to 1.0–1.1 $g{\cdot}min^{-1}$, and another group containing galactose and fructose is oxidized at much lower rates (up to approximately 0.6 $g{\cdot}min^{-1}$). As such, for exercise lasting approximately 1–2 h, carbohydrate ingestion in the form of glucose or glucose polymers is recommended to allow for high exogenous carbohydrate oxidation rates of approximately 1.0–1.1 $g{\cdot}min^{-1}$. This guideline agrees with the American College of Sports Medicine (ACSM) joint position statements which recommend athletes consume 30–60 g of carbohydrate per hour to enhance performance during moderate- to high-intensity exercise lasting >60 min [54, 55].

With respect to studies examining the dose-response effect of exogenous carbohydrate oxidation rates on exercise performance, very few well-controlled and well-designed studies have been published. Regardless, evidence is pointing towards the existence of a dose-response relationship as, for example, greater amounts of carbohydrate ingested during an Ironman triathlon have been correlated with an improvement in performance [56]. Recently, a large multicenter study was conducted examining the relationship between the carbohydrate dose (from 0 to 120 $g{\cdot}h^{-1}$) which was ingested during 2 h of constant load cycling at ~70 % VO_{2peak} and the proceeding 20 km time trial in an effort to identify an optimal range of carbohydrate ingestion rates for endurance performance [57]. Carbohydrate ingestion (mixture of glucose, maltodextrin, and fructose in a 1:1:1 ratio) and endurance performance appeared to be related in a curvilinear dose-response manner, with the best 20 km time-trial performance occurring when carbohydrates were ingested at a rate of 78 $g{\cdot}h^{-1}$ during the 2 h of constant load cycling [57]. These results seem to be in line with an earlier study which tested the performance effects following carbohydrate ingestion rates of 15, 30, and 60 $g{\cdot}h^{-1}$ [58]. Using a similar study design, 20 km time-trial performance was fastest when carbohydrates were ingested at 60 $g{\cdot}h^{-1}$ and slowest when ingested at 15 $g{\cdot}h^{-1}$ during the 2 h of constant load cycling [58]. Moreover, exogenous carbohydrate oxidation rates were higher following ingestion of 60 $g{\cdot}h^{-1}$, implying that high exogenous carbohydrate oxidation rates further improve endurance performance [58]. However, a ceiling effect seems to occur around 60–70 $g{\cdot}h^{-1}$ whereby further increasing the amount of ingested carbohydrate does not further increase exogenous carbohydrate oxidation rates or exercise performance. Consequently, many research groups have focused on developing nutritional strategies to maximize exogenous carbohydrate oxidation rates during exercise. Recent research has demonstrated that under the right conditions the ingestion of multiple transportable carbohydrates can increase exogenous carbohydrate oxidation rates to values well in excess of 1.0–1.1 $g{\cdot}min^{-1}$. However, for athletes participating in endurance events lasting no longer than 3 h, up to 60 g of glucose or glucose polymers should be consumed per hour of exercise in an effort to maximize exercise performance (Table 1).

3.3 Role of Multiple Transportable Carbohydrates

In recent years, there has been much discussion on the potential benefits of using multiple transportable

Table 1 Recommendations for carbohydrate intake during exercise events of different durations (adapted from Jeukendrup [171], with permission)[a]

Event	Exercise duration	CHO required	Amount of CHO recommended	Type of CHO recommended	Single CHO	MT CHO
Very short, high-intensity exercise	<0.5 h	None	NA	NA	NA	NA
Short, high-intensity exercise	0.5–1.25 h	Very small amounts	Mouth rinse	Most forms	Yes	Yes
Intermittent/team sports, short duration	0.5–1.25 h	Very small amounts	Mouth rinse	Most forms	Yes	Yes
Intermittent/team sports, moderate duration	1–1.5 h	Moderate amounts	Up to 60 $g \cdot h^{-1}$	Fast-oxidizing CHO	Not optimal	Recommended
Intermittent/team sports, long duration	>2 h	Large amounts	Up to 90 $g \cdot h^{-1}$	MT CHO only	No	Yes
Endurance-type exercise	1–3 h	Moderate amounts	Up to 60 $g \cdot h^{-1}$	Fast-oxidizing CHO	Not optimal	Recommended
Prolonged endurance-type exercise	>2.5 h	Large amounts	Up to 90 $g \cdot h^{-1}$	MT CHO only	No	Yes
Starting exercise with suboptimal CHO	>2 h	Large amounts	Up to 90 $g \cdot h^{-1}$	MT CHO only	No	Yes
Recovery for multi-day competition	<24 h recovery	Large amounts	1.2 g $CHO \cdot kg^{-1} \cdot h^{-1}$	Fast-oxidizing CHO	Not optimal	Recommended
Recovery for multi-day competition with suboptimal CHO intake during recovery	<24 h recovery	Large amounts	0.8 g $CHO \cdot kg^{-1} \cdot h^{-1}$ + 0.4 g $PRO \cdot kg^{-1} \cdot h^{-1}$	Fast-oxidizing CHO + fast protein	Not optimal	Recommended

CHO Carbohydrate, *MT CHO* multiple transportable carbohydrates, *NA* not applicable, *PRO* protein

[a] These guidelines are intended for athletes exercising at >moderate intensity (>4 kcal/min) who wish to optimize their performance. If the absolute exercise intensity is below moderate, carbohydrate intake should be adjusted downwards accordingly

carbohydrates in the composition of sports drinks as a means to further increase exogenous carbohydrate oxidation rates [59–67] and enhance prolonged exercise performance [68]. As previously discussed, it was generally believed that exogenous carbohydrate oxidation rates cannot exceed 1.0–1.1 $g \cdot min^{-1}$ regardless of how much glucose or glucose polymers were ingested [50]. Reasons for reaching this plateau were unclear, but may be related to the limitations at the level of intestinal glucose uptake during exercise [69]. Glucose is absorbed through a sodium-dependent glucose transporter protein called SGLT1. This transport protein is located in the brush border membrane of the small intestine and has a high affinity for glucose and galactose but not fructose [70]. In theory, intestinal SGLT1 may become fully saturated when large amounts of glucose or glucose polymers are ingested (>1.2 $g \cdot min^{-1}$), thereby becoming a key limiting factor for exogenous carbohydrate oxidation [60, 65]. Fructose, however, is absorbed independently from glucose by a non-sodium-dependent intestinal transporter (GLUT-5) [71]. Therefore, the combined ingestion of glucose and fructose should result in an increased capacity for total intestinal carbohydrate absorption and thus lead to higher exogenous carbohydrate oxidation rates. Recent literature has confirmed this theory by demonstrating that the ingestion of multiple transportable carbohydrates (such as glucose and fructose) during prolonged, endurance-type exercise can result in 20–55 % higher exogenous carbohydrate oxidation rates [59, 60, 62, 63, 65, 67, 72], accompanied by increased fluid delivery and improved oxidation efficiency [69] when compared with the ingestion of an iso-caloric amount of glucose.

Jentjens and colleagues [62] recruited trained male cyclists who performed 2 h of cycling exercise on four different occasions during which they ingested either (a) water, (b) 1.2 $g \cdot min^{-1}$ glucose, (c) 1.8 $g \cdot min^{-1}$ glucose or (d) 1.2 $g \cdot min^{-1}$ glucose plus 0.6 $g \cdot min^{-1}$ fructose. Compared with the glucose-only trials, the combined ingestion of glucose plus fructose resulted in ~55 % greater exogenous carbohydrate oxidation rates (1.26 $g \cdot min^{-1}$ compared with a peak of 0.83 $g \cdot min^{-1}$ in the glucose-only trials). This study was followed by a subsequent investigation [65] comparing various other combinations of carbohydrates (co-ingestion of glucose and sucrose compared with co-ingestion of glucose and a glucose-polymer) with glucose only to confirm that exogenous carbohydrate oxidation rates were higher following the combined ingestion of carbohydrates that are absorbed via different intestinal transporters (i.e. co-ingestion of glucose and sucrose). Much of the research investigating the use of multiple transportable carbohydrates has been published by Jeukendrup and colleagues [60–66, 68, 73]. From their work, it has become evident that when ingesting large amounts of glucose (1.2 g·min^{-1}) plus fructose (1.2 g·min^{-1}), exogenous carbohydrate oxidation rates can reach peak values (1.75 g·min^{-1}) that are 65 % higher than maximal carbohydrate oxidation rates achieved when ingesting large amounts of glucose only [61].

Perhaps more importantly, the higher exogenous carbohydrate oxidation rates following the ingestion of multiple transportable carbohydrates have also been demonstrated to further improve exercise performance. When combinations of multiple transportable carbohydrates were ingested during prolonged endurance exercise, subjects' ratings of perceived exertion were lower [66] and subjects reported a reduced feeling of fatigue [67]. Furthermore, it was also demonstrated that the combined ingestion of glucose and fructose improved time-trial performance [68]. Trained cyclists performed 2 h of moderate-intensity cycling at 55 % of their maximal workload (W_{max}), during which they ingested water, glucose (1.8 g·min^{-1}), or a combination of glucose (1.2 g·min^{-1}) plus fructose (0.6 g·min^{-1}) [68]. Following the 2 h of cycling exercise, subjects performed an ~1 h time trial. Glucose ingestion during the 2 h cycling exercise improved mean power output in the time trial by 10 % when compared with the water trial. Most surprising, however, was the observation that when glucose plus fructose was ingested, mean power output during the time trial improved by an additional 8 % when compared with the ingestion of glucose only. This was the first study to demonstrate that ingestion of multiple transportable carbohydrates provides a clear performance advantage over glucose only during prolonged moderate- to high-intensity exercise [68]. Subsequent research has since been published in support of multiple transportable carbohydrates improving mountain bike performance in addition to laboratory-based, high-intensity cycling when compared with single-transport carbohydrates [74]. From a practical viewpoint, some of this performance improvement has been linked to less gastrointestinal distress/discomfort following the ingestion of multiple transportable carbohydrates when compared with the ingestion of large amounts of glucose and/or glucose polymer mixtures [74, 75].

However, it may be necessary to fully saturate glucose transporters in the intestine before any substantial increase in exogenous carbohydrate oxidation rates can be observed following the ingestion of multiple transportable carbohydrates [59]. For example, when carbohydrates are ingested at a more moderate rate of 0.8 g·min^{-1}, there is no difference in the rates of exogenous carbohydrate oxidation when compared with an equivalent amount of glucose plus fructose [59], as intestinal glucose transport is not yet full saturated. Therefore, ingestion of multiple transportable carbohydrates will only elevate the rate of exogenous carbohydrate oxidation during prolonged exercise when glucose or glucose polymers are already being consumed at near maximal rates (~1.2 g·min^{-1}). As such, many of these guidelines are only relevant for well-trained athletes who compete at a high absolute workload and are used to consuming large amounts of carbohydrate during exercise. For those well-trained athletes who have difficulty consuming such large amounts of carbohydrate during exercise, the gut is a trainable and adaptable organ and with proper practice these athletes can improve their tolerance for exogenous carbohydrate intake during exercise [76], thereby allowing a greater increase in exogenous carbohydrate oxidation rates. Consequently, all athletes are encouraged to 'practise' their nutritional feeding strategies so that they are able to tolerate higher rates of carbohydrate ingestion during exercise without experiencing any gastrointestinal distress. In an effort to maximize performance, well-trained athletes who exercise at a high absolute workload for more than 2.5 h are advised to ingest glucose and/or glucose polymers (1.2 g·min^{-1}) plus fructose (0.6 g·min^{-1}) during exercise (Table 1).

3.4 Form of Ingested Carbohydrate: Liquid, Gel, or Solid?

A collection of research studies have reported that the form in which carbohydrates are provided during prolonged exercise (liquid, semi-liquid, or solid) does not alter its ergogenic effects [21, 77–81]. Hargreaves and colleagues [21] examined the effects of providing carbohydrate in the form of a candy bar (43 g of carbohydrate, 9 g fat, and 3 g protein) and observed a 45 % improvement in sprinting capacity following 4 h of submaximal exercise when compared with the ingestion of a placebo. In line, others have reported similar improvements in performance following liquid and solid carbohydrate feedings compared with a placebo [80, 81]. Murdoch and colleagues found no differences in blood glucose concentrations during cycling exercise (70 % VO_{2peak}) when slurried (semi-solid) or solid bananas were ingested prior to exercise [79]. Moreover, Pfeiffer and colleagues recently demonstrated that a carbohydrate semi-solid (gel) [78] and solid carbohydrate [77] supplement are oxidized to the same extent as liquid carbohydrate. Taken together, these results suggest that the form in which carbohydrates are provided (whether it is in a liquid, semi-solid, or solid state) does not alter the ergogenic effects of carbohydrate ingestion during prolonged exercise. As such, for practical recommendations, the form of ingested carbohydrate can be dictated by the preference of the athlete with regard to proper fluid intake which is required to facilitate gastric emptying and to compensate for sweat loss.

4 Carbohydrate Ingestion During High-Intensity Exercise

Interestingly, the ergogenic benefits of carbohydrate ingestion during exercise may not be limited to prolonged, endurance-type exercise events. Carbohydrate ingestion has also been shown to improve performance during high-intensity (>75 % VO_{2peak}) exercise of a relatively short duration (~60 min) [7, 82–86]. Jeukendrup and colleagues [83] recruited cyclists to perform a 40-km time trial (~1 h) with and without carbohydrate ingestion (7.6 % carbohydrate solution provided in a volume of 14 mL·kg^{-1}). Subjects were ~1 min faster in the carbohydrate trial compared with the placebo trial, representing a 2.3 % improvement in performance [83]. However, there is no apparent metabolic explanation for this observation as endogenous carbohydrate stores should not form a limiting factor for optimal performance during exercise of such a short duration [83].

This phenomenon was further explored by Carter and colleagues [87] who investigated the impact of glucose administration during short, high-intensity exercise trials to determine whether an increase in blood glucose levels would enhance exercise performance. They infused glucose (1.0 g·min^{-1}) or placebo (saline) in a group of cyclists during a 1 h time trial. Although the glucose infusion resulted in elevated blood glucose levels and increased glucose uptake, no differences were observed in 1 h time-trial performance [87]. Based on their results, the authors speculated that glucose ingestion might modulate exercise performance by a mechanism that becomes relevant even prior to glucose uptake. To explore this, Carter and colleagues designed a subsequent study during which subjects rinsed their mouths with a carbohydrate solution or an identical tasting placebo during the ~1 h time trial [88]. During a carbohydrate mouth rinse protocol, a carbohydrate solution is taken in the mouth but instead of being ingested, the solution is spat out to omit any impact of exogenous carbohydrate uptake. Interestingly, in contrast to intravenous glucose infusion, mouth rinsing with a 6.4 % maltodextrin solution every 12.5 % of the completed trial improved 1 h time-trial performance by 2.8 % [88]. These findings suggest that there might be receptors in the oral cavity that are able to sense the (upcoming) availability of exogenous glucose and communicate this towards the brain. Although speculative, exposing the oral cavity to a carbohydrate solution may initiate a signaling response to the central nervous system as the presence of carbohydrate in the mouth has been found to facilitate corticomotor output in the fasted state to both fresh and fatigued skeletal muscle [89]. Interestingly, oropharyngeal signaling pathways have also been found to play an important role in the perceptual response during rehydration and exercise performed in the heat [90, 91]. Oral rehydration resulted in lower values for ratings of perceived exertion and thirst sensation compared with an equivalent amount of intravenous hydration [91].

Other groups [92], however, have not consistently confirmed the findings by Carter and colleagues. A limited number of studies have since used a carbohydrate mouth rinse and have demonstrated evidence both for [93–96] and against [97, 98] any improvements in exercise performance when compared with a placebo. The discrepancy in the literature has been speculated to be due to the nutritional state of the subjects, who exercise either in the fed [92, 97] or fasted (post-absorptive) state [93, 96], which may be of particular relevance as, in post-absorptive conditions, liver glycogen stores may be more compromised.

Although it is common practice for athletes to avoid eating immediately prior to training or competition, most athletes will consume a small carbohydrate-rich meal 2–3 h prior to an exercise bout. The latter is of particular relevance in an effort to optimize pre-exercise liver glycogen stores. As previously mentioned, the pre-exercise carbohydrate-loaded status of the subject seems to be the common variable between studies that have, and have not, shown an effect of carbohydrate feeding on performance during short-duration, high-intensity exercise. In line, the effect of hunger and satiety on the central response to taste has recently been investigated by Haase and colleagues [99] using functional magnetic resonance imaging (MRI). In line with the theory on performance improvements using a carbohydrate mouth rinse, brain activation in the hunger condition produced a more robust activation to pure taste stimuli relative to water. Moreover, tasting carbohydrate was reported to result in more vigorous brain activation compared with all other taste stimuli, including the use of artificial sweeteners [99, 100]. The fact that regions of the brain have been found to be activated by the presence of carbohydrate and not non-nutritive sweeteners [99, 100], and may be dependent on the pre-exercise nutritional state of the body [99], may provide a mechanistic explanation for the performance effects found when applying a carbohydrate mouth rinse. Fares and Kayser [94] examined the performance effects of using a carbohydrate mouth rinse in both the fasted and fed state. Surprisingly, carbohydrate mouth rinsing improved cycling time to exhaustion at 60 % W_{max} following both an overnight fast and after the ingestion of a carbohydrate-rich breakfast 3 h prior to exercise. This improvement is in contrast with other work in the fed state [92]. However, unlike other carbohydrate mouth-rinse studies, the subjects included in the work by

Fares and Kayser [94] were untrained, and performance was measured using an exercise test to exhaustion. Nevertheless, when performance was measured using a time trial in a group of trained cyclists, carbohydrate mouth rinsing was also found to improve performance in both the fed and fasted state [101]. Lane and colleagues [101] found that, compared with the fed state, carbohydrate mouth rinsing improved performance to a greater extent after an overnight fast. Overall, however, the fastest time trials were performed in the fed state with the addition of a carbohydrate mouth rinse. Although this study provides support for the use of a carbohydrate mouth rinse, it also reminds athletes that optimal performance is achieved in a fed condition compared with a fasted condition.

Alternatively, the type of exercise (cycling compared with running) used to evaluate performance and/or the applied performance study design may strongly modulate the ergogenic properties of carbohydrate mouth rinsing. Although only a small number of studies have investigated the potential ergogenic benefits of carbohydrate mouth rinsing during high-intensity exercise, two [97, 98] out of the three [92, 97, 98] studies that failed to report ergogenic properties involved athletes participating in running exercise. Furthermore, when a control group (no rinse) was added to an experiment examining the effects of a carbohydrate mouth rinse compared with a placebo on a 1000 kJ cycling time trial, there was no significant difference in performance between the control trial (no rinse) and the carbohydrate rinse trial, suggesting that mouth rinsing during high-intensity exercise may not be as beneficial as originally believed [102] and may be related to a placebo effect [103]. Further research in this area is warranted, however, as the carbohydrate trial non-significantly improved performance by 2.8 % compared with the placebo trial, which is a similar (if not greater) improvement in performance to that reported by previous carbohydrate mouth-rinse studies [88, 93]. Therefore, this study may have been under-powered and, with a larger sample size, may have reached statistical significance.

Clearly, a series of studies are urgently needed to assess the proposed ergogenic properties of carbohydrate mouth rinsing in normal, practical situations in which athletes from various sports try to maximize performance. From a practical perspective, mouth rinsing with a carbohydrate solution could have some advantages over the ingestion of carbohydrate. If carbohydrate mouth rinsing assists individuals to self-select higher exercise intensities, individuals attempting to lose weight may benefit from greater energy expenditure during exercise without consuming any additional calories during the exercise bout [104]. In line, self-selecting higher exercise intensities would provide a greater training stimulus for those athletes attempting to train in the fasted state. Moreover, for those athletes who are sensitive to gastrointestinal issues, mouth rinsing instead of ingesting carbohydrate during short-duration, high-intensity exercise would avoid any potential unwarranted gastrointestinal symptoms [104, 105]. Therefore, athletes competing in short (30–75 min) high-intensity exercise bouts are encouraged to either use a mouth rinse or ingest small amounts ($<20\ g{\cdot}h^{-1}$) of carbohydrate to improve performance by attenuating central fatigue (Table 1).

5 Carbohydrate Ingestion During Intermittent-Type Exercise

Intermittent-type exercise accurately describes most team sports, including soccer, basketball, ice hockey, and field hockey, and some individual sports such as tennis and badminton. These intermittent-type exercise activities may last from 40 min to a few hours and are characterized by high-intensity exercise bouts interrupted by short periods of reduced exercise intensity or relative rest. Athletes participating in intermittent-type exercise activities are generally required to sprint, accelerate, and jump, thus rapidly increasing their exercise intensity and energy requirements. Match analysis has demonstrated that athletes participating in field-based team sports (e.g. soccer, rugby, and field hockey) work at a rate equivalent to 70–80 % VO_{2peak}, which is similar to participating in more intense endurance-type exercise [7, 106]. Prolonged exercise at these intensities requires a large amount of glycogen to be metabolized through substrate-bound phosphorylation (i.e. anaerobic glycolysis), resulting in rapid provision of adenosine triphosphate (ATP) accompanied with a rapid depletion of muscle glycogen stores. Thus, the availability of muscle glycogen during prolonged, intermittent, high-intensity exercise often limits work output, distance covered and sprinting frequency, particularly during the later stages of exercise [107]. As such, ingesting carbohydrate solutions during sports requiring intermittent bouts of high-intensity exercise (with a duration >45 to 60 min) may prove beneficial by attenuating performance decrements that may occur towards the later stages of a match or game.

Some of the earlier studies examining the influence of carbohydrate ingestion during prolonged, intermittent-type exercise found improved cycling performance at the end of an intermittent cycling bout [33, 108]. Murray and colleagues [33] required subjects to perform 1.6 h of cycling (55 and 65 % VO_{2peak}) interspersed with five rest periods. During each rest period, subjects ingested a carbohydrate solution at a volume of $2\ mL{\cdot}kg^{-1}$. Following the conclusion of the 1.6 h of intermittent cycling, subjects performed a 480 revolution cycling test. Cycling performance improved by 11–13 % following the ingestion of a glucose-sucrose or glucose polymer-fructose solution compared with a placebo. Although these early studies used exercise protocols that were considered ‘intermittent’, the structure and prolonged duration of the workloads are not consistent with the activity pattern or physiological demands of generic intermittent-type (team sports) exercise. Using a protocol specifically designed to replicate the physiological demands of soccer [109], Nicholas and colleagues [110] were the first to demonstrate a 33 % improvement in intermittent-type exercise capacity when a carbohydrate solution was consumed immediately prior to and during the Loughborough Intermittent Shuttle Test (LIST). Subjects who ingested a carbohydrate solution immediately prior to exercise (5 $mL \cdot kg^{-1}$) and every 15 min thereafter (2 $mL \cdot kg^{-1}$) were able to continue running longer when compared with the placebo condition. Numerous well-controlled laboratory studies using similar high-intensity, intermittent exercise protocols have since shown that carbohydrate ingestion can improve performance, as reflected by an increase in the amount of time spent cycling and (shuttle) running before exhaustion [111–118]. In studies where muscle glycogen concentration has been measured, carbohydrate ingestion has also been shown to attenuate muscle glycogen depletion during a soccer match [119] and following intermittent shuttle running [114]. Although time to fatigue (time to exhaustion) performance tests are often criticized for not being representative of how an athlete actually trains and races, with respect to intermittent-type sports, time to fatigue during shuttle running tests (e.g. LIST) may be viewed as an assessment of the ability to maintain high-intensity exercise, which is a recognized marker of performance and fatigue during field-based team games [120].

However, improved shuttle running and/or cycling time to exhaustion are not the only significant predictors of superior performance during intermittent-type sports activities. Carbohydrate ingestion during intermittent-type exercise protocols has also been associated with significantly better maintenance of motor skills and mood state [115, 121] and a reduced perception of exertion [122, 123], fatigue [115], force production [121], and attenuated decrements in shooting performance [124] during the later stages of exercise. Using soccer-specific tasks, Currell and colleagues [125] found significant improvements in performance for dribbling, agility, and shooting when a 7.5 % maltodextrin solution was ingested compared with a placebo. In other intermittent sports-specific research, carbohydrate ingestion (0.7 $g \cdot kg^{-1} \cdot h^{-1}$) during 2 h of simulated tennis match play improved stroke performance [126]. Of course, one of the limitations of certain intermittent-type sports activities is the inability to consume carbohydrates at regular intervals. In soccer, for example, players are only able to drink at half-time (following 45 min of game time) and/or during pauses in play provided that the player has enough time to obtain and consume a carbohydrate-containing solution on the sidelines. To determine whether the (in)frequency of carbohydrate consumption influences the ergogenic effect, Clarke and colleagues [127] investigated the effect of the provision of a carbohydrate drink on soccer-specific exercise. In an effort to mimic real-world soccer play, carbohydrate (or placebo) solutions were ingested at 0 and 45 min. In a separate trial, the same volume of carbohydrate was consumed in smaller volumes every 15 min. Interestingly, manipulating the timing of carbohydrate intake did not affect the metabolic response, yet there was no improvement in sprinting performance in either carbohydrate trial when compared with the placebo trial. However, ingesting smaller volumes of fluid at more frequent intervals has been shown to reduce the sensation of gut fullness [128] as gastric emptying of liquids has been demonstrated to be slower during brief, intermittent, high-intensity exercise compared with rest or steady-state moderate exercise conditions [129]. Despite the potential limitations, the ingestion of carbohydrates during prolonged, high-intensity, intermittent sports is recommended to optimize performance. For carbohydrate ingestion during exercise, similar guidelines as provided to the endurance athletes are given to the intermittent sports athletes (Table 1): small amounts of carbohydrate for short games, up to 60 $g \cdot h^{-1}$ for moderate game demands (60–90 min) and perhaps up to 80–90 $g \cdot h^{-1}$ for large game demands (>2 h) when players are extremely mobile, or for those players who started the game improperly fueled [130, 131]. However, as previously mentioned, athletes should ‘practise’ their nutritional feeding strategies because gastric emptying of liquids has been shown to be attenuated during brief, intermittent, high-intensity exercise when compared with steady-state exercise conditions [129, 132].

6 Carbohydrate Ingestion During Multi-day Racing

Athletes participating in multi-day competition (e.g. cycling stage races, heats, and finals) are encouraged to follow the guidelines for carbohydrate ingestion during their athletic event as depicted in Table 1. However, rapid repletion of liver and skeletal muscle glycogen stores are prerequisites for these athletes in the acute post-exercise recovery period as fatigue is generally associated with low glycogen availability. For example, during resting conditions, skeletal muscle glycogen stores range from 500 to 600 $mmol \cdot kg^{-1}$ dry weight in trained athletes [133, 134] but can decrease by 50–75 % following 3 h of cycling at 70 % VO_{2peak} [45, 133]. Therefore, the restoration of glycogen stores during immediate recovery from prolonged (>90 min) exhaustive exercise is one of the most important factors to define the capacity to maintain performance in a subsequent exercise bout. Although dietary interventions to achieve super-compensated glycogen concentrations in preparation for competition have been well-defined and with proper carbohydrate ingestion, complete restoration of muscle glycogen will generally occur within 24 h following exhaustive exercise [135–138], these procedures are not useful for athletic events that require a more rapid repletion of liver and skeletal muscle glycogen stores within a short (<8–24 h) timeframe. This is especially true for those athletes participating in multiple training sessions or multiple events (heats/finals) scheduled within a 24 h period. Therefore, this subsection focuses on carbohydrate ingestion during immediate post-exercise recovery to effectively replenish liver and skeletal muscle glycogen stores when exercise performance needs to be restored well within 24 h.

Although the liver plays an integral role in preventing hypoglycemia during prolonged exercise [139], there is very limited research in the area of liver glycogen repletion following prolonged exercise in humans [140–142]. Research using a rodent model has suggested that liver glycogen repletion has priority over muscle glycogen repletion when carbohydrate is administered after prolonged exercise [143] and the type of ingested carbohydrate may exert differential effects on the rate of liver glycogen metabolism [144]. A fructose load administered either orally or intravenously, for example, is taken up by the liver and converted to glucose [139] without any resulting increase in hepatic glucose output. Therefore, fructose may stimulate hepatic glycogen synthesis, reduce hepatic glycogenolysis, or both. In humans, a fructose infusion following an overnight fast has been demonstrated to result in higher liver glycogen repletion rates compared with a glucose infusion [139].

In line with fructose, galactose ingestion may also result in more rapid liver glycogen repletion when compared with the ingestion of glucose or glucose polymers. The liver is a prominent site for galactose uptake, and postprandial galactose clearance from the blood has been used as a marker for the assessment of general liver function. Using MRI, Décombaz and colleagues [140] quantified hepatic glycogen repletion following the ingestion of a maltodextrin with either glucose, fructose, or galactose. Following a standardized glycogen-depleting exercise, the combined ingestion of maltodextrin with fructose or galactose resulted in a ~twofold higher liver glycogen repletion rate over 6.5 h of post-exercise recovery when compared with the ingestion of maltodextrin plus glucose [140]. Therefore, although the work assessing liver glycogen repletion remains scarce, the limited research available suggests that when there is limited post-exercise recovery time, the ingestion of carbohydrate mixtures containing fructose and/or galactose may accelerate liver glycogen repletion.

Only a few studies have directly investigated the effect of different rates of carbohydrate ingestion on muscle glycogen repletion following exhaustive exercise [145, 146]. Initially, it was suggested that 0.35–0.75 $g \cdot kg^{-1} \cdot h^{-1}$ of carbohydrate ingested at 2 h intervals was sufficient to maximally stimulate muscle glycogen repletion rates [145, 146]. Ivy and colleagues found no further increase in muscle glycogen repletion when 1.5 g carbohydrate$\cdot kg^{-1} \cdot h^{-1}$ was provided compared with 0.75 $g \cdot kg^{-1} \cdot h^{-1}$ [146]. However, when van Loon and colleagues [147] compared carbohydrate ingestion at 0.8 versus 1.2 $g \cdot kg^{-1} \cdot h^{-1}$ with supplements administered every 30 min for 5 h following a glycogen-depleting protocol, they reported a 150 % higher glycogen content when subjects were fed the higher carbohydrate amount. The increase in glycogen repletion found when feeding 1.2 g carbohydrate$\cdot kg^{-1} \cdot h^{-1}$ may have been due to the frequency and timing of carbohydrate supplementation. Carbohydrate supplements provided at infrequent intervals (i.e. every 2 h) may not adequately maintain blood glucose and insulin levels for the entire period between feedings [148]. Moreover, in the absence of carbohydrate intake, the contraction-induced increase in post-exercise glucose transport rapidly reverses, with the number of glucose transporters at the plasma membrane returning to baseline values within less than 2 h after cessation of exercise [149]. Consequently, when carbohydrate ingestion is delayed for 2 h post-exercise, Ivy and colleagues [150] reported a 45 % lower muscle glycogen repletion rate compared with immediate post-exercise feeding.

As such, studies that provided more frequent carbohydrate feedings (every 15–30 min) commencing immediately post-exercise, report higher muscle glycogen repletion rates [147, 151–153] than when carbohydrate supplements are provided at 2 h intervals or when there is a time lapse between the cessation of exercise and the commencement of post-exercise carbohydrate feeding [146, 150]. However, when frequent carbohydrate feedings are further increased up to 1.6 $g \cdot kg^{-1} \cdot h^{-1}$, muscle glycogen repletion rates do not seem to increase to higher levels [154]. Consequently, frequent carbohydrate feedings at 1.2 $g \cdot kg^{-1} \cdot h^{-1}$ during the acute post-exercise recovery period seem to allow maximal muscle glycogen repletion rates.

Further efforts to maximize the rates of muscle glycogen synthesis include post-exercise amino acid and/or protein co-ingestion with carbohydrate. Protein and/or amino acid co-ingestion has been well-established as an effective dietary strategy to strongly augment postprandial insulin release [155–157]. As insulin stimulates both glucose uptake and glycogen synthase activity in skeletal muscle tissue [158–160], it has been suggested that co-ingestion of an insulinotropic amino acid and/or protein mixture can further accelerate post-exercise muscle glycogen synthesis. In accordance, when amino acid and/or protein was co-ingested with 0.5–0.8 g carbohydrate$\cdot$kg$^{-1}\cdot$h^{-1}, post-exercise muscle glycogen synthesis rates were substantially increased [147, 161–163]. However, protein and/or amino acids do not seem to further accelerate muscle glycogen repletion when (supra)maximal amounts of carbohydrate are ingested during post-exercise recovery (>1.0 g carbohydrate$\cdot$kg$^{-1}\cdot$h^{-1}) [151, 152, 154, 164]. From a practical perspective, ingestion of such large amounts of carbohydrate may be difficult for some athletes to tolerate during acute post-exercise recovery. Therefore, athletes could choose to consume less carbohydrate (<1.0 g$\cdot$kg$^{-1}\cdot$h^{-1}) with added protein (0.4 g$\cdot$kg$^{-1}\cdot$h^{-1}) to accelerate muscle glycogen resynthesis rates [147], thereby increasing the efficiency of glycogen repletion.

Additional efforts to maximize the rates of muscle glycogen synthesis by changing the form of carbohydrate supplementation (solid compared with liquid) have been largely unsuccessful [136, 165]. However, with respect to the type of carbohydrate, several studies have reported lower rates of muscle glycogen repletion when fructose, as opposed to glucose, was ingested [143, 145, 166]. van den Bergh and colleagues [166] measured muscle glycogen repletion rates over 8 h using MRI and found that glycogen repletion rates were almost twofold higher when glucose was ingested compared with fructose (~40 g carbohydrate$\cdot$h^{-1} for 8 h). The slower muscle glycogen repletion rate with fructose-only may be due to the slower absorption rate of fructose from the intestine [167] in addition to the need for fructose to be converted to glucose (or lactate) in the liver before it can be metabolized in the skeletal muscle [168, 169]. Nonetheless, as previously mentioned, fructose may be of more benefit in the restoration of liver glycogen [139, 143]. As such, when fructose is co-ingested with glucose (either as sucrose or a glucose-fructose co-ingestion), research has found similar rates of muscle glycogen repletion compared with glucose only [145, 170]. On two separate occasions Wallis and colleagues [170] had trained males perform glycogen depleting exercise followed by the ingestion of glucose (90 g$\cdot$h^{-1}) or the combined ingestion of glucose (60 g$\cdot$h^{-1}) and fructose (30 g$\cdot$h^{-1}) for 4 h. The authors concluded that both carbohydrate solutions were equally effective at restoring muscle glycogen. Therefore, when high glycogen repletion rates are required, glucose or the co-ingestion of glucose with fructose is recommended over fructose-only. However, the co-ingestion of fructose with glucose may support liver glycogen repletion without impairing the rate of muscle glycogen repletion. In short, to accelerate post-exercise liver and muscle glycogen repletion when recovery time is limited, 1.2 g of carbohydrate$\cdot$kg$^{-1}\cdot$h^{-1} which contains both glucose/glucose polymers and fructose/galactose should be ingested and provided frequently (every 15–20 min), over a 4–6 h period (Table 1). Combined ingestion of carbohydrate and protein may accelerate glycogen resynthesis when suboptimal amounts of carbohydrate are ingested (Table 1).

7 Conclusions and Recommendations

Carbohydrate ingestion during prolonged (>2 h) moderate to high-intensity exercise is essential for optimal performance of the endurance athlete. The performance-enhancing impact of carbohydrate ingestion during prolonged exercise is likely attributed to the sparing of skeletal muscle and liver glycogen stores and maintaining high rates of carbohydrate oxidation. For exercise lasting no longer than 3 h, a modest amount of carbohydrate should be ingested (60 g$\cdot$h^{-1}). For events lasting longer than 2.5 h, up to 90 g carbohydrate$\cdot$h^{-1} can be metabolized by well-trained athletes. However, multiple transportable carbohydrates should be ingested (e.g. glucose or glucose polymers plus fructose or sucrose) to allow such high rates of exogenous carbohydrate oxidation. However, as not all individuals will be able to tolerate such high carbohydrate intake rates, feeding strategies during prolonged exercise need to take into account personal preference and gastro-intestinal tolerance, and require proper practice. As such, many of these carbohydrate ingestion guidelines are directed towards well-trained endurance athletes who can perform prolonged exercise at a high absolute workload and who are used to ingesting large amounts of carbohydrate during exercise. Although the ingestion of multiple transportable carbohydrates is not required during exercise events of shorter duration (<2.5 h), they can be used at will as they do not impede performance either. For short-duration, high-intensity exercise lasting approximately 30–75 min, a carbohydrate mouth rinse (or ingestion) with minimal amounts of carbohydrate may prove to be useful. The mechanism(s) responsible for any ergogenic benefit are likely to be more central than metabolic in nature. Moreover, intermittent/team sports athletes can follow similar carbohydrate feeding guidelines as their endurance counterparts, taking into account the intensity and duration of their game and pre-game status of their endogenous carbohydrate stores.

During acute post-exercise recovery, rapid restoration of liver and muscle glycogen is important for those athletes who need to maximize performance during multi-day competition or for those who need to perform twice daily. Under such conditions, athletes are encouraged to consume 75–90 g carbohydrate (1.2 g$\cdot$kg^{-1}) per hour for 4–6 h after cessation of exhaustive exercise. A combination of glucose or glucose polymers with fructose or galactose is recommended to target both liver and skeletal muscle glycogen repletion. Combined ingestion of carbohydrate with some protein and/or amino acids (0.2–0.4 $g \cdot kg^{-1} \cdot h^{-1}$) may accelerate muscle glycogen resynthesis rates when suboptimal amounts of carbohydrate are provided (<1.0 $g \cdot kg^{-1} \cdot h^{-1}$), and may facilitate skeletal muscle repair and post-exercise reconditioning. Finally, it is the athlete's personal preference whether to consume carbohydrate in the form of a liquid, solid, or semi-solid (gel) during and in the immediate post-exercise recovery period; however, the athlete may wish to balance fluid intake to facilitate gastric emptying and compensate for sweat loss.

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