

Module 1. The role of carbohydrate in a player's diet

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Unit 1.1. An introduction to carbohydrate

The aim of this course is to build on your understanding of macronutrients in a player's diet. In the first unit in each module, the macronutrient of interest will be introduced, followed by Unit 2, where the macronutrients' relevance to football will be discussed. Knowing each macronutrient will provide the basis on how to compose meals and manipulate a player's diet to achieve health, performance, and body composition goals. Therefore, where relevant the theory will be translated into foods and recipes to help guide and bring to life the recommendations.

Carbohydrate is one of the most studied macronutrients in the disciplines of sports nutrition and football science. This is because, for nearly 100 years, carbohydrate ingestion has been associated with improved exercise/football performance. Specifically, the availability of carbohydrate has long been known to be important to provide fuel for the players' muscles and central nervous system. Thus, carbohydrate availability is vital in the maintenance of high intensity running and the skills required for football activity. The digestion and absorption of carbohydrate will be summarised, so that the factors that speed or inhibit the delivery of carbohydrates to the players' body can be understood. Common dietary sources of carbohydrate will be identified and, finally, the mechanisms by which carbohydrate may influence performance will be discussed.

Carbohydrate

Carbohydrates are composed of carbon, hydrogen, and oxygen. The general formula for carbohydrates is $(CH_2O)_n$. The chemical formula for glucose is $C_6H_{12}O_6$.

Key point

Carbohydrates include all the sugars, starches, and fibres in a player's diet.

In general, carbohydrates can be classified by the number of monosaccharides (single sugars) they contain. The single sugars are joined by glycosidic bonds to form two or more sugars in sequence. A disaccharide is the term used to refer to two sugars joined together,

which is very common. A polysaccharide is a chain of three to thousands of sugars (see figure 1). Carbohydrates with a large number of glucose sugars are called starches. Amylose is a straight chain starch and it is more resistant to digestion in comparison to amylopectin, which is a branched chain starch.

Figure 1. Carbohydrates classification by structure

Monosaccharides:

Single sugars

 **glucose**

 **fructose**

 **galactose**

Oligosaccharides:

2-10 sugars bonded chemically:
disaccharides – very common

 **maltose**

 **sucrose**

 **lactose**

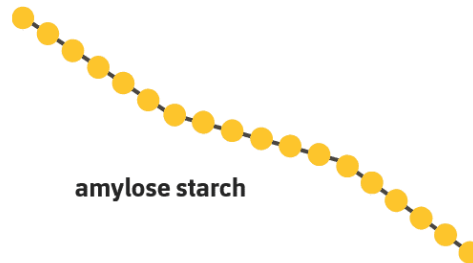
 **isomaltulose**

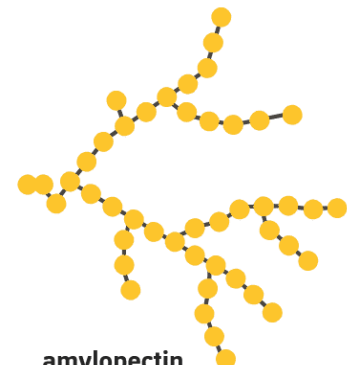
 **trehalose**

Polysaccharides:

Three to thousands of sugars
linked together


maltodextrin


amylose starch


amylopectin starch

Source: own source.

Did you know?

Saccharide is another word for sugar.

Carbohydrate digestion and absorption

A player's body stores of carbohydrate are finite. Therefore, to maintain the supply of energy for muscle (and brain) metabolism, carbohydrates must be replenished. Thus, in football, the most prevalent interventions used to impact on a player's performance involve the ingestion of dietary sources of carbohydrate. Correspondingly, the effectiveness of nutritional interventions is dependent upon the regulation and absorption of carbohydrates by the gastrointestinal (GI) tract.

The GI tract is a tube of approximately nine meters long that extends from the player's mouth to the anus. When players ingest food, it is moved along the GI tract by strong peristaltic contractions. As the food is moved through the GI tract, it is mixed with



extensive secretions of fluid containing various enzymes which aid in the digestion and absorption of nutrients.

Did you know?

When food is ingested, it gets chewed and mixed into a small round mass, and, when swallowed, it is referred to as a 'bolus'.

The digestion of carbohydrates begins in the player's mouth. Food is broken down mechanically by mastication and mixed with saliva secreted by the salivary glands. The salivary amylase begins the breakdown of starch into smaller oligosaccharides. It is in the mouth where the tongue begins the analysis of food, determining whether it is nutritive (*i. e.* sugar) and should be ingested or whether it is potentially harmful and, therefore, it should be expectorated (Katz *et al.*, 2000).

The palatability of solutions is an important consideration when providing drinks to players. Several studies have reported that flavouring or sweetening beverages can substantially increase the voluntary intake of fluid both during exercise and recovery from exercise (Passe *et al.*, 2000). Nevertheless, it is advised to provide several different flavours of beverage which the player 'prefers'. This will allow the flavour of drinks to be changed either during the week or during the season to avoid flavour fatigue.

Did you know?

Mastication is another word for chewing.

Food and beverages move from the player's mouth to the stomach. In the stomach, the food is moved vigorously to mix with gastric juices, secreted from the stomach glands, and form chyme. The stomach acts as a reservoir to receive food whilst intermittently delivering the chyme to the intestine. Ingested food stays in the stomach between 1 and 4 hours.

The absorption of nutrients occurs almost entirely along the walls of the small intestine. Therefore, the benefits of ingesting carbohydrates and fluids at rest or during football exercise are only obtained following the movement of chyme from the stomach into the duodenum (gastric emptying). Numerous factors, such as temperature (Costill & Saltin, 1974), osmolality (Brouns *et al.*, 1995), and pH (Hunt & Knox, 1968) have been investigated as possible regulating factors of gastric emptying. However, none appear to be of greater importance than the volume or energy content of the ingested food.

Key point



The metabolic benefits of ingesting carbohydrates and fluids at rest or during exercise are only obtained following the movement of food from the stomach into the intestines.

Energy density

Water empties rapidly from the stomach. As carbohydrate is added to the solution, which is typical in sports drinks, the energy content of the solution is increased, and the rate of gastric emptying is slowed. Studies investigating the ingestion of equivalent volumes of solutions have reported that drinks containing a carbohydrate content of 2.5% or less empty at approximately the same rate as water. Increasing the concentration of carbohydrate in the solution to greater than 6% has been shown to result in a small, but significant slowing of gastric emptying (Costill & Saltin, 1974). It has been suggested that gastric emptying could be increased by including a mixture of carbohydrates within the ingested solution. For example, adding fructose to a glucose solution has been shown to increase fluid delivery compared to a glucose only solution (Jeukendrup & Moseley, 2008). The fact that most sports drinks have a carbohydrate concentration of 5-8% is reflective of the balance between maintaining a high rate of gastric emptying, whilst delivering adequate concentrations of carbohydrate to the intestine. It is for this reason that 6% carbohydrate beverages would be recommended for players to ingest 'during' the match or breaks in play.

Specialised sports foods have been developed with 'hydrogel technology' which aims to optimise carbohydrate delivery, without compromising gastric emptying or increasing risk of gastrointestinal discomfort (Sutehall *et al.*, 2022a). Hydrogels combine typical carbohydrate sources with pectin (a soluble fibre) and alginate (a polymer derived from seaweed). This combination of ingredients undergoes gelation when in the stomach, as they combine with low pH solutions. This process encapsulates the carbohydrate, speeding its delivery from the stomach. However, to date studies do not support the claimed benefits of hydrogel when compared to the use of well-sporulated sports drinks as outlined above (King *et al.*, 2020). Nonetheless, hydrogels do not impair performance (Sutehall *et al.*, 2022b). As a nutritionist in football, you should be aware of all the options available for the player. Hydrogels may well suit individual players, or be introduced for impact or player engagement at key points of the season.

Gastric volume

The stomach is highly distensible with the ability to change its capacity from approximately 50 ml when empty to 1000 ml when full, with only minimal changes in gastric pressure (Maughan & Murray, 2001). The gastric volume is an important determinant of the rate of gastric emptying. For example, the ingestion of different

volumes of a dilute glucose solution (200, 400, 600, 800, and 1000 ml) was shown to influence the rate of gastric emptying, recorded 15-minutes following ingestion (Costill & Saltin, 1974). The ingestion of 600 ml resulted in a greater rate of emptying in comparison to 400 ml, which emptied faster than 200 ml. However, when volumes above 600 ml were ingested, there was no further benefit regarding the gastric emptying rate. This suggests that there is a limit at which additional fluid ingestion results in no further benefit to gastric emptying. Of course, advising the ingestion of volumes of 600 ml or greater is not practical and it would not be recommended for players prior to training or matches. Studies which have employed a repeated drinking design suggest that the gastric volume and, therefore, the pattern of drinking during exercise have a significant influence on the rate of both carbohydrate and water delivery from any solution (Noakes *et al.*, 1991). Thereby, refilling the stomach at regular intervals ensures that the volume of the stomach is kept high, and faster rates of gastric emptying can be maintained. However, unfortunately, applying this pattern of drinking is not possible during football match play. Instead, carbohydrate intakes can be achieved by ingesting more concentrated carbohydrate beverages (12%), before and at half time, with ad-libitum water intake to allow for individual fluid needs (Funnell *et al.*, 2017; Harper *et al.*, 2017).

Carbohydrate absorption

After leaving the stomach, the chyme enters the duodenum, which is the first part of the small intestine that links the stomach with the jejunum. The duodenum receives bile from the gall bladder and pancreatic secretions, which are important to facilitate the absorption of fats and the digestion of proteins.

The jejunum (approximately 2.5 m in length) is a long, convoluted tube, characterised by strong, rapid, peristaltic contractions that sweep along its length. Most of the absorption of nutrients (carbohydrate, electrolyte, and water) occurs in the jejunum region. Carbohydrates entering the small intestine must first be hydrolysed to its constituent monosaccharides before their absorption and use (Holdsworth & Dawson, 1964). Water is absorbed passively as a result of an osmotic gradient created between the intestinal lumen and the interstitial space by the movement of glucose, sodium (Na⁺), and other nutrients.

The terminal digestion of carbohydrate occurs at or on the surface of the intestinal epithelium (Holmes, 1971). Disaccharides are located on the brush border and microvillous membrane. The brush border contains several disaccharidases which hydrolyse the end products of pancreatic α -amylase digestion. Thus, maltase acts on maltose liberating glucose; sucrase acts on sucrose releasing glucose and fructose, and lactase hydrolyses lactose to glucose and galactose (Holmes, 1971) (see figure 1).



The transport mechanisms involved in the absorption of monosaccharides from the intestinal lumen are located in the brush border of the epithelial cells. The absorption of glucose occurs mainly in conjunction with the active transport of Na⁺. Dietary monosaccharides are transported across the brush-border membrane of enterocytes (intestinal absorptive cells) by the Na⁺/glucose cotransporter SGLT1 (Dyer *et al.*, 2003). Glucose and galactose compete for the same transport. Fructose is absorbed by a separate transport system (Holdsworth & Dawson, 1964). Fructose is transported by a different protein-carrier, GLUT-5 (Kristiansen *et al.*, 1997), which is not Na⁺ dependent and it is less rapidly absorbed than glucose (Fordtran, 1975). The hepatic portal system is a system of blood vessels consisting of hepatic portal veins which carry nutrients absorbed from the intestine to the player's liver for processing.

The final section of the small intestine is the ileum (of approximately 3.6 m long), which provides a reserve of absorptive capacity. The ileum terminates at the ileocecal valve, where the large intestine begins. The large intestine (approximately 1.6 m in length) consists of the cecum, appendix, colon, and anal canal. The colon is the main part consisting of three relatively straight sections: the ascending colon, the transverse colon, and the descending colon—and sigmoid colon that leads to the rectum and, in turn, to the anal canal. The large intestine receives the liquid by-product of digestion and it is the main location of the gut microbiome, which will be covered in later modules. The absorption of most water and electrolytes along its tract forms the solid consistency of faeces. Peristalsis is slower and less propulsive in the large intestine if it is compared to the small intestine. Food can remain in the large intestine for approximately 10 h to several days.

Did you know?

Flavour fatigue refers to players becoming 'bored' with the taste of a drink or food. If this happens, it can make it more difficult to encourage voluntary fluid intake. Being able to provide a variety of flavours reduces the risk of flavour fatigue over a season.

Glycogen

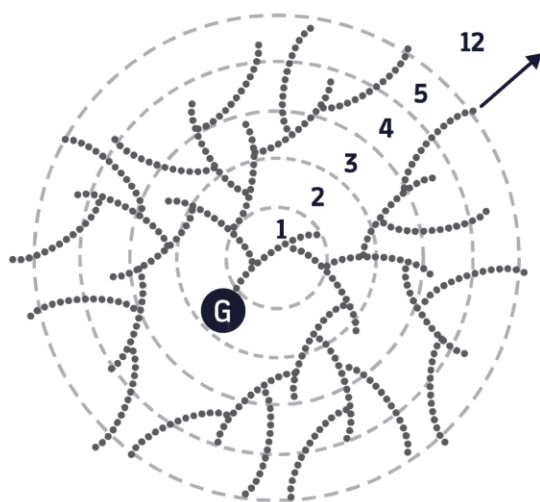
Carbohydrate is available to the working muscles from blood glucose and muscle glycogen. Stores of glycogen are found in the liver (80 – 100 g) and muscles (250-500 g), and there is also a small energy reservoir of glycogen in the brain (3-4 mol/g).

The structure of glycogen granule consists of type A and type B chains. Both chains are uniform in length with a mean value of thirteen glucose residues. The A chains are not branched (1-4 glycosidic bonds), whereas the B chains are branched, each with two branching points (1-6 glycosidic bonds) that create either A or B chains. There are 4 glucose residues between branches and a tail after the second branch in the B chains.



Glycogen phosphorylase can only work on A chains, as the tail of the B chain is too short (~4 glucose residues, the limit of phosphorylase action). As a consequence of the degree of branching ($r=2$), the number of chains on any tier is twice that of the previous one. Therefore, the glycogen molecule is organised into a spherical shape and arranged into concentric tiers, with every A chain in the most external tier. The arrangement of glucose into the glycogen polymer is a very efficient way of amassing large quantities of glucose, without causing a significant change in cell osmolality (Melendez-Hevia *et al.*, 1993). In the liver, glycogen can be formed directly by ingested glucose or through gluconeogenic precursors, such as lactate, alanine, and pyruvate (Katz & McGarry, 1984).

Figure 2. Glycogen structure



Source: adapted from Melendez-Hevia *et al.*, 1993.

Figure 2. The molecule has a spherical shape with 12 concentric tiers in the full molecule (only 5 are shown in the diagram). Glycogenin (G) the protein primer for glycogen synthesis is located at the core of the granule.

Did you know?

Glycogen phosphorylase is the enzyme that breaks down the glycogen molecule into the single sugar (glucose) units.

Key point

Storing carbohydrate as glycogen allows the accumulation of a large quantity of cytoplasmic glucose, without causing a significant change in cell osmolality.

Central recognition

There is emerging evidence of a 'central' response to ingesting carbohydrates. This has been investigated by using functional magnetic resonance imaging (fMRI, a method that can measure the activity of the brain). In one study, participants ingested 300 ml of water (control), others glucose solution, others an aspartame (sweet taste) solution, and others a maltodextrin (non-sweet carbohydrate) solution. It was reported that both sweet taste and energy content are required for a hypothalamic response (Smeets *et al.*, 2005).

In addition, the activation of the hypothalamus was reported to be dose dependent to carbohydrate, *i.e.*, the greater concentration of carbohydrate, the greater the response. Thus, a relationship was observed between the hypothalamic response and changes in the blood insulin concentration (Smeets *et al.*, 2005).

Both glucose (sweet) and maltodextrin (non-sweet) in the mouth have been reported to activate regions in the brain associated with reward. These findings suggest that there may be a class of—so far unidentified—oral receptors that can detect and respond to carbohydrates independently of sweetness (Chambers *et al.*, 2009). Regions of the brain associated with reward are also believed to mediate behavioural responses to rewarding stimuli, such as taste (Rolls, 2007).

Type of carbohydrates

Different types of carbohydrates elicit different physiological responses following ingestion. This is because carbohydrates are digested at different rates, which influences the players' blood glucose concentrations. Carbohydrate foods are commonly classified as either 'simple' or 'complex'. The classification is largely based on the quantity of fibre the carbohydrate food source contains, which influences its digestion and absorption, and, subsequently, its impact on the player's blood glucose concentrations.

The glycaemic index is a method used to rank how carbohydrate foods impact on blood glucose concentrations after eating them (Stevenson *et al.*, 2005). Thus, a more accurate classification of carbohydrates is based on the glycaemic response two hours after the ingestion of a standard amount of food. The reference food is usually glucose or white bread, which has a glycaemic index of 100. Those carbohydrates that result in a slow rise and a low peak in blood glucose concentrations are termed 'low glycaemic' carbohydrates. Those carbohydrates that produce a rapid rise and high peak in blood glucose concentrations are termed 'high glycaemic' carbohydrates. The glycaemic index of carbohydrate can be calculated as follows:

glycaemic index = area under the curve of the test food/areas under the curve for reference food x 100.

The value of high-glycaemic index carbohydrates is between 71 and 100; moderate-glycaemic index foods are between 56 and 70, and low-glycaemic index carbohydrates have a score equal to or less than 55. Examples of high, moderate, and low glycaemic index foods are shown in figure 3.

Figure 3. Examples of high-, moderate- and low-glycaemic index carbohydrate foods

High	Moderate	Low
<ul style="list-style-type: none"> • glucose • sucrose • cane • maple syrup • corn syrup • honey • corn flakes • raisins • white rice • white bread 	<ul style="list-style-type: none"> • whole grain bread • spaghetti (pasta) • corn • oatmeal • orange • grapes 	<ul style="list-style-type: none"> • lentils • yogurt • peanuts • peas • beans • apple • peach • pear • figs • milk

Source: own source.

It is important to note that the glycaemic index of any given food may vary considerably among players. The overall quantity of carbohydrates a player eats is also important. In addition, the principle of glycaemic index is limited, as players will typically ingest ‘foods’ and ‘meals’ that contain a variety of carbohydrate sources as well as other nutrients. It is rare for players to ingest carbohydrates in isolation, with the exception of acutely before and during exercise, which will be discussed in the next section. The foods listed in figure 3 aim to provide a guide. Knowledge of high-glycaemic foods, for example, may be useful when attempting to reduce the number of energy-dense foods in a player’s diet while managing body composition. In general, replacing high-glycaemic index foods with foods with a lower glycaemic index, such as beans, lentils, fruits, and vegetables, improves the satiety of the player, constitutes a good carbohydrate choice, and can help the player manage their body weight. When translating this piece of advice to the player, using more common terms such as ‘simple’ and ‘complex’ and applying them to different foods may be more relatable and may help them make better carbohydrate choices depending on the requirement.

Key point

The energy yield of carbohydrate is 4 kcal/g of carbohydrate.

Carbohydrates ingestion during exercise

Ingesting carbohydrates during exercise has several key effects, which may potentially influence football performance. Ingesting carbohydrate, especially during prolonged (>60 minutes), intense (>60% maximal oxygen uptake) football exercise helps delay the onset of fatigue by the following:

- preserving blood glucose concentrations;
- maintaining the required rate of carbohydrate oxidation;
- reducing liver glycogen breakdown;
- reducing muscle glycogen breakdown.

Research studies have investigated the effect and efficacy of ingesting different types of carbohydrates during exercise. Special techniques are used to determine the quantity of carbohydrates that has been taken up from the blood and used for energy metabolism. This method captures when and how much of the ingested carbohydrate is used, and a comparison between the different types of carbohydrates can be made.

During exercise, the majority of carbohydrate oxidation takes place inside the muscle. When carbohydrate is ingested during exercise and appears in the circulation, it will be used by active muscles (Jeukendrup *et al.*, 1999). Increasing the quantity of carbohydrate ingested during exercise from 1 g/min to 3g/min has been shown to have no influence on the rate at which carbohydrate is used by the body (Jentjens *et al.*, 2003). Instead, ingesting different types of carbohydrates may improve the use of carbohydrate during exercise. The rate of ingested (exogenous) carbohydrate use typically peaks at 60 minutes and beyond following ingestion.

The ingestion of carbohydrates during exercise, including glucose, fructose, galactose, sucrose, maltose, and glucose polymers, have been investigated (see figure 1). In summary, glucose is used by the muscle at a rate of 0.8 g/min. Fructose is oxidised at lower rates than glucose and galactose oxidation rates are half that of glucose (Burelle *et al.*, 2006). These differences are due to the aforementioned absorption of the different carbohydrates and to the fact that fructose and galactose must be delivered to the liver and converted to glucose first, before they can be used for metabolism in the muscle. The disaccharide maltose and glucose polymers are used at the same rate as glucose. This suggests that the digestion of these sources of carbohydrate is not a limiting factor for their use. Interestingly, sucrose (glucose and fructose) ingestion has been shown to result in high rates of carbohydrate use. Less common carbohydrate sources, such as *isomaltulose* and *trehalose*, are oxidised at lower rates. The different types of carbohydrates can, in general, be divided into two categories: (a) fast carbohydrates,



which are those used rapidly during exercise (up to ~60 g/h or 1 g/min); (b) slow carbohydrates, which are those that are oxidised relatively slowly during exercise (up to ~30 g/h or 0.5 g/min). Rapidly oxidised carbohydrates include glucose, maltose, sucrose, maltodextrin, and amylopectin starch. Slower oxidised carbohydrates include fructose, galactose, isomaltulose, trehalose, and amylose (Jentjens & Jeukendrup, 2005).

The use of ingested carbohydrate during football exercise depends upon the speed at which it can be digested and absorbed to enter the blood stream. Thus, the digestion and absorption of carbohydrates is the major limiting factor to their use. With respect to the digestion of the different carbohydrate sources discussed earlier, the ingestion of a combination of carbohydrates that use different intestinal transporters for absorption has been shown to increase carbohydrate delivery and use by the muscle. An increase in carbohydrate oxidation is observed when the transport of glucose in the intestine is saturated (SGLT1) and a different transport system (GLUT-5) is used to transport carbohydrate simultaneously, *i.e.*, glucose and fructose (Jentjens *et al.*, 2004).

Achieving high exogenous rates of carbohydrate may be more relevant to endurance sports (>90 minutes in duration), as it is unlikely that the glucose transporters will become saturated during football with current ingestion recommendations (Unit 2). Nevertheless, the ingestion of multiple transportable carbohydrates (glucose, sucrose/fructose) may be relevant to players, as they have also been shown to increase fluid delivery and reduce the risk of gastrointestinal distress (Baker & Jeukendrup, 2014).

Did you know?

Fibre in a player's diet is resistant to digestion and absorption in the intestine.

Dietary fibre

Dietary fibre is the parts of plants that can be eaten, but are not digested or absorbed in the small intestine. Sufficient fibre in a player's diet is associated with a number of health benefits, including lowering the risk of heart disease, reduced risk of constipation, and softening of stools (making them easier to pass) (Liu *et al.*, 2015; Fu *et al.*, 2022). In general, adult players aged 16 years and older should aim to ingest approximately 30 g of fibre daily.

It is surprising that the only 'official' fibre-related recommendations in the American College of Sports Medicine (ACSM)—as a sports nutrition position statement for athletic performance—are concerned with limiting fibre intake prior to exercise. Although we do not discuss fibre in the UEFA expert statement for Nutrition for football, advice is aligned to ACSM guidelines. Players are recommended to choose easy to consume carbohydrate-

rich sources that are low in fibre/residue to reduce the risk of gastrointestinal complaints during exercise. High fibre foods are discouraged in the pre-match meal, where the delivery of carbohydrate to increase in the body glycogen stores is the priority.

However, it is common for practicing sports nutritionists in football to implement strategies that manipulate the fibre content of the players' diet to achieve individualised goals. These strategies are often based on anecdotal experiences or on the re-application of practices developed in clinical nutrition scenarios (*e.g.*, weight management, gastrointestinal issues). The role of dietary fibre in the players' health will be discussed in later modules. Specifically, we will cover the importance of dietary fibre for the players gut microbial community (intestinal microbiota composition and function and intestinal barrier).

Examples of dietary sources of fibre for the player to consume

- Breakfast cereals (high fibre): porridge oats, oat bran. Sweet potato, potato skin, wholemeal or wholegrain bread, and pasta.
- Pulses as baked beans and hummus.
- Vegetables: broccoli, carrot, peas, frozen mixed vegetables, green beans.
- Fruits: all. Apple, pear, cherries, strawberries, Kiwis, raspberries, blackberries, plums, bananas and oranges.
- Nuts: almonds, hazelnuts, and peanut.

Table 1. Common food sources providing 30 g and 100 g of carbohydrate respectively



~30g	~100g
1 bottle Gatorade (500ml) 29g carbohydrate and 120kcal	Large plate pasta (300g) 100g carbohydrate and 515kcal
1 glass of orange (150ml) and apple juice (150ml) 25g carbohydrate and 115kcal	Large plate rice (300g) 95g carbohydrate and 430kcal
1 glass chocolate milk (300ml) 32g carbohydrate and 220kcal	Large plate couscous (300g) 100g carbohydrate and 545kcal
1 square of flapjack (50g) 30g carbohydrate and 240kcal	2 large plates quinoa (600g) 105g carbohydrate and 700kcal
5 rice cakes (45g) 32g carbohydrate and 160kcal	2 plates of noodles (500g) 105g carbohydrate and 550kcal
1 handful raisins (45g) 30g carbohydrate and 135kcal	2 jacket potatoes (500g) 105g carbohydrate and 500kcal
Handful of dried mango (40g) 28g carbohydrate and 155kcal	1 large sweet potato (350g) 95g carbohydrate and 430kcal
1 medium bowl of porridge with milk (220g) 27g carbohydrate and 250kcal	4 medium bowls of porridge with milk (880g) 108g carbohydrate and 990kcal
Half a bagel (45g) 25g carbohydrate and 120kcal	2 bagels (180g) 95g carbohydrate and 500kcal
2 slices wholemeal bread (75g) 28g carbohydrate and 170kcal	7 slices wholemeal bread (260g) 100g carbohydrate and 600kcal
1.5 medium bananas (225g) 30g carbohydrate and 90kcal	5 medium bananas (750g) 100g carbohydrate and 450kcal
1.5 large oranges (300g) 30g carbohydrate and 150kcal	5 large oranges (1000g) 97g carbohydrate and 520kcal

Source: own source.

Summary

- Carbohydrates are all the sugars and starches in a player's diet.
- Carbohydrates can be classified by the number of monosaccharides (single sugars) they contain and can be broadly categorized as 'simple' or 'complex', depending on their digestion and absorption profile.
- Carbohydrates with a 'fast' digestion and absorption rate are recommended during training and matches.

- Carbohydrate digestion begins in the mouth and is transported into players' body by the small intestine.
- Carbohydrate is stored as glycogen, which constitutes an efficient way to store large quantities of carbohydrate in the body.
- Fibre is a carbohydrate that cannot be absorbed by the body, but which is important for players' general and gastrointestinal health.

Unit 1.2 Carbohydrate and football

The aim of this unit is to build your understanding of the role that carbohydrates play on football performance. A brief historical view of the literature will be provided as background on how we have arrived at the current recommendations. Importantly, this unit will address how carbohydrates influence football performance and the potential mechanisms which underpin the efficacy of carbohydrate feeding for football-specific performance.

Historical perspective

The benefits of carbohydrate ingestion during exercise can be traced back to the early 1900s. Observations made by the Boston marathon in 1925 have become infamous (Gordon *et al.*, 1925). Specifically, it was reported that ingestion of sweets (sugar/confectionery) by runners during the run prevented hypoglycaemia. Importantly, ingesting sweets also improved race times in comparison to when no sweets were consumed.

For intermittent sports, some 50 years later in the 1970s, studies were completed at the University of Florida, United States. In 1971, Dr. Cade and colleagues reported the effects of exercise on blood glucose changes in four players of the University of American football team during a vigorous two-hour training session, with no food or fluid intake (Cade *et al.*, 1971). The American football players' blood glucose concentration decreased progressively throughout the practice. This observation was followed by a study in 1972 to determine whether carbohydrate ingestion could prevent the disturbances in blood glucose concentration (Cade *et al.*, 1972). Cade and colleagues found that performance during a standardized walk-run test (7-mile course) was significantly improved when 1 L of a 3% glucose-electrolyte solution was consumed compared with when the players drank the same volume of water. Blood glucose concentration decreased during the water trials (by 1.3 mmol/L), whereas it increased (by 1.0 mmol/L) when the players were drinking the 3% glucose-electrolyte solution.

At a similar time, the importance of muscle glycogen to football performance was also being investigated in Europe. By using the muscle biopsy technique, Agnevik (1970) reported that male football players' glycogen stores were nearly empty of muscle glycogen after a 90-minute football match (Agnevik, 1970). The greatest rate of glycogen depletion occurred in the first half of the match. In follow up studies, muscle samples were biopsied from the quadriceps femoris of recreational players at the beginning, halftime, and at end of a football match (Saltin, 1972).

Professor Bengt Saltin (1972) reported that muscle glycogen concentrations were significantly lower on completion of the match (pre: 96 mmol/kg wet weight (w.w.); halftime: 32 mmol/kg w.w.; end: 9 mmol/kg w.w.). Significantly, those players who began the match with low muscle glycogen (45 mmol/kg w.w.) had almost depleted stores by halftime. This was the first study to report the performance implication associated with muscle glycogen concentrations. Specifically, players who began the match with high muscle glycogen covered a greater distance and spent more of the total time completing high-intensity running compared with those players who began the game with low muscle glycogen (24% vs. 15% of the match time in high vs. low muscle glycogen players, respectively). These findings corresponded with studies analysing the activity profile of professional football players in the UK. In these studies, professor Thomas Reilly reported that players covered less distance in the second half compared with the first half of a match. Since these seminal carbohydrate studies, there has been continued research exploring carbohydrate ingestion and intermittent sports performance (Baker *et al.*, 2015). Key to our understanding on carbohydrate ingestion for sports performance has been the contribution of professor Clyde Williams OBE and his research team at Loughborough University in the UK.

Did you know?

Professor Clyde Williams is a pioneer of applied sports nutrition and the professionalism of the profession. Professor Williams was the founding chairman of the British Association of Sports Sciences (now British Association of Sport and Exercise Sciences [BASES]) for which he was awarded an Honorary Fellowship, and became a founding fellow of the European College of Sports Science. He remains an Emeritus Professor of Sports Science, at Loughborough University in the UK.

Match preparation

Carbohydrate is a key macronutrient for players during match preparations. On the day before to the match (match day -1), players are advised to ingest between 6-8 g of carbohydrate/kg body mass (BM) to increase muscle glycogen stores. To date, it has not



been possible to establish the glycogen use of male players during an elite match. Data from research studies where football activity has been simulated or 'friendly' games played demonstrates that approximately 50% of muscle fibres are classified as empty or partially empty after match play (Krustrup *et al.*, 2006). In professional women players, 80% of type 1 and 69% of type 2 muscle fibres have been found to be glycogen depleted after competitive matches, which likely contributes to declines in repeated sprint performance (Course 4) (Krustrup *et al.*, 2022).

When there are multiple matches in a week, for example, domestic fixtures, European competition, international games, carbohydrate intake should be maintained or perhaps even increased up to 10 g/kg BM for the 48-72 hours between games. This elevated carbohydrate intake has been shown to promote adequate glycogen storage and maintain running capacity between games (Nicholas *et al.*, 1997). Studies on professional players suggest that carbohydrate consumption is less than recommendations and it is in fact closer to an intake approximately 4 g/kg body mass (Anderson *et al.*, 2017). To this end, practitioners should focus on the availability of rich carbohydrate foods (Unit 1), when carbohydrate intake needs to be elevated. The intake of carbohydrate should be prioritised at the expense of fat intake (and possibly protein intake) to ensure adequate glycogen restoration. See figure 1.

Table 2: A guide to convert daily carbohydrate consumption requirements based on body mass and training/match demands. BM = body mass

BODY MASS		RECOMMENDED CARBOHYDRATE INTAKE (G) PER DAY BASED ON BODY MASS					
kg	lb	3 g/kg BM/d	4 g/kg BM/d	5 g/kg BM/d	6 g/kg BM/d	7 g/kg BM/d	8 g/kg BM/d
40	88	120	160	200	240	280	320
45	99	135	180	225	270	315	360
50	110	150	200	250	300	350	400
55	121	165	220	275	330	385	440
60	132	180	240	300	360	420	480
65	143	195	260	325	390	455	520
70	154	210	280	350	420	490	560
75	165	225	300	375	450	525	600
80	176	240	320	400	480	560	640
85	187	255	340	425	510	595	680
90	198	270	360	450	540	630	720

Source: own source.

Pre-match carbohydrate



On match day, the ingestion of carbohydrates before, during, and after exercise is one of the most important considerations. Within the guideline of 6-8 g/kg body mass carbohydrate (table 1), it is recommended that players consume a carbohydrate-rich meal (2-3 g/kg body mass) 3-4 hours before kick-off in order for players to begin the match with adequate glycogen stores (Williams, 1993).

The pre-match meal is important to 'top-up' liver glycogen stores, which can be reduced by about 50% following an overnight fast. This is particularly important for players when the kick-off time is scheduled for a lunchtime or early kick-off. In these circumstances, the intake of carbohydrates on the day prior to the match also takes on greater importance.

The benefits of pre-match meals may also extend to players technical abilities. Briggs and colleagues showed that Academy football players dribbling speed was enhanced when a larger breakfast (500 kcal versus 250 kcal, with 60% carbohydrate) was ingested 135 minutes before a match (Briggs *et al.*, 2017). Indeed, data from many studies suggest that higher carbohydrate intakes before as well as during a match can delay fatigue (Holway & Spriet, 2011) and enhance the capacity for intermittent high-intensity exercise (Russell & Kingsley, 2014).

Pre-match meal timing is also a significant aspect. Although focused on endurance type cycling exercise, the omission of a carbohydrate-rich breakfast followed by consuming an *ad-libitum* lunch impairs evening exercise performance. This result appears to be due to breakfast omission *per se*, rather than lower carbohydrate intake. This is because when studies have matched overall energy (1457 ± 134 kcal) and macronutrient (carbohydrate: $81.5 \pm 0.4\%$, fat: $5.8 \pm 0.1\%$, protein: $12.7 \pm 0.3\%$) intake over the day performance is improved when breakfast is included as a meal time occasion (Metcalf *et al.*, 2021). Therefore, even for evening kick-offs, breakfast is an important meal time occasion to plan for on match day.

Table 3. Recommended carbohydrate intake in the pre- and post-match periods based on body mass

BODY MASS		Pre-match Fuelling		
		Re-Fuelling*		
		RECOMMENDED CARBOHYDRATE INTAKE (G) IN THE PRE- AND POST-MATCH PERIODS BASED ON BODY MASS		
kg	lb	1 g/kg BM	2 g/kg BM	3 g/kg BM
40	88	40	80	120
45	99	45	90	135
50	110	50	100	150
55	121	55	110	165
60	132	60	120	180
65	143	65	130	195
70	154	70	140	210
75	165	75	150	225
80	176	80	160	240
85	187	85	170	255
90	198	90	180	270

Source: own source.

Table 2. A guide to the quantity of carbohydrate to consume in the pre- and post-match periods based on player body mass. Players should consume 1-3g carbohydrate per kg body mass 3-4 hours before kick-off. Re-fuelling recommendations are 1 g carbohydrate per kg body mass per hour for 4 hours. BM = body mass.

Did you know?

Professor Bengt Saltin was a world leading human physiologist. As a medical doctor, he devoted his life to researching the effects of physical exercise on health and performance. His studies continue to inspire scientists to study sports nutrition and the nature of human physiology (3 June 1935 — 12 September 2014) (Calbet *et al.*, n. d.).

Carbohydrate during match play

The available research shows performance benefits in protocols simulating football matches when carbohydrate is consumed during exercise at rates of ~30–60 g/h (Baker *et al.*, 2015). In general, it is recommended that 30 g of carbohydrate be consumed post warm-up and at half time to meet these guidelines (Funnell *et al.*, 2017; Harper *et al.*, 2017).

Current practices of elite players have been reported to be in the lower end of recommended carbohydrate intakes. For example, one study reported that players in the English Premier League reported carbohydrate intakes of 32 g per hour during a match



(Anderson *et al.*, 2017). This may be attributed to match scheduled breaks in play, which lends ingestion opportunities to the warm-up and half time. Low carbohydrate intake may also be due to the players fear or actual experience of gastrointestinal problems during matches. This may be alleviated through practicing carbohydrate intake on training days. Stoppages during the match may provide valuable opportunities for players to ingest carbohydrates and fluids. In these situations, the ingestion of well-formulated sports drinks is advised to optimise the delivery of fluid and carbohydrate to the player.

Despite the prevalence of extra time during major international football tournaments, there has been little research in this area of nutrition. It is intuitive that carbohydrate intake may require special attention in matches where extra time (2 x 15 minutes) is played. Studies that have shown improved endurance capacity (running time to fatigue) with carbohydrate ingestion following 90 minutes of simulated match play are relevant to extra time. However, there has been only one study to directly investigate the impact of carbohydrates on extra time performance (Harper *et al.*, 2016). In this study, carbohydrate-electrolyte gel ingestion raised blood glucose concentrations and improved dribbling performance during the extra-time period of simulated football match play.

How important extra time is?

Prevalence of extra time and penalties in three major competitions since 2010:

European Championships

- 2012 Euros: 2 games went to extra time (2/2 to penalties).
- 2016 Euros: 5 games went to extra time (including the final).

World Cup

- 2014 Brazil World Cup: 8 games went to extra time (including the final).
- 2018 Russia World Cup: 5 games went to extra time (4/5 to penalties).
- 2022 Qatar World cup: 5 games went to extra time (including the final).

Champions League

- Champions League final 2016: extra time and penalties.
- Champions League final 2014: extra time.
- Champions League Final 2012: extra time and penalties.
- Champions league semi-final 2024: extra time and penalties.

Did you know?

Hypoglycaemia refers to low levels of blood glucose concentrations. Blood glucose concentrations of < 3 mmol/L.

Carbohydrate and football skill

In football, players perform a variety of sport specific skills usually during or immediately after running, often at sprint speed. The quality of the skill performed is likely influenced by the volume of work done in attacking and defending over the duration of the match. Even the most highly skilful players succumb to the impact of fatigue both physical and mental, that may result in underperforming skills at key moments in a match (Rollo & Williams, 2023).

The skill proficiency of the player and a number of specific technical actions reduces as a match duration progresses (Rampinini *et al.*, 2009).

Adopting carbohydrate ingestion strategies will delay a rapid loss of the body's glycogen stores and it will help maintain players work-rate during matches. The question is whether it also helps prevent a loss of skill. A simple answer would be that if we can delay fatigue, it will intuitively reduce the risk of skill execution being impaired.

As such, carbohydrate ingestion during intermittent exercise is associated with improved shooting performance (Currell *et al.*, 2009; Russell & Kingsley, 2014), dribbling speed (Harper *et al.*, 2017), and passing (Ali & Williams, 2009), although the effects on sprinting, jumping, change of direction speed, and cognition are less consistent (Baker *et al.*, 2015). It is likely that inconsistencies in research findings are the result of small sample sizes, variability in carbohydrate intake protocols (*e.g.*, amounts consumed) and poor measurement precision. It is important to note that 'skill' *per se* is extremely difficult to assess. This is because of the typical day-to-day variation in a player's ability to apply a skill. In addition, the execution (accuracy/speed) of the skill needs to be quantified. Match-specific conditions, such as the crowd, opposing player pressure, speed to play, are almost impossible to replicate in laboratory conditions.

In a study investigating the impact of carbohydrate ingestion on skill, tests were undertaken on a player's dominant and non-dominant limbs. Using a 90 min soccer specific protocol, higher passing scores were achieved by both dominant and non-dominant feet following the ingestion of carbohydrate (30 g, before and at half time, compared with placebo whilst drinking water ad-libitum) (Rodriguez-Giustiniani *et al.*, 2019). This effect was evident from 60 min onwards. Importantly, improved performance was attained without loss of passing speed, which was better maintained in the non-



dominant foot with carbohydrate ingestion. This observation is of interest because it is consistent with other studies in sports such as tennis, where non-dominant or weaker sides (backhand) shots respond positively to carbohydrate ingestion, especially when fatigued (McRae *et al.*, 2012).

The assessment of complex skilled actions on the non-dominant side may require greater activation of the central nervous system (CNS) and, therefore, it may be more susceptible to fatigue. Thus, the performance of skill on the player's non-dominant sides appears to have a greater sensitivity to carbohydrate ingestion even though the 'non-dominant' side is likely to be inferior in performing skills (Rollo & Williams, 2023). This skill execution is an interesting metric that the nutrition can observe in training and matches. It is also something which the sports nutritionist can partner with sports medical team if identified in any specific players.

Recovery from match play

After a competitive match, the aggressiveness of the nutrition recovery strategy will depend on when the player is next required to train or perform. Nevertheless, the general principle is to speed up the time required for the player to fully recover (Nedelec *et al.*, 2012). This is particularly important during periods of fixture congestion (2-3 matches per week) and pre-season. To speed their recovery, players should rapidly replenish their carbohydrate stores. Post-match meals should target a carbohydrate intake of ~1 g/kg/h in the first 2 hours after exercise and continue for 4 hours (Burke *et al.*, 1996). This recommendation is based on the observation that the rate of muscle glycogen restoration can be increased when carbohydrate is fed immediately after exercise in comparison to when carbohydrate feedings are delayed two hours post exercise (Ivy, 1998). The carbohydrate intakes can be met by providing carbohydrate beverages and snacks in the changing rooms followed by post-match meals. The post-match meal can be provided whilst travelling and/or upon returning home (see table 3).

When assessed 24 hours post exercise, the timing of carbohydrate feedings has little impact on glycogen concentrations, as long as a sufficient carbohydrate has been ingested (Parkin *et al.*, 1997). Nevertheless, football activity involves a significant eccentric component. Eccentric muscle contractions are associated with muscle damage, which may interrupt the uptake of glucose into the muscle. Consequently, muscle glycogen resynthesis may be impaired following football matches or training with a large eccentric component (Asp *et al.*, 1995). To this end, it is important to combine carbohydrate with other nutrition recovery strategies to speed the muscle remodelling and glycogen resynthesis (module 2).

Did you know?



The autonomic nervous system regulates actions that occur in the player's body without their voluntary control, for example, heart rate or blood pressure. It consists of both the sympathetic and parasympathetic nervous systems.

The sympathetic nervous system prepares the player's body for stress (football competition), also known as the fight or flight response; this acts, for example, increasing heart rate and increasing blood flow to the muscles.

The parasympathetic nervous system works in opposition and helps maintain the player's normal bodily functions when stimulated, such as reducing the heart rate and increase digestive functions.

Training

Carbohydrate requirements for training were discussed in course 1. Please see table 3 for a summary of different training occasions and corresponding recommended carbohydrate intakes.

Table 4. Dietary carbohydrate intake modification in response to changing training and match requirements

Training occasion	Training objectives	Desired training adaptations	Typical daily external training load parameters (quantified during pitch-based training: GPS; HSR, denotes high speed running => 19,8 km.h ⁻¹)	Suggested daily CHO range	Comments
Pre-season training	<ul style="list-style-type: none"> • Player health (avoid illness/injury) • Improve player physical / mental / tactical qualities • Prepare players for a full playing season 	<ul style="list-style-type: none"> • Increase aerobic and anaerobic fitness • Increase/maximise strength, speed, power for performance and injury prevention • Increase lean mass / reduce fat mass 	Duration (min): 60-180 Total distance (km): 3-12 HSR (m): >400	4-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range accommodates likely variations in training in loads as well as individual training goals (e.g. manipulation of body composition to accommodate weight loss and fat loss or weight gain and lean mass gain)
In-season training (1 game per week)	<ul style="list-style-type: none"> • Maintain / improve player physical qualities • Player health (avoid injury / illness) 	<ul style="list-style-type: none"> • To maintain aerobic and anaerobic fitness, strength and lean mass 	Duration (min): 45-90 Total distance (km): 2-7 HSR (m): >400	3-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range accommodates likely variations in loads across the micro-cycle (e.g. low load days and MD-1 CHO loading protocols) as well as individual training goals
In-season training (congested fixture periods)	<ul style="list-style-type: none"> • To avoid injury and illness • To accelerate recovery 	<ul style="list-style-type: none"> • Restore muscle function as quickly as possible • Promote glycogen resynthesis • Fluid replacement: rehydration • Alleviate mental fatigue 	Duration (min): <60 Total distance (km): <3 HSR (m): <50	6-8 g.kg ⁻¹ body mass	Carbohydrate ingestion range is to accommodate the requirement to replenish muscle glycogen stores in the 48-72 h period between games

Source: adapted from UEFA consensus document, Collins et al. 2021.

Mechanisms by which carbohydrate impacts football performance

Carbohydrate ingestion can improve football physical and technical performance by providing substrate for energy metabolism in skeletal muscle tissue. However,



carbohydrate is also the main substrate for energy metabolism in the brain and central nervous system. As such, we coined the phrase ‘the primary, secondary, and tertiary effects’ of carbohydrate ingestion on performance (Rollo *et al.*, 2020). To summarise, ingested carbohydrate is primarily detected by receptors in the oral cavity and on the tongue. Its presence is relayed to reward and other centres in the brain resulting in a series of actions that include release of insulin. Secondary, after digestion, glucose is transported across the intestine into the systemic circulation in association with the active transport of Na⁺. Uptake of glucose in the GI tract seems to be limited by its intestinal uptake via SGLT-1. As fructose is transported over the intestinal membrane via a different transporter protein, so that the combined ingestion of glucose and fructose can further increase the capacity to absorb exogenous carbohydrate. Consequently, combining the ingestion of fructose and glucose can augment intestinal carbohydrate uptake, increase post-prandial glucose availability, and increase exogenous carbohydrate oxidation rates by 40-50%. The ‘tertiary’ effects of carbohydrate ingestion include the hepatic glucose output, which is distributed to both the brain and skeletal muscles so as to prevent hypoglycaemia and improve player performance (Rollo *et al.*, 2020).

Metabolic effects of carbohydrate

Fundamentally, the deterioration of running and skill performance during football is a consequence of fatigue. Due to the physiological demands of football fatigue manifests at different times during training and matches and can be a consequence of distinctly different mechanisms. For example, players experience temporary fatigue following the most intense periods throughout a game and more permanent fatigue in the final phases of a game (Baker *et al.*, 2015).

The precise mechanisms underpinning transient fatigue are beyond the scope of this module but are unlikely to be influenced by carbohydrate provision as long as glycogen concentrations remain above a certain critical level (~200 mmol/kg dry weight (d.w) in active muscle (Rollo & Williams, 2023). It is well established that carbohydrate and fat are the two primary fuel sources oxidised 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 absolute and relative contribution from carbohydrate as exercise intensity increases above 60% V_O2max (Cermak & van Loon, 2013). Muscle glycogen provides a rapidly available substrate for energy production when completing high intensity efforts during intermittent activity, as covered in Course 1 (Williams & Rollo, 2015).

For example, in a single 6-sec sprint muscle glycogen contributes ~50% to adenosine triphosphate (ATP) turnover within the muscle (Gaitanos *et al.*, 1993). Thus, the consequence of repeated sprint activity is a net reduction in muscle glycogen



concentrations (Bendiksen *et al.*, 2012). Although glycogen is depleted in type I and II muscle fibre types, it may be the specific depletion of glycogen in type II muscle fibres that results in the significant loss in power output during repetitive sprints. It may be that the decrease in muscle glycogen below a critical level in response to variable intensity running contributes to the more permanent fatigue experienced towards the end of a game (Mohr *et al.*, 2005). Furthermore, the impact of low muscle glycogen is likely to have a greater consequence in football, where the endogenous store of glycogen is insufficient to meet the energy demands over the duration of the exercise (*e.g.*, extra time) (Baker *et al.*, 2015).

In one study (employing the Loughborough intermittent shuttle running test [LIST], the protocol mimicking the demands of football), muscle biopsy analysis revealed a significant reduction in muscle glycogen concentration in type I and II muscle fibres, from before to after exercise (Nicholas *et al.*, 1999). However, muscle glycogen concentrations were 22% higher when players ingested a 6.9% carbohydrate solution throughout exercise compared with placebo. The elevated muscle glycogen availability is a viable mechanism to explain why players consuming carbohydrate are able to sustain high-intensity running in the second half of live football matches. For example, the performances of ten football players were video-recorded on two separate occasions: when players drank either 400 mL of a concentrated carbohydrate solution (16% maltodextrin) or placebo before and during halftime of the match. The players who drank the carbohydrate solution ran ~40% greater distance during the second half of the game, in comparison with when the placebo beverage was consumed (Kirkendall *et al.*, 1988; Baker *et al.*, 2015).

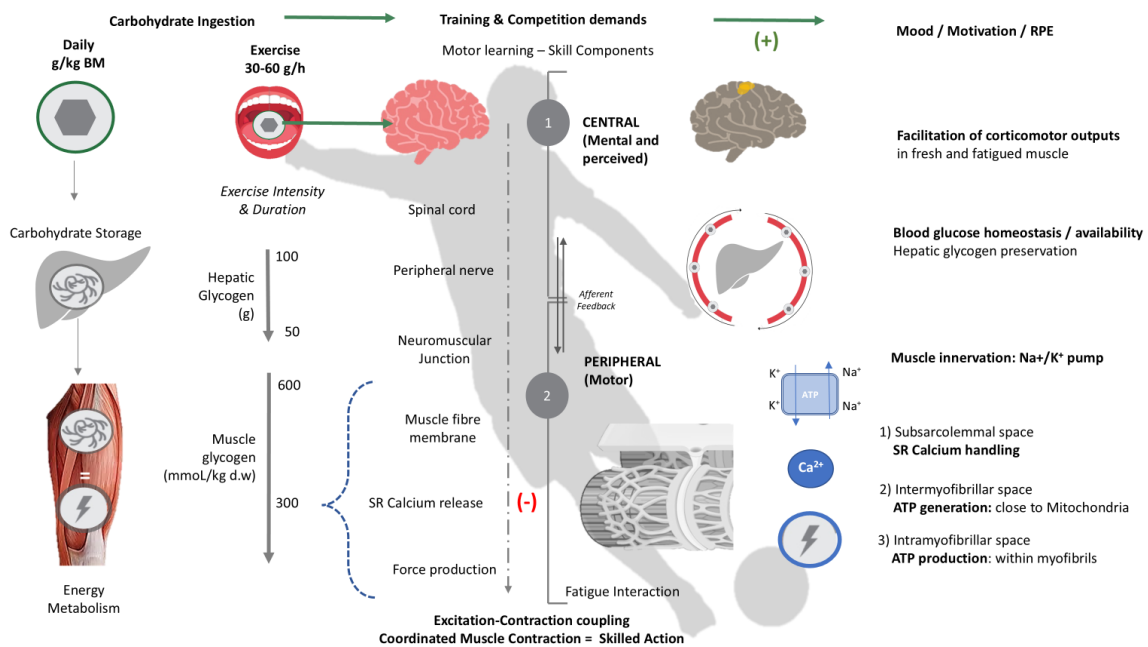
An important consideration when interpreting performance data during any team sport is the high variability observed between games, as the tactical formation and level of competition have been reported to influence the distance a player covers at high speed. Thus, although an interesting measure, assessing the impact that carbohydrate ingestion has on team sport performance in live matches is challenging due to the complex interaction between physical and technical components (Rollo, 2019).

A study using the Copenhagen football test (CST) obtained frequent and rapid measurements of muscle and blood metabolites allowing insight regarding the anaerobic energy turnover and rates of muscle glycogen use in various phases of a 90-min simulated football match (Bendiksen *et al.*, 2012). Both type I and type II muscle fibres exhibited significant glycogen depletion, with ~80% of fibres being depleted or almost depleted (<200 mmol/kg d.w) of glycogen after 90 minutes of intermittent activity. Muscle glycogen concentrations <~200 mmol/kg d.w have been shown to significantly decrease the glycolytic rate. In addition, the depletion of muscle glycogen in sub-cellular glycogen compartments (*i.e.*, sarcoplasmic reticulum) results in concomitant reductions in muscle



calcium handling. A reduced rate of sarcoplasmic reticulum vesicle calcium release has been reported to reduce peak power output (Gejl *et al.*, 2014). Thus, low muscle glycogen influences the flux of calcium and impairs the contractile property of the muscle (Rollo & Williams, 2023). Figure 4, aims to summarise the impact that carbohydrate availability has on the electro-chemical chain of events between the brain and force generation in the skeletal muscles.

Figure 4. The electro-chemical chain of events between the brain and skeletal muscles, and how carbohydrate ingestion may impact skill performance



Source: Rollo & Williams, 2023, p. 11.

Figure 4. Translating thoughts into skilled actions. The electro-chemical chain of events between the brain and skeletal muscles, that carbohydrate ingestion may impact skill performance. BM = body mass; SR = sarcoplasmic reticulum; Ca⁺ = calcium; Na⁺/K⁺ = sodium; potassium pump; ATP = adenosine triphosphate; + = positive influence upon, - = negative influence upon. Mood; motivation; RPE; facilitation of corticomotor outputs; blood glucose availability; hepatic glycogen preservation; muscle innervation: SR calcium handling, ATP generation. Redrawn with permission (Rollo & Williams, 2023).

Did you know?

Sarcoplasmic reticulum is a structure found within muscle cells which stores and releases calcium in the muscle required for muscle contractions.



The rate of muscle glycogen use has been found to decrease from the first to the second half of a simulated football match. Specifically, in a study employing the Copenhagen football test, the rate of muscle glycogen use was reported to be the highest during the warm-up and the first 15 min of simulated play. By comparison, muscle glycogen use was significantly lower from 15 to 60 minutes and lower still from 60 to 90 minutes (Bendiksen *et al.*, 2012).

In a study using the LIST protocol, participants ingested either a 6.4% carbohydrate-electrolyte solution (~90 g/h) or a placebo immediately before and at 15-min intervals during exercise. A similar rate of muscle glycogen use from before exercise to 90 minutes was reported in the carbohydrate and placebo trials (Foskett *et al.*, 2008). In this study, participants continued to complete blocks of the LIST after 90 minutes to volitional fatigue. All participants ran longer during the carbohydrate trial (158.0 ± 28.4 minutes) compared with the placebo trial (131.0 ± 19.7 minutes), representing a 21% increase in intermittent running capacity. Fatigue occurred at similar muscle glycogen concentrations in both trials (~200 mmol/kg d.w). Concentrations of plasma glucose and serum insulin were higher in the carbohydrate trial than the placebo trial at the point of fatigue, suggesting a role of greater glucose availability in the superior performance.

The role of blood glucose

The metabolic response to carbohydrate ingestion differs depending whether the player is at rest or exercising. At rest, the response to elevated blood glucose is an upregulation in the synthesis and secretion of insulin within the pancreas (beta cells of the islets of Langerhans). Insulin causes decreased lipolysis and increased glucose uptake in liver, skeletal muscle, and fat cells.

A key role of liver glycogen is the regulation of blood glucose concentration (euglycemia: 4.0–5.5 mmol/L). At the onset of exercise, muscular contraction causes an increased uptake of glucose from the blood. In opposition to the effect of insulin, liver glycogenolysis is activated by the actions of glucagon and epinephrine. Russell *et al.* (2014) reported that the insulin response to carbohydrate ingestion during the warm-up period prior to team sport activity is inhibited by the actions of epinephrine, which accounts for the elevated blood glucose concentrations typically observed during this stage of exercise. It has long been established that, as exercise duration increases, blood glucose has an increasing contribution to carbohydrate oxidation in the muscle (Coyle *et al.*, 1986; Russell *et al.*, 2014). Blood glucose concentration can increase in response to intermittent sport activity due to an increase in circulating catecholamines (Bangsbo, 1994).

Although glucagon is reported to be relatively unchanged during a match, concentrations of epinephrine and norepinephrine increase through the stimulation of the sympathetic



nervous system. Epinephrine stimulates glycogenolysis in the liver, which results in an increase in blood glucose concentration above resting values (Bangsbo, 1994). Although transient decreases in blood glucose concentration have been reported following half time of a match (Russell *et al.*, 2014), hypoglycaemia is relatively rare in players during football specific exercise lasting 90 minutes in fed individuals (Ekblom, 1986), suggesting that liver glycogen is sufficient to maintain or even increase blood glucose concentration during a match (Krustrup *et al.*, 2006).

Nevertheless, players are advised to ingest carbohydrate during exercise for the benefits to preserving endogenous glycogen and ability to maintain high intensity running and skill performance late in exercise (Williams & Rollo, 2015). An effect of ingesting carbohydrate-electrolyte beverages during intermittent exercise is an increase in blood glucose concentrations during exercise, compared with the ingestion of non-caloric beverages. Although mechanisms remain unclear, authors have suggested that decision-making and successful skill execution during a match may be influenced by blood glucose concentrations. Elevated blood glucose has been associated with an overall improvement in skill performance in football (Russell & Kingsley, 2014; Baker *et al.*, 2015).

Bandelow *et al.* (2010) showed that high plasma glucose concentration from sports drink ingestion during a football match was related to faster response speeds during several cognitive/motor skill tests, including fine motor skill, complex visual discrimination, working memory, following a 90-minute match (Bandelow *et al.*, 2010). However, it is important to note that, in this study, the faster response speed in working memory came at the expense of reduced accuracy, so this may have simply been an artifact of a speed/accuracy 'trade off'.

Blood glucose concentration may influence skill performance. This is because the brain and central nervous system are almost entirely dependent on a continuous supply of glucose from the circulation for optimal functioning (Duelli & Kuschinsky, 2001). Elevations in blood glucose have been reported to increase the supply of glucose to the brain and preserve the integrity of the central nervous system. Furthermore, elevated blood glucose concentrations have also been associated with muscle glycogen sparing (Tsintzas *et al.*, 1995), improved neuromuscular function (Nybo *et al.*, 2009), and reduced central fatigue (Nybo, 2003).

Both a 9.6% carbohydrate solution (plus carbohydrate gel, 142 g carbohydrate/h) and a 5.6% carbohydrate solution (plus placebo gel, 54 g carbohydrate/h), before and at half time, increased blood glucose concentrations compared with the ingestion of a placebo during a protocol, which simulates match play (Kingsley *et al.*, 2014). Mean sprint speed was consistently faster in both the carbohydrate trials (9.6% solution: 5.73m/s; 5.6% solution: 5.66m/s) in comparison with placebo (5.58 m/s), from the start to end of 90



minutes. It is important to note that it is not possible to distinguish if the improved performance was due to a dose dependent effect of carbohydrate ingestion on blood glucose concentration, as the participants also ingested caffeine (6 mg/kg body mass) with the 9.6% carbohydrate solution. A study by the same research group investigated the impact of carbohydrate (0.7 g/kg body mass) or placebo ingestion on physical and skill performance in the extra time-period of a simulated football protocol. In this study, carbohydrate was provided in the form of glucose and maltodextrin gels before exercise, half time, and at 90 minutes. The carbohydrate trial increased blood glucose concentrations and it was associated with improved dribbling precision in the extra time period (90–120 min). However, the elevated blood glucose was not able to attenuate the reduction in sprinting and jumping performance observed in this time (Harper *et al.*, 2016).

When carbohydrate stores are severely reduced during the latter stages of prolonged exercise, the threat to brain metabolism may be prevented by discontinuing exercise (Foskett *et al.*, 2008). It is likely that during exhaustive, high-intensity, and intermittent exercise, the performance decreases, and ultimately volitional fatigue is a multifaceted consequence of peripheral as well as central mechanisms. Nybo *et al.* (2023) demonstrated that, when endurance-trained cyclists developed hypoglycaemia, neuromuscular performance (sustained maximal voluntary contraction) was impaired. The lower force production was reported to be a consequence of central fatigue (*i.e.*, a diminished activation drive from the central nervous system) (Nybo 2003). When glucose was fed to cyclists to preserve blood glucose concentrations throughout exercise, neuromuscular performance was maintained. The mechanism underlying the hypoglycaemia-induced central fatigue has been speculated to be directly related to a reduced delivery of glucose as a substrate to the brain.

With regard to intermittent sports, large regions of the brain, such as the motor cortex, will be activated, as well as regions involved in cardiorespiratory regulation. Endothelial glucose transport may become rate limiting for the cerebral metabolic rate of glucose when the concentrations of arterial glucose fall to hypoglycaemic levels (Nybo, 2003). Interestingly, transient changes in blood glucose concentrations have been reported during intermittent high-intensity exercise. Specifically, elevated blood glucose concentrations observed during the first half of football-specific exercise are negated in the early stages of the second half, when replicating carbohydrate ingestion and passive half-time practices typical of football.

This observation is of relevance because physical performance has been reported to be reduced in the early stages of the second half compared with the opening stages of a match (Mohr *et al.*, 2005). Russell *et al.* (2014) reported that blood glucose values recorded at the beginning of the half time period dropped 30% by the beginning of the second half period (Russell *et al.*, 2014). In this and other studies which have observed a transient fall



in blood glucose over the half time period in response to carbohydrate feedings, blood glucose concentrations are typically similar to those observed in the placebo trials. Importantly, consistent with reports from endurance exercise the transient drop in blood glucose following half time has not been associated with decrements in football performance (Jeukendrup & Killer, 2010; Baker *et al.*, 2015). In general, elevated blood glucose is associated with superior skill performance, whilst the maintenance of blood glucose concentrations would improve skill and running performance under circumstances of fatigue and/or hypoglycaemia.

Non-metabolic effects of carbohydrates

In addition to providing the muscle with substrate, carbohydrate ingested during exercise may exert a 'non-metabolic' central effect. Studies in running and cycling have reported a benefit of routinely mouth-rinsing and expectorating a carbohydrate solution on high intensity endurance performance lasting 30–70 min (Rollo *et al.*, 2011). Thus, the ergogenic effect of carbohydrate ingestion when the exercise is of high intensity (>75% $\dot{V}O_{2max}$) and relatively short duration may be mediated via the activation of brain pathways associated with reward and motivation, in response to carbohydrate recognition in the mouth (Rollo & Williams, 2011).

To date, the benefits of mouth-rinsing carbohydrate on repeated sprint (football) performance remain unclear. Dorling & Earnest (2013) found no effect of mouth rinsing a 6.4 % maltodextrin solution on the average or fastest time to complete 3 repeated sprint ability tests during the LIST protocol (Dorling & Earnest, 2013). However, this performance measure during the LIST protocol, in which the subjects were not able to self-pace, may not have been sufficiently sensitive to detect a potential influence of carbohydrate mouth rinse. By contrast, we used a validated self-selected pacing LIST protocol (Ali *et al.*, 2014). In this study, mouth rinsing a 10% maltodextrin solution was associated with increased self-selected jogging speed and also an 86% likelihood of benefiting 15-meter sprint performance during the final stages (75–90 minutes) of exercise, in comparison with mouth rinsing a placebo (Rollo *et al.*, 2015).

Whether mouth rinsing carbohydrate is sufficient to improve skill performance is an interesting question. Although specific research examining the effect of carbohydrate mouth rinse on skill performance is currently lacking, the relevance of the results would be questionable due to the aforementioned benefits of carbohydrate ingestion on endogenous glycogen and blood glucose. Nevertheless, practically the use of mouth-rinsing carbohydrate during match-play could potentially be advantageous for those players seeking to enhance performance but carbohydrate consumption is limited by gastrointestinal concerns (Rollo *et al.*, 2015). Finally, there is no evidence of a dose-



response performance effect to increasing the concentration of the carbohydrate beverage rinsed in the mouth (James *et al.*, 2017).

In summary, the mechanisms by which carbohydrate ingestion before and during football are complex. The importance of carbohydrate availability for football is evident by studies which have reported severe reduction in endogenous stores of carbohydrate during exercise. The associated fatigue observed with low muscle glycogen translates directly to reduced performance, which may manifest in less high intensity running and reduced skill. Carbohydrate ingestion prior to exercise blunts the hepatic release of glucose and thus preserves the limited endogenous glycogen stores. The magnitude of the impact that carbohydrate ingestion has on football performance is likely to be dependent on the carbohydrate status of the player; that is, carbohydrate ingestion has the greatest impact on performance under circumstances eliciting permanent fatigue and/or hypoglycaemia. When ingesting carbohydrate-electrolyte beverages during exercise, players may gain an 'additional' benefit by simply mouth-rinsing the solution prior to ingestion (Rollo *et al.*, 2011; Rollo *et al.*, 2020).

Practical considerations

It is important to note that, in general, it is not difficult to encourage players to ingest enough carbohydrate around matches. This is because carbohydrate is 'sweet' and, therefore, a 'favourite' option. The challenge is to provide carbohydrate to players who need it. For example, on a match day, when carbohydrate options are readily available or provided 'buffet' style, the entire squad has access. Thus, despite not needing additional carbohydrate, substitutes (and staff) are known to 'raid' the carbohydrate options provided. This may result in unfavourable energy balance for those players, which, if left unaddressed, may negatively affect body composition. Several options may be used to resolve this, such as removing the buffet and providing individual player options, or providing alternative foods/beverages for the substitutes, in concert with an education program. If the starting 11 is known at the time of the pre-match meal, example 'starter' and 'substitute/impact player' plates can be prepared to provide visual guidance for players, as to what their plate should look like. Other practical approaches should also include preparing tray liners, which provide guidance for players when self-serving from buffets. Finally, as with all food and daily dietary intakes, excess ingestion of sugars may negatively impact on players' dental health (Venables *et al.*, 2005). Thus, it is simply advised that players brush their teeth following training and matches when carbohydrate is ingested.

Summary



- A carbohydrate-rich meal (2-3 g/kg body mass) should be ingested 3-4 hours before kick-off in order for players to begin the match with adequate glycogen stores.
- The player's store of glycogen is limited and it is gradually depleted during football training and matches.
- Ingestion of carbohydrate (30 g before and at half time) is associated with improved running and skill performance, especially under circumstances of fatigue and/or hypoglycaemia.
- There are multiple mechanisms: primary, secondary and tertiary mechanisms by which carbohydrate ingestion benefits football performance.
- After a match, the ingestion of carbohydrate (~1 g/kg BM /h) will speed up the rate of muscle glycogen resynthesis.
- The ingestion of carbohydrate post exercise should be achieved in concert with other nutrition goals to speed up players' recovery (fluid and protein).



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