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The Effectiveness of Commercially Available Sports Drinks

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Abstract

The purpose of this review is to evaluate the effectiveness of commercially available sports drinks by answering the questions: (i) will consuming a sports drink be beneficial to performance? and (ii) do different sports drinks vary in their effectiveness? To answer these questions we have considered the composition of commercially available sports drinks, examined the rationale for using them, and critically reviewed the vast number of studies that have investigated the effectiveness of sports drinks on performance. The focus is on the drinks that contain low carbohydrate concentrations (<10%) and are marketed for general consumption before and during exercise rather than those with carbohydrate concentrations >10%, which are intended for carbohydrate loading.

Our conclusions are 3-fold. First, because of variations in drink composition and research design, much of the sports drinks research from the past cannot be applied directly to the effectiveness of currently available sports drinks. Secondly, in studies where a practical protocol has been used along with a currently available sports beverage, there is evidence to suggest that consuming a sports drinks will improve performance compared with consuming a placebo beverage. Finally, there is little evidence that any one sports drink is superior to any of the other beverages on the market.

1. Composition of Commercially Available Sports Drinks

The production and sale of sports drinks is a lucrative and competitive industry, as demonstrated by the rapidly growing variety of products being marketed, each with claims of benefits superior to rival beverages. The worldwide demand for sports drinks is immense: the US market alone is worth $US1.2 billion a year. As a result, selecting a sports drink can be an overwhelming task for the consumer. Table I lists only a fraction of the sports drinks that are available internationally. This list demonstrates the variation in the type and concentration of carbohydrates and electrolytes in commercially available sports drinks.

Sports drinks are typically formulated to: (i) prevent dehydration; (ii) supply carbohydrates to augment available energy; (iii) provide electrolytes to replace losses due to perspiration; (iv) conform to requirements imposed by regulatory authorities; and, probably the most important, (v) be highly palatable. Sports drinks can be classified as having either a low carbohydrate concentration (<10%) or a high carbohydrate concentration (>10%). The higher carbohydrate content drinks are marketed for carbohydrate loading rather than for general consumption before and during exercise. The more popular drinks are those that contain low carbohydrate concentrations; these beverages will be the focus of this review. A general comparison of the low carbohydrate sports drinks is provided in table I. An important point is that the composition of some sports drinks has changed over time. For example, the formulation of Gatorade that was used in studies during the 1970s and 1980s is different from what is now commercially available. Studies reviewed that used sports drinks with a different composition from those presently available will be noted in this review.

1.1 Carbohydrate Content

The beverages described in table I contain between 6 and 8% carbohydrate, with considerable variation in the combination of carbohydrate sources used by manufacturers. The major carbohydrates used in sports drinks are the monomers glucose and fructose, the dimer sucrose, and the synthetic polymer maltodextrins, also known as glucose polymers. The use of glucose polymers in sports drinks has increased in recent years as they allow for provision of more carbohydrate without a resultant increase in osmolality. When designing the composition of sports drinks, a manufacturer balances the efficacy of the carbohydrate combination with palatability.

1.2 Electrolyte Content

Small amounts of electrolytes, generally sodium, potassium and chloride, are added to sports drinks to improve palatability and to, theoretically, help maintain fluid/electrolyte balance. The goal of the manufacturer is to provide a sports drink that is isotonic with respect to the plasma. In the past, sports drinks were made hypertonic because of the overuse of simple sugars and electrolytes and were detrimental to performance. In the 1980s, many sports drink manufacturers began using maltodextrins in their drinks in addition to simple sugars. Maltodextrins allow for the carbohydrate content to be kept constant even with the addition of relatively high concentrations of electrolytes to improve palatability. As shown in table I, electrolyte composition does vary slightly between beverages. For example,

TABLE I HERE

Allsport contains 50% less sodium than Gatorade, whereas Hydrafuel contains more potassium and less sodium than most of its competitors. Whether these differences in electrolyte provision translate to physiological differences that make one beverage superior to another has been difficult to ascertain.

Given the knowledge that electrolyte losses decrease as the training level of an athlete increases, it is likely that differences in electrolyte composition play a significant role only for the untrained athlete or during particularly severe conditions of exercise and heat exposure.[1,2] Therefore, it is apparent that the majority of individuals engaged in exercise neither require, nor measurably benefit from, the consumption of electrolytes during exercise.[3] However, it must also be mentioned that a dilute electrolyte solution can be consumed during exercise without risk of inducing fluid/electrolyte imbalance.[4]

2. Rationale for Using Sports Drinks

Whether plain water or a carbohydrate/electrolyte formulation is superior for preventing homeostatic disturbances and improving performance has been the topic of extensive research since the 1970s. The potential benefits derived from consumption of sports drinks, compared with water, depend on what components of the ingested fluid enter the vascular system and how quickly this transport takes place. This, in turn, is a function of: (i) the quantity of the beverage ingested; (ii) the time it takes for the drink to be emptied from the stomach; (iii) how long the drink takes to be absorbed from the intestine; and (iv) whether the drink attenuates endogenous carbohydrate oxidation. These 4 factors have been widely studied. However, the beverages investigated are frequently not equivalent to what is commercially available to sports drink consumers. Therefore, it is difficult to draw conclusions regarding the efficacy of currently available sports drinks based on this research. However, these data do provide insight into what properties of sports drinks may lead to performance benefits. This section of the review will discuss the effects of carbohydrate and electrolyte composition on fluid ingestion, gastric empty-

Table I. Comparison of the contents of popular sports drinks

Sports drink	Energy (kCal/250ml)	Sodium (mg/250ml)	Potassium (mg/250ml)	Chloride (mg/250ml)	Osmolality (mOsm/kg)	Total carbohydrate (g/250ml)	Carbohydrate concentration (%) [w/v]	Sugars (g/250ml)	Vitamins	Carbohydrate source
10K	60	55	30	NS	350	15	6.0	NS	NS	High fructose corn syrup (% NS)
Allsport	80	55	55	NS	NS	21	8.4	10	NS	High fructose corn syrup (56%), glucose (43%), maltodextrins (1%)
Endura	62	80	160	NS	NS	16	6.4	NS	NS	NS
Exceed	70	50	45	80	250	17	6.8	NS	NS	Maltodextrins, fructose (% NS)
Gatorade	63	103	30	1	320-360	15	6.0	14	None	Sucrose (38%), glucose (34%), fructose (28%)
Gatorade (Europe)	50	110	30	8	378	14	5.6	14	NS	Sucrose (38%), glucose (34%), fructose (28%), maltodextrins (8%)
Hydrafuel	66	25	30	NS	NS	17	6.8	NS	C, E	Maltodextrins, glucose, fructose (% NS)
Isosport	42	103	29	NS	NS	18	7.2	15	NS	Sucrose (43%), glucose (24%), fructose (19%), glucose polymers (14%)
Isostar	70	110	45	8	280	17	6.8	NS	C, E, β-carotene	NS
Powerade	70	70	30	NS	NS	19	7.6	15	NS	High fructose corn syrup, maltodextrins (% NS)
Rivella Marathon	NS	24	136	4	240	12	4.8	NS	NS	NS
Sponser	NS	69	110	11	326	16	6.4	NS	NS	NS
Sport Plus	72	91	54	NS	NS	18	7.2	18	NS	Sucrose (71%), glucose (29%)
Staminade	51	58	49	NS	NS	13	5.2	13	NS	Glucose (100%)
Xcel	62	47	70	NS	NS	15	6.0	NS	NS	NS

NS = not stated.

ing, intestinal absorption and fuel utilisation, using as examples concentrations that are similar to those of commercially available sports drinks where possible.

2.1 Fluid Ingestion

The rate of voluntary fluid ingestion has been shown to approximate only 50% of the rate of fluid loss as sweat during exercise.[5] However, scheduling fluid intake to match sweat losses results in less cardiovascular drift, a more constant core temperature and a smaller decline in plasma volume.[6-8] Prevention of these homeostatic disturbances translates to improvements in performance.[9] The volume and frequency of voluntary fluid consumption is affected by beverage characteristics such as temperature, taste, aroma, mouthfeel and appearance, with pleasantly flavoured, cool beverages more likely to be consumed.[3,10-13]

Johnson et al.[13] concluded that the major benefit of commercial sports drinks is promotion of an increase in voluntary fluid intake, which results in prevention of compromised hydration status. The authors compared the effects of water and 3 commercial sports drinks, Olympade and Sportade (neither of which are available today) and Gatorade (which now has a different formulation) on performance and metabolic balance. They found that all of the drinks, including water, were equally effective in maintaining water, electrolyte and mineral balances as well as physical performance. However, voluntary consumption of the commercial beverages was greater than that of water, suggesting that these drinks were more appealing to the participants.

2.2 Gastric Emptying

2.2.1 Effect of Carbohydrate Content

The rate at which carbohydrate/electrolyte drinks are emptied from the stomach is influenced primarily by the volume of fluid ingested and the carbohydrate content of the beverage.[9,14-19] Although it is known that the presence of a large volume of fluid in the stomach stimulates emptying, the effect of increasing the carbohydrate content on the gastric emptying rate is somewhat confusing. Studies have shown an inverse relationship between glucose concentration and gastric emptying rate.[14,15,20] However, when expressed as the rate at which calories were emptied from the stomach (kcal/min) there was either no difference,[20] or an increase in substrate availability to the intestine with increasing carbohydrate concentration.[4,15] The fact that increasing the carbohydrate content may increase substrate availability, but decrease the availability of water, is of concern. Therefore, it is recommended that carbohydrate content should be lower than 10% when water absorption is a priority.[21]

With sports drinks containing between 6 and 8% carbohydrate, the question of whether this small change in carbohydrate content affects gastric emptying was addressed by Noakes et al.[22] These investigators reported that solutions containing up to 8% carbohydrate appear to have little effect on the rate of gastric emptying. This finding, along with others to be discussed in section 2.3.2, has prompted manufacturers to limit the carbohydrate concentration in their beverages to 8% (see table I). It also suggests that the small differences in carbohydrate content of presently available sports drinks (6 to 8%) will have little or no effect on gastric emptying.

2.2.2 Effect of Carbohydrate Type

The effect of carbohydrate type on gastric emptying has not been thoroughly investigated using currently available sports drink formulations. Studies on the effect of ingesting glucose, compared with maltodextrins or sucrose, have shown little difference between these carbohydrates with respect to gastric emptying.[23] Interestingly, fructose solutions have been shown to empty from the stomach at faster rates than equimolar glucose solutions.[14] Similarly, addition of 2 to 3% fructose to solutions that also contain glucose appears to enhance gastric emptying, compared with glucose alone.[24] Although the mechanisms and practical implications of this effect remain poorly understood, these findings, along with those discussed in section 2.3.1, may have prompted all manufacturers listed in table I to add a small amount of fructose to their formulations.

2.2.3 Effect of Osmolality

The osmolality of fluids consumed appears to be of secondary importance with respect to gastric emptying.[19,21,23] The belief that osmolality is a chief influence on gastric emptying is based on the popular misconception that beverages must become isotonic prior to passage from the stomach. To the contrary, the osmolality of fluid leaving the stomach has been shown to be near to that at which it was ingested.[25] Osmolality may be perceived as important in determining the rate of gastric emptying partly because of the relationship between osmolality and caloric content of a beverage.[26-28] However, volume and caloric density of fluids are considered the primary influences on the rate of gastric emptying, with osmolality exerting more influence on intestinal water absorption, as will be discussed in section 2.3.

2.3 Intestinal Absorption

The absorption of water, electrolytes and carbohydrates are interrelated determinants of how effective a sports drink will be in maintaining homeostasis during exercise. Variations in carbohydrate type and concentration, and in electrolyte composition, have a complicated effect on the absorption rate of carbohydrates, electrolytes and, most importantly, water. The purpose of this section is not to explain all the intricacies of these relationships, but rather to highlight principles of intestinal absorption that must be considered when evaluating the effectiveness of currently available sports drinks.

2.3.1 Effect of Carbohydrate Type

Sucrose, glucose, fructose and maltodextrins are the carbohydrates used in commercial sports drinks. The type of carbohydrate present in a sports drink can influence intestinal absorption. However, the effects of multiple types of carbohydrates become somewhat complicated. In an attempt to simplify the known principles regarding the influence of carbohydrate type on intestinal absorption of water, carbohydrate, and electrolytes, we have summarised these principles in table II.

These principles provide justification for manufacturers to include multiple carbohydrate sources in sports drink formulations. To our knowledge, a comparison of the absorption rate as a function of the carbohydrate composition of currently available sports drinks has not been published. However, a study by Shi et al.[38] did compare a solution containing glucose and sucrose (the main 2 carbohydrates in Gatorade) with a drink containing glucose and fructose (the main 2 carbohydrates in Allsport). The sucrose/glucose drink tended to promote the greatest water and sodium absorption, but stimulated only a moderate amount of carbohydrate absorption; conversely, the glucose/fructose solution induced the highest carbohydrate absorption and a moderate water absorption, but the lowest sodium absorption. Overall, the investigators concluded that solutions containing 2 transportable substrates enhance solute and water flux more than solutions with 1 substrate, despite the fact that combining substrates can significantly increase osmolality. This effect has been attributed to stimulation of more transport mechanisms with the addition of a second substrate.

In summary, the carbohydrate content of all the commercially available sports drinks shown in table I is congruent with the principles thought to govern absorption. It remains to be determined whether the differences between these beverages are physiologically relevant.

2.3.2 Effect of Carbohydrate Concentration

The concentration of carbohydrate in sports drinks is another important factor governing the absorption of water, electrolytes and carbohydrate itself. The principles regarding carbohydrate concentration and intestinal absorption that are widely accepted in the scientific and athletic communities are also summarised in table II.

Investigations comparing the intestinal absorption of presently available sports drink formulations based on actual carbohydrate concentration are lacking. A study by Gisolfi et al.[36] compared 2, 4, 6 and 8% solutions of glucose, sucrose, maltodextrin or corn syrup to determine the effects of both concentration and type of carbohydrate on intestinal absorption. The authors concluded that water absorption was independent of carbohydrate type in solutions containing up to 6% carbohydrate with the same osmolality and caloric concentration. However, increasing carbohydrate concentration up to 8% significantly reduced water absorption from

Table II. Principles governing the influence of carbohydrate type and concentration on intestinal absorption of water, carbohydrate and electrolytes

Carbohydrate type
Fluid absorption in the proximal small intestine depends on the segment studied[29]
The dimer sucrose cannot be absorbed but is broken down to the monomers glucose and fructose[30]
Glucose polymers need to be broken down to glucose monomers for absorption[31]
Glucose absorption requires sodium-specific carrier proteins and is an active process[32]
Fructose absorption is via facilitated diffusion and is independent of sodium[33]
In the absence of other carbohydrates, it is possible to exceed the absorptive capacity for fructose[21]
When ingested in large amounts (>10%), fructose can produce gastrointestinal distress[34] and decreased water absorption[35]
When fructose is ingested in equal amounts with glucose or consumed as sucrose, its absorption is dose dependent[36]
Although glucose and fructose are both absorbed at higher rates together than when glucose is ingested alone, the disadvantage of monomers is the resultant increase in osmolality which limits water absorption[36]
Other sugars such as sucrose[31] and maltodextrins[37] can be substituted for glucose without impairing glucose or water uptake
Sucrose and maltodextrins have the advantage of providing a high carbohydrate load with minimal impact on osmolality[21]
Solutions containing sucrose and glucose have been shown to be associated with the greatest water and sodium absorption, but only a moderate amount of carbohydrate absorption[38]
Solutions containing free glucose and fructose induce the highest carbohydrate absorption and moderate water absorption, but the lowest sodium absorption[38]
Carbohydrate concentration
The concentration of carbohydrate in the lumen of the intestine is determined by both the concentration of carbohydrate in the sport drink and the residue from the last meal[21]
Luminal concentration of glucose from 80 to 200 mmol/L maximises the fluid absorption rate[35,39]
Fluid absorption, although improved compared with ingesting water alone, is not significantly altered by carbohydrate concentrations up to 8%[36,40]
When the luminal concentration of glucose is > 10%, fluid enters the intestine from the vascular space, promoting dehydration[41]

isocaloric solutions of glucose and corn syrup solids, but not from 8% solutions of sucrose or maltodextrin. Although these results increase our understanding of intestinal absorption, it is somewhat difficult to extend these data to the relative effectiveness of commercially available sports drinks because of the variable effects of different carbohydrate sources on intestinal absorption.

2.3.3 Effect of Sodium Concentration

Gisolfi et al.[42] measured intestinal absorption while perfusing a carbohydrate solution containing different sodium concentrations into volunteers, using a triple lumen tube. The authors reported that sodium concentrations of 0, 25 or 50 mEq/L in a 6% carbohydrate solution have similar effects on the absorption of water, sodium and glucose from the duodenojejunum. Furthermore, Hargreaves et al.[43] used the same concentrations of sodium in a 10% glucose beverage and found that the sodium concentration had no influence on glucose availability during moderate intensity exercise. Therefore, it appears that the relatively small amounts of sodium added to sports drinks have minimal effects on intestinal absorption.

2.3.4 Effect of Osmolality

The effects of altering osmolality on intestinal absorption have been extensively investigated. The following tenets should be considered when discussing the effectiveness of commercially available sports drinks.

- The osmolality of the sports drink is affected by the concentration and type of carbohydrates used and the electrolyte concentration.[36]
- A negative correlation exists between the osmolality of luminal contents and water absorption.[44,45]
- Solutions hypertonic to human plasma (>280 mOsm/kg) stimulate less water absorption and more secretion into the gastrointestinal lumen, resulting in a potential for dehydration.[4]
- Hypotonic and isotonic solutions (<280 mOsm/kg) promote water absorption.[15,39,45]

2.3.5 Overview

The absorption of water, electrolytes and carbohydrates from the small intestine is highly interrelated. Fluid absorption is related to solute transport which, in turn, is related to the type of carbohydrate in the beverage. Over the past 25 years, sports drink research has established a number of important principles regarding the effects of carbohydrate type and concentration and electrolyte composition on intestinal absorption of the beverages. Presently available sports drinks have been formulated using these principles to maximise their effectiveness. What remains to be determined is the impact of slight variations in carbohydrate and electrolyte content on the effectiveness of these beverages.

2.4 Fuel Utilisation

An important question to address is whether consuming sports drinks immediately prior to or during exercise attenuates endogenous carbohydrate oxidation during exercise. A number of recent studies have investigated this topic using labeled isotopes.[46-51] Bosch et al.[47] reported that ingesting a 10% carbohydrate sports drink increased exogenous and decreased endogenous carbohydrate utilisation during a 180-minute cycle. However, muscle glycogen utilisation was unaffected by the carbohydrate ingestion.[47] Further work from this laboratory found that the progressive increase in plasma glucose oxidation is related to muscle glycogen content and occurs irrespective of whether carbohydrates are ingested.[51] In addition, a recent study by Manzon et al.[49] found that more circulating glucose is used by muscle during exercise and early recovery, suggesting that muscle glycogen is spared. Peronnet et al.[50] reported that after a diet low in carbohydrate, the oxidation of exogenous glucose and of glucose released from the liver is increased and partly compensates for the reduction in muscle glycogen availability and oxidation.

The findings of these studies suggest that ingesting carbohydrates immediately before and/or during exercise can attenuate endogenous carbohydrate oxidation as well as increasing glucose uptake during exercise. These changes may prolong time to exhaustion by increasing muscle glycogen concentration, sparing muscle and liver glycogen and/or causing a reduction in gluconeogenesis that would delay the onset of hypoglycaemia.

3. Methodologies to Evaluate the Effectiveness of Sports Drinks

The Appendix contains details of over 60 studies that have examined the effectiveness of sports drinks on performance. Comparisons between these studies are difficult because of variations in research design. These differences include the pre-exercise glycogen status of the participants, timing of beverage consumption, composition of the drink and rates of administration. Other considerations when making overall conclusions concerning the effectiveness of sports drinks on performance include the training status of the participants, the environment, whether a placebo control was used, and the type of tests used to evaluate performance.

3.1 Pre-Exercise Glycogen Content

A very important consideration when evaluating the different sports drinks performance studies is the muscle and liver glycogen content of the volunteers before the exercise test. Some studies have used overnight fasting to decrease hepatic glycogen reserves prior to the exercise test. Although this practice results in similar pre-exercise glycogen levels between volunteers, the practical relevance of this protocol is questionable as few athletes fast for long periods of time prior to performing. More importantly, a decline in performance is observed in a glycogen-depleted state compared to a glycogen-sufficient state.[52] Therefore, the benefits of sports drink consumption will be more readily observed in glycogen-depleted individuals.

3.2 Timing of Pre-Exercise Sports Drink Consumption

Another controversial issue in sports science that requires discussion before analysing performance-based sports drink research is whether intake of carbohydrates results in a hyperinsulinaemic response that may be detrimental to performance. The hyperinsulinaemic response may be due to a rise in blood glucose, which has been shown to occur within 5 to 15 minutes following carbohydrate intake. This results in a 4-fold increase in insulin, which enhances glucose storage and, therefore, hypoglycaemia, inhibiting lipolysis and further depleting muscle glycogen.[53]

An early study by Costill et al.[54] showed that when 75g of glucose was ingested 30 to 45 minutes before exercising at 70 to 75% of maximal oxygen uptake ($\dot{V}O_{2max}$), plasma glucose and insulin were elevated at the start of exercise and muscle glycogen was used at a faster rate during the exercise. This is counterproductive to the goal of sparing muscle glycogen; performance has been shown to decrease by 19% with such a treatment.[55] In contrast with this early study, a recent review of this topic indicated that the blood glucose and plasma insulin responses to pre-exercise glucose feedings are quite variable, with only some participants experiencing a decrease in blood glucose.[56]

The effect of pre-exercise carbohydrate ingestion on the hyperinsulinaemic response is likely to be dependent on at least 5 factors: (i) the timing of carbohydrate consumption before exercise; (ii) the amount of carbohydrate consumed; (iii) the extent of muscle glycogen synthesis following consumption; (iv) individual variations in the hyperinsulinaemic response; and (v) the change in the rate of muscle glycogen depletion during exercise. These factors can complicate the interpretation of studies investigating performance benefits associated with sports drink consumption. For example, pre-exercise glucose ingestion could improve performance if the increase in muscle glycogen stores is sufficient to offset the greater rate of glycogen depletion during exercise.

The change in the rate of muscle glycogen depletion during exercise is related to the intensity of the exercise. During prolonged low intensity exercise, participants did not experience a similar drop in blood glucose following pre-exercise glucose feedings[57] compared with a higher intensity exercise.[54] This difference between blood glucose responses to high and low intensity exercise is presumably associated with a slower rate of glucose removal by working skeletal muscles during low intensity exercise.

3.3 Beverage Composition

The composition of drinks used to evaluate the effectiveness of carbohydrate beverages in improving performance also warrants further discussion. A general consensus in sports science is that carbohydrate consumption during exercise delays fatigue and improves performance.[1] The studies most commonly cited to support this notion are those of Coyle et al.[26,58] and Coggan and Coyle.[59-61] As this present review is concerned with commercially available low carbohydrate sports drinks, a number of points need to be clarified with regard to the research designs used in these 4 studies. First, these investigations required volunteers to fast for 12 to 16 hours prior to exercise testing. As discussed previously, the benefits of carbohydrate consumption are more significant in glycogen-compromised individuals. Secondly, the volunteers consumed a 50% carbohydrate beverage during the exercise trial, which resulted in supply of a carbohydrate dosage between 2 and 12 g/h/kg bodyweight. To achieve similar carbohydrate delivery from an 8% sports drink would require the individual to consume at least 1750 ml/h. This beverage consumption is obviously impractical and makes it difficult to relate performance findings using high carbohydrate content beverages to commercially available sports drinks. In fact, of the 69 studies detailed in the Appendix, only 16 used drinks that are currently commercially available.

3.4 Assessment of Performance

As can be seen from the Appendix, exercise performance has been assessed by measuring: (i) the time necessary for volunteers to exercise to exhaustion at a preset work rate; (ii) the time required to complete a predetermined work task; or (iii) the amount of work accomplished in a given period of time. In addition, most research has been conducted using cycle ergometry, because of the relative ease of ingesting fluids and collecting data without interrupting exercise. The summary table makes reference to significant versus nonsignificant effects on performance. Caution does need be exercised when interpreting these performance results. For example, there can be tremendous variability in maximal performance times between individuals, making it difficult to detect statistically significant differences between treatments. One should remember that although small improvements in performance may not be statistically significant, they may be physiologically significant in athletic competition.

4. Performance-Based Research

Sports drinks may be one of the most frequently researched sports science topics to date. The Appendix contains details of the majority of studies that have examined the effects of carbohydrate-electrolyte beverages on exercise performance. We have separated the studies according to exercise duration [short term (<1 hour), prolonged (1 to 4 hours), ultraendurance (>4 hours)] and type (e.g. continuous *vs* intermittent). Where the authors have tested the effects of ingesting a sports drink both before and during exercise, the studies are listed twice. The aim of this section is to discuss how these findings may apply to determine the effectiveness of currently available beverages.

4.1 Ingestion Before Short Term Intense Exercise

Eight studies have assessed the efficacy of consuming a sports drink prior to an intense (>80% $\dot{V}O_{2max}$) exercise bout lasting 1 hour or less.[55,62-68] In the past, the need for sports drink consumption during this intensity of exercise has been thought to be negligible.[4] This notion has been based on the findings that although intense exercise relies heavily on carbohydrate metabolism, substrate availability is unlikely to play a significant role in limiting exercise performance. In addition, it has been shown that the total amount of water lost by sweating during intense exercise of short duration is likely to be small. Therefore, the need for fluid replacement is thought to be minimal during high intensity exercise of 1 hour or less.

Taking the above into consideration, it is somewhat surprising to see that 5 of the 8 studies have reported significant improvements in performance following consumption of a carbohydrate beverage prior to short term high intensity exercise.[55,63,65,66,68] Unfortunately, none of these studies utilised a currently available sports drink. In fact, 4 of the 5 studies that found ergogenic effects used carbohydrate concentrations of 10% or greater,[55,65,66,68] making it difficult to draw conclusions from these data in relation to the most popular commercially available sports drinks, which contain less than 10% carbohydrate.

In the only study that did use a beverage of less than 10% carbohydrate,[63] the performance measure was the total distance completed in 1 hour. The authors report that when volunteers consumed the 8% carbohydrate beverage they covered a significantly greater mean distance, 41.5km, compared with 41.0km when consuming a placebo drink.

Three of the 5 studies that found a significant improvement in performance used a pre-exercise fast of at least 12 hours in their research design.[63,65,66] As discussed previously, a decline in performance was observed in a glycogen-compromised state compared with a glycogen-sufficient state,[52] suggesting that the benefits of glucose consumption may be more readily observed in glycogen-compromised individuals. One of the 5 studies also found significantly improved performances with water, as well as a 33% glucose drink and a 33% fructose drink, compared with placebo.[65]

In summary, although a quick scan of the literature might suggest that sports drink consumption is effective in improving performance when consumed prior to short term high intensity exercise, a closer inspection of these studies gives a different picture. In individuals who are glycogen sufficient, there is little evidence that consumption of a sports drink with less than 10% carbohydrate before exercise of 1-hour duration or less will provide any ergogenic benefit. The literature suggests that optimal sports drink formulations for high intensity exercise may contain a greater carbohydrate content than the commonly used sports drink.

4.2 Ingestion During Short Term Intense Exercise

There is evidence that sports drink consumption during short term intense exercise is effective at improving performance. Nine studies are listed in the Appendix,[62,69-76] with 6 of these reporting an ergogenic effect employing sports drinks containing 10% carbohydrate or less.[69-72,75,76] Of these 6 studies, it is also encouraging to note that 2 used a more practical 4-hour fast before the exercise test.[69,76]

Five of the studies used sports drinks that are currently available to consumers (Ball et al.[70] and Below et al.[71] used Gatorade, Jeukendrup et al.[72] used Isostar, Powers et al.[73] used Exceed and Millard-Stafford et al.[75] compared Powerade with Gatorade). Four of these investigations reported a significant improvement in performance.[70-72,75] The mechanism responsible for this improvement has not been elucidated, but appears to be related to the effect of fluid replacement attenuating increases in core temperature and heart rate, as well as an increased substrate availability.

In an attempt to determine the combined and separate effects of fluid and carbohydrate on performance, Below et al.[71] had participants cycle for 50 minutes at 80% $\dot{V}O_{2max}$ and then complete a performance test that required them to perform a given amount of work in the fastest possible time. Both the fluid alone solution and the carbohydrate (Gatorade) solution improved the high intensity cycling performance compared with the placebo. However, the improvements seen with the combination of carbohydrates and fluids were greater than with carbohydrates or fluids given individually, suggesting that the effects of carbohydrate and fluid on performance during short term high intensity exercise are additive.

The study by Millard-Stafford et al.[75] was one of the few found in the literature that compared the effectiveness of 2 presently available sports drinks. In this study, volunteers completed a 15km treadmill run in warm conditions and the last 1.6km run time was used as a measure of performance. The authors reported that both Gatorade and Powerade significantly improved performance compared with placebo, with no differences between the 2 drinks.

In conclusion, it appears that consumption of a sports drink during short duration high intensity exercise may enhance performance. Evidence suggests that supplementation with both fluid and carbohydrates may play a role in enhancing performance. No evidence exists suggesting superiority of one beverage compared with another.

4.3 Ingestion During Prolonged Intermittent Exercise

Twelve studies were designed to simulate the intermittent nature of many recreational and competitive activities by using prolonged intermittent exercise followed by brief high intensity sprints.[13,60,77-86] Nine of these studies reported significant increases in performance from the consumption of a sports drink.[60,77,79-85] Seven of these 8 studies used drinks with 10% carbohydrate or less.[77,79,80,82-85] Only 1 investigation incorporated a currently available sports drink,[79] although a number of these studies were completed using Gatorade's previous formula.

Another important observation concerning these studies was that 4 of the 9 studies that reported an ergogenic benefit used a pre-exercise fasting period of less than or equal to 4 hours.[81,83-85] As discussed in section 3.1, this nutritional regimen would be more appropriate than longer pre-exercise fasting protocols.

Of historical interest is one of the first studies published regarding the use of sports drinks. The researchers, who were responsible for the original formulation of Gatorade, tested their carbohydrate-electrolyte beverage using an intermittent exercise design.[77] Untrained volunteers exercised (11.3km run-walk-run protocol) either without fluids or with *ad libitum* consumption of either a 3% glucose-electrolyte solution, a NaCl solution or water. Relative to the other drinks, the glucose-electrolyte treatment was associated with a 5% improvement in the time required to complete the protocol and a 12.5% improvement in the time required to run the final 800m of the run-walk-run. No statistical analyses of the data were reported, and it is not clear whether all participants consumed the same volumes.

Throughout the 1980s, data continued to accumulate that revealed performance enhancement resulting from carbohydrate-electrolyte beverages. This prompted America's leading sports drink manufacturer (Gatorade) to establish a laboratory devoted to evaluating the ergogenic capabilities of sports drinks. Since then, over 50 articles have been published from the Gatorade Sport Science Institute related to the testing of Gatorade. Four of these studies employed an intermittent exercise protocol.[82-85] The first of these publications determined the effect of ingesting solutions of 5% maltodextrins, 6% sucrose/glucose (Gatorade's previous formulation), 7% maltodextrins/fructose (Exceed) or water on physiological function and performance during 1.6 hours of intermittent cycling in the heat.[82] Performance during the final sprint increased as the carbohydrate content of the drink increased. Improvements were significant with the 6% sucrose/glucose drink and the 7% maltodextrins/fructose beverage, and corresponded to higher plasma glucose concentrations during the later stages of the exercise session.

In an attempt to discern which carbohydrate (glucose, fructose or sucrose) would yield the greatest improvement in performance during an intermittent cycling task, volunteers completed intermittent cycle ergometer exercise at 65 to 80% of $\dot{V}O_{2max}$ followed by a timed performance bout requiring the completion of 600 pedal revolutions. Mean cycling performance times were faster with sucrose and glucose than with fructose.[83] The fructose beverage was also associated with gastrointestinal distress. The failure of the fructose beverage to improve exercise performance agreed with a previous report.[87]

An intermittent cycling protocol was used in 2 separate studies to look at the effect of the carbohydrate content of the sports drinks on exercise performance.[84,85] In the first study, improvements were observed in sprints lasting about 14 minutes when 6 and 8% sucrose solutions were given, but not when a 10% sucrose solution was given.[84] The results of this study challenged recommendations that only water or a very dilute carbohydrate solution (< 2.5% carbohydrate) should be ingested during exercise,[88-90] and that carbohydrate feeding is needed only during prolonged exercise (>90 minutes).[88] The authors were unable to explain the finding that only the 6 and 8% sucrose treatments were associated with significantly improved performance. In the second study,[85] ingestion of a 6% glucose solution (Gatorade) and 12 and 18% maltodextrins/dextrose solutions resulted in improved performance times in the 6 and 18% solutions compared with placebo. Thus, a dose-response relationship does not appear to exist. The authors believe that once a minimum rate of carbohydrate intake has been exceeded, the ingestion of additional carbohydrate confers no added performance benefit. However, this fails to explain the enhanced performance found with the 18% solution.

To determine the upper limits of steady state exercise performance and carbohydrate oxidation late in exercise, Coggan and Coyle[60] used a prolonged cycling protocol that alternated between 60 and 85% $\dot{V}O_{2max}$. Volunteers fasted for 14 hours prior to the test and consumed a 50% carbohydrate drink 10 minutes into the ride, followed by a 20% drink every 30 minutes thereafter. The researchers reported a 19% increase in work prior to fatigue. This ergogenic benefit was associated with a prolonged maintenance of carbohydrate oxidation.

To our knowledge, the study by Johnson et al.[13] was the only one that compared the efficacy of different sports drinks on prolonged intermittent exercise performance. The investigators compared 3 sports drinks which were available at the time (Gatorade, not the current formulation; Sportade, no longer available; and Olympade, also no longer available) with water during prolonged alternating treadmill and cycle ergometry. Consumption of the carbohydrate beverages resulted in increased respiratory exchange ratio and ventilatory volumes, which may be expected with increased carbohydrate metabolism, but did not affect time to exhaustion during a maximal treadmill test at the end of the exercise bout.

In summary, the results of the reviewed studies on prolonged intermittent exercise strongly suggest that consumption of a carbohydrate beverage can improve performance during intermittent exercise. The benefits have been shown to be due to the maintenance of carbohydrate oxidation by increasing plasma glucose levels. What is important is that a number of these studies have used carbohydrate concentrations less than 10%, making these findings much more applicable to currently available sports drinks. However, given that most people participate in sports of an intermittent nature and given that only 1 study has used a beverage that is currently available to consumers, further investigation of the effectiveness of currently available sports drinks during intermittent exercise is warranted.

4.4 Ingestion Before Prolonged Exercise

Eight studies have been published that investigated the effects on performance of sports drink consumption before endurance exercise (duration 1 to 4 hours).[91-98] Only 1 of these studies used a carbohydrate concentration of less than 10%,[97] with no improvement in performance reported. However, 4 of the remaining 7 studies have reported positive ergogenic effects.[93,95,96,98]

One of the first studies to examine this topic was conducted by Gleeson et al.[93] These authors gave volunteers a 17.5% glucose drink 45 minutes before exercise to exhaustion at 73% $\dot{V}O_{2max}$. They found that although blood glucose and insulin levels rose following glucose ingestion in the pre-exercise period, there was no evidence of hypoglycaemia in any of the volunteers at any time during the exercise period. Glucose ingestion was also associated with a statistically significant 7.4% increase in performance time. Other studies that have shown improvements in performance with the consumption of carbohydrate beverage prior to exercise have used 12 and 17%,[95] 20 and 40%,[96] and 25% solutions.[98]

In contrast to these findings was the work of Tarnopolsky et al.,[97] who reported that the ingestion of 600ml of an 8% glucose polymer/fructose beverage 1 hour before a cycling test did not effect time to fatigue. Furthermore, Flynn et al.[92] used a high carbohydrate concentration form of Exceed and also found no significant difference in the total work achieved during a 2-hour cycle.

Although the evidence is far from complete, it appears that the consumption of high (>10%) concentration carbohydrate solutions immediately before prolonged exercise can help maintain normal or elevated blood glucose levels and positively affect endurance during prolonged exercise, at least at moderate intensities. However, it appears that the use of sports drinks containing less than 10% carbohydrates prior to prolonged exercise is not supported. For the majority of participants in endurance events, emphasis should be on proper maintenance of fluid and electrolyte balance rather than concerns about carbohydrate depletion, as disturbances in fluid balance and temperature regulation have potentially serious consequences. During most competitions, especially long distance running, athletes drink far less during exercise than the amount of fluid that is lost by sweating, leading to dehydration and performance impairment. Therefore, the degree of prehydration may become very important.

4.5 Ingestion During Prolonged Exercise

The most researched topic in sports science is probably the effects of carbohydrate beverage consumption on performance during prolonged (1- to 4-hour duration) exercise. The Appendix outlines 36 studies[26,40,58,59,61,81,87,92,97-124] on this topic, with 23 of these reporting that significant ergogenic benefits were observed.[26,40,58,59,61,81,87,98,99,102,103,107-109,111,112,114,115,118-122] Furthermore, 26 of the 36 studies used a beverage with a carbohydrate content of less than or equal to 10%,[40,81,87,92,97,98,100-103,105,109,110,112-124] with 14 of these showing positive effects.[40,87,98,102,103,109,111,112,114,115,118-120,122] Of these 14, only 4 used either a controlled diet before the exercise test or a fasting protocol of less than 10 hours to ensure glycogen sufficiency.[98,102,115,118] At least 8 of these 36 studies used currently available sports drinks formulations.[40,101,109,113-115,121,122] However, this number could be higher as many authors did not specify if they had used a brand name beverage.

Gatorade was the first present day sports drink formulation to be investigated.[40] In this study, it was reported that after a 10-hour pre-exercise fast, ingestion of Gatorade every 20 minutes during 2 hours of cycling improved the performance of a subsequent 30-minute bout at 75% $\dot{V}O_{2max}$. Gatorade was also shown to improve performance during a 3.5-mile sprint which followed 2 hours of cycling at 68% $\dot{V}O_{2max}$.[115] Although the purpose of this study was to examine the effects of adding nicotinic acid to Gatorade, it was designed with a practical pre-exercise feeding protocol, with volunteers consuming a standard breakfast and lunch before the exercise test. This ensured that the benefits seen with the consumption of Gatorade during exercise were in glycogen-sufficient individuals. Kang et al.[109] compared Gatorade consumption during a 2-hour cycle ride with a placebo drink. They reported that Gatorade improved exercise time to exhaustion from 154 to 189 minutes. However, the volunteers had fasted for 12 hours before exercising.

Three studies have investigated the effects of Powerade on endurance exercise. The first of these reported that Powerade consumption during a triathlon had no effect on performance time compared with a placebo beverage.[113] In the second study,[114] Powerade ingestion during a 32km run in hot humid conditions was investigated. The participants fasted overnight prior to the run and performance was evaluated by timing the final 5km. The participants were significantly faster in the Powerade trial compared with placebo. In the third study,[92] Powerade consumption was compared to Gatorade, an 8.3% carbohydrate beverage and a placebo drink. The volunteers were required to cycle at 70% $\dot{V}O_{2max}$ for 105 minutes, then complete as much work as possible in 15 minutes. The authors reported no significant differences in total work between any of the 4 trials.

In conclusion, although the majority of the research that has been done on this topic cannot be related to the consumption of commercially available sports drinks, there is sufficient evidence to suggest that the consumption of a low carbohydrate beverage during prolonged exercise will be beneficial to performance. Indeed, 5 studies have used current drinks and shown a performance improvement. However, there is little evidence indicating that any one sports drink is superior.

4.6 Ultra-Endurance Exercise

Ultra-endurance exercise is typically defined as exercise beyond 4 hours. This exercise duration will cause depletion of muscle glycogen, and therefore it is no surprise that studies where carbohydrate is supplied to the participants result in an improvement in performance compared to when only water is given. All 3 studies of this type in the Appendix showed that carbohydrate consumption during ultra-endurance exercise improved performance.[125-127] Only 1 of these studies used a low carbohydrate drink.[127] This study used treadmill walking to evaluate the performance differences between a placebo and a 7% carbohydrate drink. The authors reported that volunteers consuming the carbohydrate beverage had significantly longer endurance times compared with those consuming the placebo.

Brouns et al.[125] found that volunteers who consumed a 20% carbohydrate beverage, *ad libitum*, during 48 hours of exhaustive intermittent cycling performed 126% more work during a 90% maximal workload (W_{max}) test compared with when they consumed a placebo beverage. Langenfeld et al.[126] reported that volunteers who consumed a 25% carbohydrate drink, *ad libitum*, during an 80-mile time trial completed the time trial in 1 hour less time than those consuming water.

Reports of hyponatraemia and large sweat losses in ultra-endurance competitors indicate that some supplementation with sodium chloride may be beneficial during extremely prolonged events.[128] During these events, low exercise intensity makes consumption of large volumes of fluid reasonable.[129] In the face of electrolyte losses, a sports drink offers advantages over plain water. Supplementation with solid food may also be desirable for the ultra-endurance athlete, but not at the expense of fluid intake.

4.7 Competitive Team Sports

The efficacy of ingesting carbohydrate drinks during game play has not been thoroughly investigated, despite the fact that some sports drinks were originally developed for team use. Some studies discussed previously have used test protocols involving stationary cycling with intermittent rest periods in an attempt to simulate high intensity competitive sports.[25,78] Whether these test protocols are truly representative of many intermittent, anaerobic sports is questionable. The Appendix outlines the only 2 studies that could be found using actual team sports.

Criswell and colleagues[130] examined the effects of a 7% maltodextrins/electrolyte beverage on anaerobic performance during a 1-hour simulated American football game. Using a double-blind, counterbalanced design, 44 high school players were divided into 2 offensive and 2 defensive teams. Each team completed a 50-play scrimmage, in full pads under warm conditions. At 10-minute intervals, 170ml of either a placebo or carbohydrate beverage was consumed by an offensive and defensive team. Exercise performance, assessed by peak and average velocity of 8 successive 40-yard (36m) sprints, was not significantly improved by sports drink consumption. However, plasma volume losses were significantly lower with the sports drink (–0.5%) than with water (–5.0%), but with no differences in serum electrolytes or osmolality. Plasma insulin and glucose were also significantly higher with the sports drink. The value of sports drinks to athletes in this sport deserves further attention since the uniform design and body dimensions of most linemen (small surface area-to-mass ratio and high body fat) pose an increased risk for heat injury, even in mild conditions.

Kreider et al.[131] determined the effects of carbohydrate supplementation during intense field hockey training on aerobic performance. Seven members of the US National Field Hockey Team were matched to 7 team counterparts (n = 14). One group was blindly given a carbohydrate drink containing 1 g/kg of carbohydrate 4 times daily, while the remaining group blindly ingested a flavoured placebo during 7 days of intense training. Volunteers underwent pre- and post-training aerobic testing. Results revealed that the carbohydrate-supplemented group had a greater ($p < 0.05$) total energy intake, carbohydrate intake and change (pre *vs* post) in time to maximal exhaustion following training, while reporting less postpractice psychological fatigue.

Success in some competitive team sports, such as football, soccer, rugby and basketball, requires both the ability to perform short term, high intensity exercise and a high endurance capacity. In these sports, depletion of muscle glycogen may limit performance, especially in a tournament situation where multiple games are contested within a short time frame. Since many athletes have a relatively deficient daily carbohydrate intake,[25] the use of a carbohydrate beverage may compensate for dietary deficits and provide additional energy to sustain exercise performance.

5. Conclusion

The primary purposes of sports drinks are to: (i) supply a source of carbohydrate that can supplement the limited stores of glycogen in the muscles and the liver; (ii) replace sweat losses; and (iii) reduce the problems associated with dehydration. The ability of a sports drink to maintain fluid balance during exercise is dependent upon the rates of fluid ingestion, gastric emptying and intestinal absorption. Evaluation of the performance-based sports drinks literature is difficult because of variations in the carbohydrate and electrolyte formulations of the fluids ingested and the pre-exercise fasting protocols.

Glycogen-compromised individuals undoubtedly benefit from consumption of carbohydrate-containing sports drinks. However, improvement of performance in glycogen-sufficient individuals is less certain. Consumption of a sports drink during intermittent exercise, as well as prior to and during prolonged exercise, appears to improve performance. However, there is little evidence that any commercially available sports drink can be deemed superior to the others. Continued research is indicated to elucidate the role of sports drink use in glycogen-sufficient individuals.

Table III. Appendix: studies measuring the effects of carbohydrate beverage consumption on exercise performance

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity (%$\dot{V}O_{2max}$)	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)a	Performance
Ingestion before short term (< 60 minutes) intense exercise										
Bonen et al.[62]	Cycling	T	30 min	Glycogen depleted	Continuous at 80%	NS	565ml 15 min before	a = 20% glucose; b = no CHO	1.5 g/kg	Times to exhaustion: a = 26.6 min, b = 29.9 min. No significant difference
el-Sayed et al.[63]	Cycling	T	60 min	Glycogen depleted	1h time trial	NS	4.5 mg/kg/min 25 min before	a = 8%; b = placebo	0.4 g/kg	Distance covered: a = 41.5km, b = 41.0km. CHO significantly improved performance
Foster et al.[55]	Cycling	T	5 or 60 min	3h fast	Continuous at 10% (approx. 5 min) then on another visit continuous at 80% (approx. 60 min)	Moderate	300ml 30 min before	a = 25% glucose; b = water	1.1 g/kg	Time to exhaustion at 100% $\dot{V}O_{2max}$: a = 360 sec, b = 345.6 sec. No significant difference. Time to exhaustion at 80% $\dot{V}O_{2max}$: a = 53 min, b = 43 min. CHO significantly improved performance
Koivisto et al.[64]	Cycling	T	30 min	Controlled diet and overnight fast	Continuous at 75%	NS	250ml 45 min before	a = 30% glucose; b = 30% fructose; c = placebo	1.0 g/kg	Times to exhaustion: a = 29.3 min, b = 30.1 min, c = 30.4 min. No significant difference
McMurray et al.[65]	Treadmill run	T women	60 min	Overnight fast	Continuous at 80%	NS	300ml 45 min before	a = 33% glucose; b = 33% fructose; c = placebo; d = water	1.5 g/kg	Times to exhaustion: a = 64 min, b = 62 min, c = 52 min, d = 65 min. CHO (a + b) + water significantly improved performance
Neufer et al.[66]	Cycling	T	60 min	12h fast	45 min continuously at 77% then 15 min at maximum	Moderate	400ml 5 min before	a = 11.25% (8.25% glucose polymer + 3% fructose); b = placebo	0.6 g/kg	Total work during final 15 min: a = 175 kNm, b = 159 kNm. CHO significantly improved performance
Snyder et al.[67]	Cycling	T	25 min	10h fast then liquid meal 4h before ride at 80 or 90%	4 × 1.6km performance rides with 4.8 or 1.8km steady state rides in between	NS	5 ml/kg (approx. 375ml) 15 min before	a = 19.7% glucose polymer; b = placebo	1 g/kg	Performance ride times: a = 25.2 min, b = 25.6 min. No significant difference
Ventura et al.[68]	Treadmill run	UT	10 min	3h fast	Continuous at 82%	Moderate	100ml 30 min before	a = 75% glucose; b = 75% fructose; c = placebo	11 g/kg	Times to exhaustion: a = 644 sec, b = 611 sec, c = 584 sec. CHO (a) significantly improved performance

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity (%VO_{2max})	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)[a]	Performance
Ingestion during short term (<60 min) exercise										
Anantaraman et al.[69]	Cycling	T	60 min	4h fast	Continuous at 90%	NS	300ml before then 300ml every 15 min (1500 ml/h)	a = 10% glucose polymer; b = placebo	2.14	Total work: a = 599 kJ, b = 560 kJ. CHO significantly improved performance
Ball et al.[70]	Cycling	T	50 min	Overnight fast	2 × 50 min time trials, each trial followed by Wingate test to measure performance	NS	2 ml/kg (approx. 150ml) every 10 min (900 ml/h)	a = 6% (Gatorade); b = placebo	0.90	Peak, mean and minimum power were all significantly improved in CHO trial
Below et al.[71]	Cycling	T	60 min	Overnight fast	50 min continuously at 80% then 10 min at maximum	Warm	Ad libitum (total 1330 ml/h)	a = 60% (Gatorade); b = placebo	1.11	Performance ride times during final 10 min: a = 10.2 min, b = 10.9 min. CHO significantly improved performance
Bonen et al.[62]	Cycling	T	30 min	Glycogen depleted	Continuous at 80%	NS	600ml every 3 to 5 min during ride (7200 ml/h)	a = 20% glucose; b = no CHO	20.57	Times to exhaustion: a = 26.1 min, b = 29.9 min. No significant difference
Jeukendrup et al.[72]	Cycling	T	60 min	Overnight fast	Perform a certain amount of work as fast as possible	Moderate	8 ml/kg during warm-up, then 2 ml/kg at 25, 50, 75% of set work (980 ml/h)	a = 7.6% (Isostar); b = placebo + 5 g/L fructose	1.06	Times to complete work task: a = 58.7 min, b = 60.2 min. CHO significantly improved performance
Powers et al.[73]	Cycling	T	40 min	6h fast	Continuous at 85%	Moderate	210ml before then every 15 min during ride (1050 ml/h)	a = 6% glucose polymer (Exceed); b = nonelectrolyte placebo; c = electrolyte placebo	0.90	Times to exhaustion: a = 39.2 min, b = 35.8 min, c = 40.2 min. No significant difference
Meyer et al.[74]	Cycling	Children (aged 9 to 12y)	60 min	3h fast	1 × 20 then 2 × 15 min at 50% with 10 min rest periods, then 90% until exhaustion	Hot	1.8 ml/kg (approx. 80ml) every 15 min (320 ml/h)	a = 6% (4% sucrose, 2% fructose); b = placebo	0.27	Total time: a = 6.18 min, b = 5.24 min. No significant difference. Total work performed: a = 35.2kJ, b = 33.4kJ. No significant difference
Millard-Stafford et al.[75]	Treadmill run	T	60 min	10h fast	15km time trial	Warm	1L before then *ad libitum* during run	a = 6% (Gatorade); b = 8% (Powerade); c = placebo	a = 0.7, b = 1.0	Last 1.6km run times: a = 344 sec, b = 341 sec, c = 358 sec. CHO (a, b) significantly improved performance

Mitchell et al.[76]	Cycling	T	60 min	4 to 6h fast	7 × 12 min bouts at 70% with 3 min rests, then final 12 min sprint	Moderate	2.1 ml/kg (approx. 170ml) during rest periods (approx. every 15 min) [680 ml/h]	a = 5% (54% glucose polymer, 46% glucose); b = 6% (36% glucose polymer, 31% fructose, 33% sucrose); c = 7.5% (74% glucose polymer, 26% fructose); d = placebo	a = 0.49, b = 0.58, c = 0.70	Exact data not given. CHO (a, b, c) significantly improved performance
Ingestion during prolonged intermittent exercise										
Cade et al.[77]	Walk/run	NS	1.4h	NS	7-mile walk/run intervals at own pace	Hot/humid	NS, ad libitum	a = 3% glucose; b = placebo	NS	Performance times: a = 78.2 min, b = 83.1 min. CHO significantly improved performance
Coggan & Coyle[60]	Cycling	T	2-3h	14h fast	Alternated every 15 min between 60 and 85%	NS	135ml at 10 min then 200ml every 30 min (467 ml/h)	a = 50% (85% glucose polymer, 15% sucrose) at 10 min then 20% (85% glucose polymer, 15% sucrose) every 30 min; b = placebo	2.0	Total work performed: a = 2.74 MJ, b = 2.29 MJ. CHO significantly improved performance
Davis et al.[78]	Cycling	T	2h	10h fast	2 × 60 min at 65% with 3 min exhaustive ride after, then 20 min rest and 1 more exhaustive ride	Warm/humid	275ml at 10 min then every 20 min (963 ml/h)	a = 6% glucose; b = 12% glucose + electrolytes; c = water	a = 0.83, b = 1.65	Performance times for the 3 exhaustive rides: a = 151, 157, 134 sec, b = 150, 170, 156 sec, c = 151, 175, 165 sec. No significant difference
Davis et al.[79]	Cycling	UT (men and women)	1.5h	10h fast	Alternated between 1 min at 120-130% then 3 min rest until fatigue	NS	4 ml/kg per session (4200 ml/h)	a = 6% (Gatorade); b = placebo	8.5	Times to exhaustion: men, a = 89.5 min, b = 58.1 min; women, a = 84.9 min, b = 62 min. CHO significantly improved performance
Hargreaves et al.[80]	Cycling	UT	4h	Overnight fast	8 × 30 min segments (20 min at 50% then 10 min of intermittent bouts of 30 sec with 2 min rest) then final ride to exhaustion	NS	(400 ml/hr)	a = 9.3% (solid: 172g sucrose with 1600ml fluid); b = placebo	0.53	Times to exhaustion in final ride: a = 126 sec, b = 87 sec. CHO significantly improved performance
Johnson et al.[13]	Running/cycling	NS	4h	NS	Alternated between cycle and treadmill (55 min on each with a 5 min rest)	Hot, 30-40% humidity	*Ad libitum* resulted in: a = 616 ml/h, b = 606 ml/h, c = 529 ml/h, d = 475 ml/h	a = 5% (Olympade); b = 10% (Sportade); c = 5% (Gatorade); d = placebo	a = 0.44, b = 0.87, c = 0.38	No significant difference on times to exhaustion between any of the beverages (data not given)

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity (% VO_{2max})	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)a	Performance
Mitchell et al.[81]	Cycling	T	2h	Consumed liquid diet 3h before ride at maximum	7 × 15 min at 70% with 3 min rests, then 15 min	Moderate	Approximately 150ml every 15 min (595 ml/h)	a = 12% (8.5% glucose polymer, 3.5% fructose); b = placebo	1.02	Total work in last 15 min: 12% CHO = 2.22 Nm × 10^5, placebo = 2.01 Nm × 10^5. CHO significantly improved performance
Murray et al.[82]	Cycling	UT	1.6h	8h fast	Exercise bouts at 55-65% for 15 min with 5 min rest periods and 2 performance rides. Final performance ride (480 rpm) used as test	Hot	115-210ml during rest periods (345-610 ml/h)	a = 5% glucose polymer; b = 6% (Gatorade); c = 7% glucose polymer, fructose; d = placebo	a = 0.35, b = 0.41, c = 0.49	Times for the cycling test: a = 401 sec, b = 384 sec, c = 375 sec, d = 432 sec. CHO (b, c) significantly improved performance
Murray et al.[83]	Cycling	UT	1.2h	4h fast	20 min at 75%, then 15 min at 80%, then 10 min at 80%, then 8 min at 80%, then performance test (4 min rest periods in between)	Moderate	6 ml/kg (approximately 365ml) at 20 min and 3 ml/kg (approx. 180ml) during the rest periods (815 ml/h)	a = 6% glucose; b = 6% fructose; c = 6% sucrose. No placebo	0.7	Times for the cycling test: a = 424 sec, b = 488 sec, c = 419 sec. CHO (a, c) significantly improved performance
Murray et al.[84]	Cycling	UT	1.25h	4h fast	3 × 25 min at 65% with 5 min rest in between, then timed cycling task (1200 rpm)	Warm	2.5 ml/kg (approximately 175ml) before start and during rest periods (525 ml/h)	a = 6% sucrose; b = 8% sucrose; c = 10% sucrose; d = placebo	a = 0.45, b = 0.60, c = 0.75	Times for the cycling test: a = 13.0 min, b = 13.3 min, c = 13.6 min, d = 14.6 min. CHO (a, b) significantly improved performance
Murray et al.[85]	Cycling	UT	2h	2-3h fast	2h alternating between 65-75%, then 4.8km test	Cool (10°C)	2 ml/kg (approximately 110ml) every 15 min (440 ml/h)	a = 6% (Gatorade); b = 12% (4% dextrose, 8% glucose polymer); c = 18% (3% dextrose, 15% glucose polymer); d = placebo	a = 0.38, b = 0.76, c = 1.13	Times for the cycling test: a = 476 sec, b = 483 sec, c = 474 sec, d = 505 sec. CHO (a, c) significantly improved performance

Sasaki et al.[86]	Treadmill run	UT	2.5h	8h fast	4 × 30 min at 62-67% with 5 min rest between, then 80% for 10 min, then 90% until exhaustion	NS	350ml prior to each set (700 ml/h)	a = 6.8% sucrose; b = placebo	0.68	Times to exhaustion: a = 17 min 28 sec, b = 14 min 55 sec. No significant difference
Ingestion before prolonged exercise (1-4 hours)										
Chryssanthopoulos et al.[91]	Treadmill run	UT	2h	NS	70% until exhaustion	NS	300ml 30 min before	a = 25% glucose; b = placebo	1 g/kg	Times to exhaustion: a = 133.8 min, b = 121.2 min. No significant difference
Flynn et al.[92]	Cycling	T	2h	12h fast	105 min at 65% then 15 min test	NS	Meal at either 4 or 8h before ride	a = 252g (Exceed high CHO source, no placebo)	3.5 g/kg	Total work in 2h: 4h pre-ride CHO = 217 kNm, 8h pre-ride CHO = 217 kNm. No significant difference
Gleeson et al.[93]	Cycling	UT	1.3h	Overnight fast	73% until exhaustion	Air-conditioned	400ml 45 min before	a = 17.5% glucose; b = glycerol; c = placebo	1 g/kg; 1 g/kg	Times to exhaustion: a = 108.8 min, b = 86 min, c = 95.9 min. CHO significantly improved performance
Hargreaves et al.[94]	Cycling	T and UT	1.5h	6h fast	Continuous at 75%	Moderate	350ml 45 min before	a = 21.5% glucose; b = 21.5% fructose; c = placebo	1 g/kg; 1 g/kg	Times to exhaustion: a = 92.8 min, b = 90.6 min, c = 92.7 min. No significant difference
Okano et al.[95]	Cycling	T	2.5h	4h fast	90 min at 62%, then 30 min at 72%, then 81% until exhaustion	Moderate	500ml 60 min before	a = 12% fructose; b = 17% fructose; c = placebo	0.9 g/kg; 1.3 g/kg	Times to exhaustion: a = 142 min, b = 154 min, c = 132 min. CHO (a, b) significantly improved performance
Sherman et al.[96]	Cycling	UT	2.25h	Controlled diet for 2 days before ride	90 min at 70% then performance test (approx. 45 min at approx. 70%)	Moderate	Approx. 400ml 1h before	a = 20% glucose; b = 40% (24% glucose polymer, 16% glucose); c = placebo	1.1 g/kg; 2.2 g/kg	Endurance times: a = 41 min, b = 42 min, c = 47 min. CHO (a, b) significantly improved performance
Tarnopolsky et al.[97]	Treadmill run/cycling	T	1.1h	Either meal 177 kcal (81% CHO/19% protein) for 3 days or placebo	Treadmill run at 76% for 60 min then cycle at 78% until exhaustion	NS	4 × 150ml every 15 min for 1h before	a = 8% (63% glucose polymer, 37% fructose); b = 8% glucose; c = placebo	0.69 g/kg	Times to exhaustion: meal + pre-exercise (a) = 9.6 min; placebo + pre-exercise (a) = 9.5 min; placebo + pre-exercise (b) = 8.3 min; placebo + pre-exercise (c) = 7.8 min. CHO (meal + a) significantly improved performance

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity ($\%VO_{2max}$)	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)a	Performance
Wright et al. 1996[98]	Cycling	T	4h	Controlled diet	70% until exhaustion with 3 min bouts of 90% every 45 min	NS	Approx. 1420ml 3h before	a = 25% (21% glucose polymer, 4% sucrose); b = placebo	5 g/kg	Times to exhaustion: a = 237 min, b = 201 min. CHO significantly improved performance. Total work: CHO = 2.9MJ, placebo = 2.5MJ. CHO significantly improved performance
Ingestion during prolonged exercise (1-4 hours)										
Bjorkman et al.[87]	Cycling	T	2.3h	NS	Continuous at 68%	NS	250ml every 20 min during ride (750 ml/h)	a = 7% glucose; b = 7% fructose; c = placebo	a = 0.75; b = 0.75	Times to exhaustion a = 137 min, b = 114 min, c = 116 min. Glucose significantly improved performance
Brooke et al.[99]	Cycling	T	4h	NS	Continuous at 67%	Moderate	250ml every 20 min during ride (750 ml/h)	a = 46% glucose syrup; b = placebo	4.93	Endurance times: a = 214 min, b = 148 min. CHO significantly improved performance
Burgess et al.[100]	Cycling	T	3h	10h fast	165 min at approx. 67%, then 2-stage ride to exhaustion	Moderate	3.5 ml/kg (approx. 260ml) every 20 min (780 ml/h)	a = 1.8% sucrose; b = placebo	0.20	Times to exhaustion: first stage a = 860 sec, b = 964 sec; second stage a = 225 sec, b = 350 sec. No significant difference
Coggan & Coyle[59]	Cycling	T	3.2h	14-16h fast	70% for approx. 170 min, then 20 min rest, then 70% until exhaustion	Moderate	6 ml/kg (approx. 420ml) 3 min after finishing first ride (400 ml/h during second ride)	a = 50% (85% glucose polymer, 15% sucrose); b = placebo	12 during second ride	Times to fatigue in second ride: a = 26 min, b = 10 min. CHO significantly improved performance
Coggan & Coyle[61]	Cycling	T	2h	14-16h fast	70% for 135 min then 85-95 rpm until exhaustion	Moderate	6 ml/kg (approx. 420ml) after 135 min (140 ml/h)	a = 50% (85% glucose polymer, 15% sucrose); b = placebo	2.5 during second ride	Total time to fatigue: a = 205 min, b = 169 min. CHO significantly improved performance
Cole et al.[101]	Cycling	T	2h	6-10h fast	70% for 105 min then max for 15 min	Moderate	9.75 ml/kg/h (approx. 175ml every 15 min during ride) [700 ml/h]	a = 6% (Gatorade); b = 8.3% high fructose corn syrup; c = 8.3% (Powerade); d = placebo	a = 0.60; b = 0.83; c = 0.83	Total work between trials: a = 191kJ, b = 190kJ, c = 190kJ, d = 186kJ. No significant difference

Coyle et al.[26]	Cycling	T	2.5h	12h fast	Continuous at 74%	Moderate	140ml at 20 min, then 300ml at 60, 90 and 120 min (520 ml/h)	a = 50% glucose polymer for first intake (at 20 min) then 6% glucose polymer at 60, 90 and 120 min; b = placebo	3.0 for first 20 min, then 0.51	Times to exhaustion: a = 157 min, b = 134 min. CHO significantly improved performance
Coyle et al.[58]	Cycling	T	3-4h	16h fast	Continuous at 71%	Moderate	Approx. 270ml every 20 min (810 ml/h)	a = 50% glucose polymer for first intake (at 20 min) then 10% glucose polymer every 20 min	3.0 for first 20 min, then 1.16	Times to exhaustion: a = 4.02h, b = 3.02h. CHO significantly improved performance
Davis et al.[40]	Cycling	T	2.5h	10h fast	2h at 75% (T1) then 30 min at 75% (T2)	Hot	275ml 15 min after start, then every 20 min during ride (850 ml/h)	a = 6% (Gatorade); b = 2.5% glucose; c = placebo	a = 0.73; b = 0.30	Performance times: a T1 = 128 min, T2 = 31 min; b T1 = 128 min, T2 = 32 min; c T1 = 129 min, T2 = 34 min. CHO (a) significantly improved performance during T2
Edwards et al.[102]	Cycling	T	3h	Controlled diet	55-mile time trial, last 9.2 miles used as performance test	Moderate	200ml approx. every 20 min during ride (600 ml/h)	a = 50% glucose polymer for first intake (at 20 min) then 7% glucose polymer every 20 min after; b = 7% (5% glucose polymer, 2% fructose); c = placebo	1.42 for first 20 min, then 0.6	Performance times: a = 25.2 min, b = 24.8 min, c = 27.3 min. CHO (both 50% and 5%) significantly improved performance
Febbraio et al.[103]	Cycling	T	2h	Overnight fast	Continuous at 70%	a = 5°C, RH approx. 50%; b = 33°C, RH approx. 25%	250ml before and every 25 min during ride 14.3 ml/kg/h (750 ml/h	a = 7% (glucose, sucrose); b = 14% (glucose, sucrose, glucose polymer); c = placebo	a = 0.75; b = 1.50	Times to exhaustion: 5°C, RH approx. 50%, a = 130 min, b = 200 min, c = 170 min (all approximate times). CHO (a) significantly improved performance. 33°C, RH approx. 25%, a = 95 min, b = 90 min, c = 80 min (all approximate times). No significant difference
Felig et al.[104]	Cycling	UT	2.5h	10-14h fast	Continuous at 60-65%	NS	200ml every 15 min during ride (800 ml/h)	a = 5% glucose; b = 10% glucose; c = placebo	a = 0.57; b = 1.14	Times to exhaustion: a = 171 min, b = 159 min, c = 164 min. No significant difference

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity ($\%VO_{2max}$)	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)a	Performance
Flynn et al.[105]	Cycling	T	2h	Overnight fast	As much work as possible during 2h ride	NS	150ml before and every 20 min during ride (750 ml/h)	a = 5% (3% glucose polymer, 2% glucose); b = 10% (5% glucose polymer, 5% fructose); c = 10% (7.7% glucose polymer, 2.3% high fructose corn syrup); d = placebo	a = 0.43; b = 0.86; c = 0.86	Total work in 2h: a = 1326 kNm, b = 1285 kNm, c = 1345 kNm, d = 1340 kNm. No significant difference
Flynn et al.[92]	Cycling	T	2h	12h fast then a CHO drink at either 4 or 8h before ride	105 min at 65%, then 15 min test	NS	500ml at either 4 or 8h before ride, then 250ml every 20 min during ride (750 ml/h)	a = 7.7% (glucose polymer, fructose)	0.83	Total work in 2h: 4h pre-ride CHO = 217 kNm, 4h pre-ride CHO + CHO during = 224 kNm, 8h pre-ride CHO = 217 kNm, 8h pre-ride CHO + CHO during = 225 kNm. No significant difference
Green & Bagley[106]	Canoeing	T	2.5h	NS	Continuous (5 laps × 2.5 miles)	NS	250ml 30 min before, then 250ml after 3 laps (approx. 1.5h) [167 ml/h]	a = 46% glucose; b = placebo	1.10	Canoeists decreased their lap times with CHO by: lap 2 = 70 sec, lap 3 = 138 sec, lap 4 = 233 sec, lap 5 = 351 sec. No mention of significant difference
Ivy et al.[107]	Cycling	T	2h	12h fast	Continuous at 80 rpm	NS	50ml before and every 15 min during ride (250 ml/h)	a = 20% glucose polymer; b = placebo	0.71	CHO increased work rate during final 30 min by 11.1% (data not given)
Ivy et al.[108]	Walking	T	4.5h	12h fast	Continuous at 45%	NS	150ml at 60, 90, 120 and 150 min during walk (240 ml/h)	a = 20% glucose polymer; b = placebo	0.69	Times to exhaustion: a = 299 min, b = 268 min. CHO significantly improved performance
Kang et al.[109]	Cycling	T	2h	12h fast	Continuous at 70%	NS	250ml every 20 min during ride (750 ml/h)	a = 6% (Gatorade); b = placebo	0.64	Times to exhaustion: a = 189 min, b = 154 min. CHO significantly improved performance
Kingwell et al.[110]	Cycling	T	2.7h	Overnight fast	Continuous at 65%, then 5 min rest, then 110% test	NS	200ml in first min of ride then every 20 min (800 ml/h)	a = 10% glucose polymer; b = placebo	1.14	Total work at 110%: a = 36.1kJ, b = 33.8kJ. No significant difference

Maughan et al.[111]	Cycling	UT	1.5h	Fasted	Continuous at 70%	NS	100ml immediately before then every 10 min (700 ml/h)	a = 36% glucose; b = 36% fructose; c = 36% glucose/ fructose; d = 4% glucose; e = placebo; f = no fluid	a = 3.60; b = 3.60; c = 3.60; d = 0.40	Times to exhaustion: a = 79.0 min, b = 65.6 min, c = 79.5 min, d = 90.8 min, e = 76.2 min, f = 70.2 min. CHO (d) significantly improved performance
McConell et al.[112]	Cycling	T	2h	Overnight fast	Continuous at 70% for 2h then 15 min test	NS	250ml immediately before then every 15 min during (14 ml/kg/min) [1250 ml/h]	a = 7% (NS); b = placebo	0.13	Total work during 15 min performance ride: a = 268kJ, b = 242kJ. CHO significantly improved performance
Millard-Stafford et al.[113]	Triathlon	T	2.3h	8h fast	1.5km swim, 40km cycling, 10km run (continuous at own pace)	Hot	2 ml/kg (approx. 150ml) 5km after swim, then at 8km intervals during cycle, then at 3.2km intervals during run (530 ml/h)	a = 7% (Powerade); b = placebo	0.53	Performance times for triathlon: a = 142 min, b = 143 min. No significant difference
Millard-Stafford et al.[114]	Running	T	2.5h	Overnight fast	32km at own pace (last 5km timed)	Hot	400ml 30 min before and 250ml (0.75 L/h) every 5km during run (750 ml/h)	a = 7% (Powerade); b = placebo	0.75	Last 5km run times: a = 21.9 min, b = 24.4 min. CHO significantly improved performance
Mitchell et al.[81]	Cycling	T	2h	Consumed liquid diet 3h before ride	105 min at 70%, then 15 min at maximum	Moderate	8.5 ml/kg/h (approx. 150ml every 15 min) [600 ml/h]	a = 6% (4% glucose, 2% sucrose); b = 12% (8.5% glucose polymer, 3.5% fructose); c = 18% (14.5% glucose polymer, 3.5% fructose; d = placebo	a = 0.78; b = 0.61; c = 0.61	Total work in last 15 min: a = $2.13 Nm \times 10^5$, b = $2.28 Nm \times 10^5$, c = $2.17 Nm \times 10^5$, d = $2.01 Nm \times 10^5$. CHO (b) significantly improved performance
Murray et al.[115]	Cycling	UT	2.1h	Standard breakfast and lunch	120 min at 69%, then 3.5-mile time trial	NS	3.5 ml/kg/h (approx. 150ml for females and 230ml for males) every 15 min during ride (500 ml/h)	a = 6% (Gatorade); b = placebo	0.36	3.5-mile time trial times: a = 641.8 sec, b = 730.6 sec. CHO significantly improved performance

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity (% VO_{2max})	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)a	Performance
Nishibata et al.[116]	Cycling	UT	1.5h	12h fast	Continuous at 73%	NS	Approx. 145ml 15 min before and at 15 and 45 min during ride (600 ml/h)	a = 10% glucose; b = placebo	a = 0.69; b = 0.69	Times to exhaustion: a = 92.1 min, b = 98.1 min. No significant difference
Riley et al.[117]	Treadmill run	T	1.5h	21h fast	Continuous at 71%	NS	200ml 20 min before and 200ml every 20 min during run (600 ml/h)	a = 7% (Exceed); b = placebo	0.61	Times to exhaustion: a = 100 min, b = 100 min. No significant difference
Sasaki et al.[118]	Treadmill run	UT	1.4h	8h fast	Treadmill run at 80% for 60 min (first run) then treadmill run at 80% until exhaustion (second run)	Moderate	200ml 60 min before, then 250ml immediately before the first run, then 250ml before the second run (500 ml/h)	a = 5% sucrose; b = placebo	0.36	Times to exhaustion: a = 58 min 29 sec, b = 39 min 45 sec. CHO significantly improved performance
Tarnopolsky et al.[97]	Treadmill run/cycling	T	1.1h	Standard diet	Treadmill run at 76% for 60 min, then cycle at 78% until exhaustion	NS	4 × 150ml every 15 min during ride (600 ml/h)	a = 8% (37% glucose, 63% glucose polymer); b = 8% glucose; c = placebo	a = 0.69; b = 0.69	Times to exhaustion: a = 9.5 min, b = 8.3 min, c = 7.8 min. No significant difference
Tsintzas et al.[119]	Road run	UT	2h	10-12h fast	30km self paced	NS	3.5 ml/kg before then 2 ml/kg every 5km during run (390 ml/h)	a = 5% (NS); b = placebo	0.28	Times to exhaustion: a = 128.3 min, b = 131.2 min. CHO significantly improved performance
Tsintzas et al.[120]	Treadmill run	UT	2h	10-12h fast	At 70% until exhaustion	Moderate	8 ml/kg before then 2 ml/kg every 20 min during run (420 ml/h)	a = 5.5% (NS); b = 6.9% (NS); c = placebo	a = 0.33; b = 0.41	Times to exhaustion: a = 124.5 min, b = 121.4 min, c = 109.6 min. CHO (a) significantly improved performance
Widrick et al.[121]	Cycling	T	2h	Either high glycogen diet (HG) or low glycogen diet (LG)	Self paced	Moderate	2.35 ml/kg every 10km (200 ml/h)	a = 9% (high fructose corn syrup); b = placebo	0.26	Performance times: LG + CHO during = 121 min; LG + placebo during = 123 min; HG + CHO during = 117 min; HG + placebo during = 119 min. No significant difference when high initial glycogen levels, significant difference when low initial glycogen levels

Wilber & Moffat[122]	Treadmill run	T	2h	12h fast	At 80% until exhaustion	NS	250ml 5 min before and 150ml every 15 min during run (850 ml/h)	a = 7% (Exceed: 85% malto-dextrins, 15% sucrose); b = placebo	0.85	Times to exhaustion: a = 115 min, b = 92 min. CHO significantly improved performance
Williams et al.[123]	Treadmill run	UT	2h	12h fast	Run 30km as fast as possible	Moderate	250ml 5 min before and 150ml every 5km during run (700 ml/h)	a = 5% (2% glucose polymer, 2% glucose); b = 5% (2% glucose polymer, 2% fructose); c = placebo	a = 0.5; b = 0.5	Performance times: a = 125 min, b = 126 min, c = 129 min. No significant difference
Wright et al.[98]	Cycling	T	4h	Either controlled diet or placebo	70% until exhaustion with 3 min bouts of 90% every 45 min	NS	Approx. 175ml every 20 min (525 ml/h)	a = 25% (21% glucose polymer, 4% sucrose) before exercise + 8% CHO (5% glucose polymer, 3% fructose) during ride; b = placebo before exercise + 8% CHO (5% glucose polymer, 3% fructose) during ride; c = placebo before exercise + placebo during ride	a = 0.19; b = 0.06	Times to exhaustion: a = 290 min, b = 266 min, c = 201 min. Significantly better in a and b than in c. Total work: a = 3.6MJ, b = 3.3MJ, c = 2.5MJ. Significantly better in a and b than in c
Zachwieja et al.[124]	Cycling	T	2h	Overnight fast	105 min at 70%, then 15 min self paced test	Moderate	8.5 ml/kg/h (150ml just before then every 15 min during ride) [750 ml/h]	a = 10% (4% glucose, 6% fructose); b = placebo	1.07	Average power for 15 min test ride: a = 263W, b = 244W. No significant difference
Ultra-endurance exercise (> 4 hours)										
Brouns et al.[125]	Cycling	T	12h	Controlled CHO-rich diet for 24h before ride	2 days of exhaustive intermittent exercise	NS	*Ad libitum*	a = 20% (16.4% maltodextrins, 3.6% fructose); b = placebo	NS	90% W_{max} test time increased by: a = 22.4 min, b = 9.9 min. CHO significantly improved performance
Langenfeld et al.[126]	Cycling	T	4.1h	Prescribed diet up to 3-4h before ride	80-mile time trial	NS	*Ad libitum*	a = 25% (10.4% maltodextrins, 14.4% fructose); b = placebo	NS	Endurance times: a = 16h, b = 17h
Levine et al.[127]	Walking	T	16h	Normal diets	45 min bouts at 1.6 m/sec, then 45 min rest periods	Hot (37°C)/dry (20%)	260ml every 10 miles (90 ml/h)	a = 7% (5% maltodextrins, 2% fructose); b = placebo	0.09	Endurance times: a = 241 min, b = 253 min. CHO significantly improved performance

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Table III. Appendix. Contd

Reference	Mode or sport	Participants	Approx. duration	Preparation	Protocol and intensity (% $\dot{V}O_{2max}$)	Environment	Fluid volume and when consumed	Beverages	CHO dosage (g/kg/h)[a]	Performance
Competitive team sports										
Criswell et al.[130]	American football	T	NS	Consumed liquid diet beverage with regular meals to reduce variation in glycogen stores	Anaerobic power test (8 × 40-yard sprints), then 50-play scrimmage, then anaerobic power test again	Hot (28°C), humid (66%)	170ml approx. every 10 min (1020 ml/h)	a = 7% (Exceed); b = placebo	1	No differences between treatments in mean and peak sprint velocities from pre-scrimmage to post-scrimmage
Kreider et al.[131]	Field hockey	T	7 days	NS	Exercise time to exhaustion using the Bruce treadmill protocol	NS	NS	a = NS; b = placebo	NS	CHO consumption significantly increased exercise time to exhaustion by 0.38 min

a Unless otherwise indicated in studies where CHO was ingested before exercise.

CHO = carbohydrate; **NS** = not stated; **RH** = relative humidity; **T** = trained; **UT** = untrained; $\dot{V}O_{2max}$ = maximal oxygen uptake; W_{max} = maximal workload.

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