

3.1 Optimising recovery and protein synthesis

3.1.1 Rapid rehydration

After hard training or a match, players generally lose 1-2 kg of body mass (Broad, Burke, Cox, Heeley, & Riley, 1996). This is classed as low to moderate dehydration. The loss of 2% body mass is not regarded as a problem but the loss of more than 2% (1.6 kg for a 80 kg player) could have an effect on performance (Nuccio, Barnes, Carter, & Baker, 2017), especially in hot conditions (as we will see in the section on extreme environments). Dehydration can affect various effect of running performance of football players, as several studies have shown, but can also affect cognitive functioning or technique (Nuccio et al., 2017). At FC Barcelona players we measured 0.5-1.3% body mass loss during training in cool-warm conditions during training. During training players had access to fluids, so with their ad libitum fluid intake, dehydration was not really an issue as it stayed within the 2% body mass loss. This is a common finding: fluid losses during football are typically below 2% body weight (Broad et al., 1996) during training, even in the summer. Based on this, one would have to conclude that dehydration is not a major issue in football in most training situations. However, there are clearly players who sweat consistently more than others and who would very likely dehydrate to more than 2% body weight in hot conditions and during match play when there is little access to fluids (unpublished findings).

In the section about extreme environments the effects of heat on thermoregulation, sweating and performance is discussed in more detail. When exercising in the heat, sweat losses can be very large and it is important to identify those players that have extremely high sweat rates. This can be done by simple measurements of body weight before and after training and games (the exact procedures are discussed in the section on extreme environments). When such measurements are conducted regularly, it is possible to eventually predict sweat rates with reasonable accuracy and the players that need extra attention can be identified. By measuring sweat losses it is also possible to give more detailed drinking advice post exercise. Often this advice is expressed as a percentage of body mass loss as we will see below.

After exercise fluid balance can be restored relatively quickly. Whether this is important or not, depends mainly on the degree of dehydration, the timing of the next training or performance (if there are less than 8 hours a more aggressive drinking strategy may be required and whether fluid can be tolerated).

A more aggressive drinking strategy to restore fluid balance is important the following conditions:

- In the case of severe hypohydration (4-5% body mass). In this situation it is important to restore fluid balance quickly. Often such levels of dehydration will affect hunger and if the player does not eat, it will affect all other aspects of recovery. With severe dehydration it is recommended to prioritise restoration of fluid balance.
- When athletes need to participate in subsequent competition in a relatively short timeframe (< 8 h, i.e., two training sessions per day). If there is more than about 8 hours until the next practice or match, normal drinking and eating will most likely restore fluid balance (Shirreffs & Sawka, 2011).
- When food cannot be tolerated, is not available or desired. Fluids are also a way to deliver other nutrients such as carbohydrate and protein, so when a player cannot eat or cannot tolerate food, it is often more practical to give them a drink.

“In most other situations, water and sodium can be consumed with normal eating and drinking practices with no urgency (Shirreffs & Sawka, 2011)” (Laitano, Runco, Baker, 2014, <https://bit.ly/2BlJG6E>). Below, we will discuss the guidelines for rapid restoration of fluid balance. What amount of fluid should be consumed? And what are the best beverages to quickly restore fluid balance?

Volume of fluid

Drinking the exact amount of fluid lost during exercise in the 2-4 hours after exercise will only result in 50-70% restoration of fluid balance. This is partly because drinking will result in an expansion of the plasma volume and this will trigger a series of responses that will result in an increase in urine production. Therefore in order to restore fluid balance within a short period of time, a player would need to drink more than the fluids lost. Shirreffs et al. (Shirreffs, Taylor, Leiper, & Maughan, 1996) gave subjects an electrolyte drink equivalent to 50 %, 100 %, 150 %, or 200 % of body mass loss during previous exercise. Net fluid balance was only completely restored 6 hours later when the fluid volume ingested was greater than fluid lost during exercise (150 % and 200%). There was no clear advantage to drinking 200 % compared to 150 %. In the same study 2 different concentrations of sodium were tested. When 61 mmol/L sodium was added this improved fluid balance more than 23 mmol/L at intake volumes of 100% or more. From these studies the guideline was extrapolated that to achieve rapid and complete rehydration athletes should drink 1.5 L of a sodium-containing fluid for each kg of body mass lost (Shirreffs & Sawka, 2011). The additional volume compensates for the diuresis stimulated by rapid consumption of large volumes of fluid.

The role of sodium

The addition of sodium to a fluid replacement beverage will help stimulate more complete rehydration after a player incurs exercise-induced hypohydration. Sodium will help to restore plasma volume and whole-body fluid balance compared to the ingestion of plain water (Gonzalez-Alonso, Heaps, & Coyle, 1992; Maughan & Leiper, 1995; Maughan, Owen, Shirreffs, & Leiper, 1994; Shirreffs, Aragon-Vargas, Keil, Love, & Phillips, 2007). Sodium intake will increase the blood sodium concentration and osmolality which in turn will stimulate renal water reabsorption. Urine output is inversely related to the sodium content of the ingested fluid (Maughan & Leiper, 1995), so higher sodium concentrations mean less urine production. It is important to note that sodium is the only electrolyte that is important in this regard. Potassium may have a role to play in the distribution of fluid within the body but sodium is the main driver of overall hydration.

The volume of fluid consumed is essential for post exercise rehydration. Sodium will further help retention. Those are likely the two most important factors that will determine post exercise rehydration. In the following section we will look at a number of different beverages and ingredients that can potentially further improve hydration (carbohydrate, protein) or worsen hydration (alcohol, caffeine).

3.1.2 Drinks with Best hydration Properties

Drinks with Carbohydrate

There is some evidence that the inclusion of carbohydrate in a fluid replacement beverage may also have an impact on fluid retention following dehydration. One study (Osterberg, Pallardy, Johnson, & Horswill, 2010) tested the effects of five different beverages on fluid retention after 90 min of exercise in hot conditions. The exercise induced mild dehydration (2-3 %). Athletes consumed water, placebo, or a carbohydrate solution in different concentrations (3 %, 6 %, or 12 %). They consumed a volume to replace 100 % of the fluid losses incurred during exercise. At the end of a 4-hour rehydration period, fluid retention was significantly greater with all carbohydrate-containing beverages compared with water. There was no significant difference between water and placebo. Similarly, Evans, Shirreffs, and Maughan (2009) compared the effects of drinks with the same electrolyte content but different carbohydrate concentrations (0 %, 2 %, and 10 %) on fluid retention in subjects who were dehydrated (1.9 % of body mass). Significantly more of the ingested fluid was retained with the 10 % carbohydrate solution than with the 0 % carbohydrate solution.

The effects of carbohydrate on fluid retention after exercise could be due to a number of factors:

- One mechanism to consider is the passive association of water with solute related to glycogen storage. Glucose transport into liver and muscle cells draws water along with the substrate, which can increase intracellular fluid retention and total body water.
- Carbohydrate could also affect fluid retention by delaying gastric emptying or intestinal absorption (from the increased energy density and/or osmolality of the higher carbohydrate beverages), which would effectively delay the appearance of fluid in the bloodstream. The delayed absorption of fluid and/or the higher plasma osmolality elicited by the carbohydrate drink would attenuate renal water excretion.
- Thirdly, insulin response to carbohydrate intake may enhance renal sodium reabsorption (DeFronzo, Goldberg, & Agus, 1976), which would in turn promote water retention.

Coconut water

Coconut water is touted as the new hydration beverage. Marketing gurus claim it has better hydrating properties than water or sports drinks. It is true that coconut water contains some carbohydrate and electrolytes. However, coconut water contains very little sodium and this, as we have just discussed, is the electrolyte that matters. It must also be noted that coconut water varies tremendously in the composition depending on many factors including the maturation process (Fagundes Neto, Franco, Tabacow, & Machado, 1993). For example, "the concentration of glucose remained constant between the 5th and 8th months, but abruptly decreased after the 9th month. In no instance did the coconut water contain sodium and

glucose concentrations of potential value as an oral rehydration solution.” (Fagundes Neto et al., 1993, <https://bit.ly/2DOY5tV>).

“Therefore claims that coconut water is a superior source of hydration are unfounded. However, it is a natural way to drink fluids that also contain some carbohydrate and electrolytes.” (Jeukendrup, 2018, <https://bit.ly/2FrFGFA>).

Table 1: Composition of coconut water compared with water and an average sports drink

Composition (per Liter)	Water	Sports drink	Coconut water
Sodium (mg)	<100	280	420
Potassium (mg)	<10	2000	120
Carbohydrate (g)	0	60-70	10-44
Kcal	0	240-280	40-176

Source: Jeukendrup, 2018, <https://bit.ly/2FrFGFA>

Studies confirm this and found (not surprisingly) that the hydrating properties of coconut water are not different from those of a sports drink (Kalman, Feldman, Krieger, & Bloomer, 2012). When sodium was added to coconut water, the hydrating properties improved and the sodium enriched coconut water resulted in more complete hydration than plain water (Ismail, Singh, & Sirisinghe, 2007). (Jeukendrup, 2018, <https://bit.ly/2FrFGFA>).

Milk

One study (Shirreffs, Watson, & Maughan, 2007) investigated the hydrating properties of low-fat milk with or without an additional 20 mmol/l NaCl (this is 340mg/L), and compared it to a sports drink and water. After losing 1.8% of their body weight during intermittent exercise in a hot environment, subjects consumed a drink volume equivalent to 150% of their sweat loss. “Cumulative urine output was less after the milk drinks were consumed;” (Shirreffs, Watson, & Maughan, 2007, <https://bit.ly/2BkRq80>) only half of the urine was produced with milk (whilst sodium had only a small additional effect). “The results of the present study suggest that milk can be an effective post-exercise rehydration drink.” (Shirreffs et al., 2007, <https://bit.ly/2BkRq80>). Of course, it will also help meet protein and carbohydrate requirements. Watson, Love, Maughan, & Shirreffs (2008) compared the rehydrating effects of skimmed milk with a commercially available sports drink. Athletes first dehydrated to 2.0% body mass loss and then consumed either skimmed milk or a carbohydrate-electrolyte sports drink equivalent to

150% body mass lost. After a rehydration period of 3h, the subjects had excreted more cumulative urine in the carbohydrate-electrolyte trial than the milk trial. The difference was equal to a net fluid balance difference of 326 mL or 0.4-0.5% body mass.

It has been suggested that the increased energy density as well as the clotting of the casein in the milk-based products delays gastric emptying (James, Clayton, & Evans, 2011) and slows intestinal fluid absorption compared to whey protein or glucose drinks. A delay in fluid entering the blood stream would consequently attenuate the reduction in serum osmolality and therefore prolong the stimulus for renal water reabsorption. (Baker & Jeukendrup, 2014, <https://bit.ly/2DzOqas>).

Sports Beer

Alcoholic beverages are generally discouraged post exercise because of their dehydrating properties and because of the negative effects on protein synthesis. However, the studies that underlie these thoughts were performed with large amounts of alcohol, leaving the question whether modest intake of alcohol has negative effects on post exercise rehydration. In a study that compared the hydrating properties of different beverages, beer did not score much worse than water (Maughan et al., 2016). Dr Ben Desbrow and colleagues performed a number of studies (Desbrow et al., 2015; Desbrow, Murray, & Leveritt, 2013) investigating the effects of alcohol containing beers on post exercise hydration.

In their studies, beer failed to completely restore fluid balance within 4 hours, independent of the strength of the beer and the electrolyte content. They did observe however that a light beer (with 2.3% alcohol) combined with 50 mmol/L of added sodium was a more effective rehydration solution than the same beer with half the sodium content or a mid-strength beer with or without 25 mmol/L of added sodium. (50 mmol/L is roughly 3 grams of table salt per liter and 25 mmol/L, 1.5 grams per liter). In summary, beer in moderation and diluted or consumed with water can help post exercise hydration. There is no reason not to have one beer, but we always have to keep in mind the negative effects of larger amounts of beer/alcohol (Jeukendrup, 2018, <https://bit.ly/2FuzNI4>).

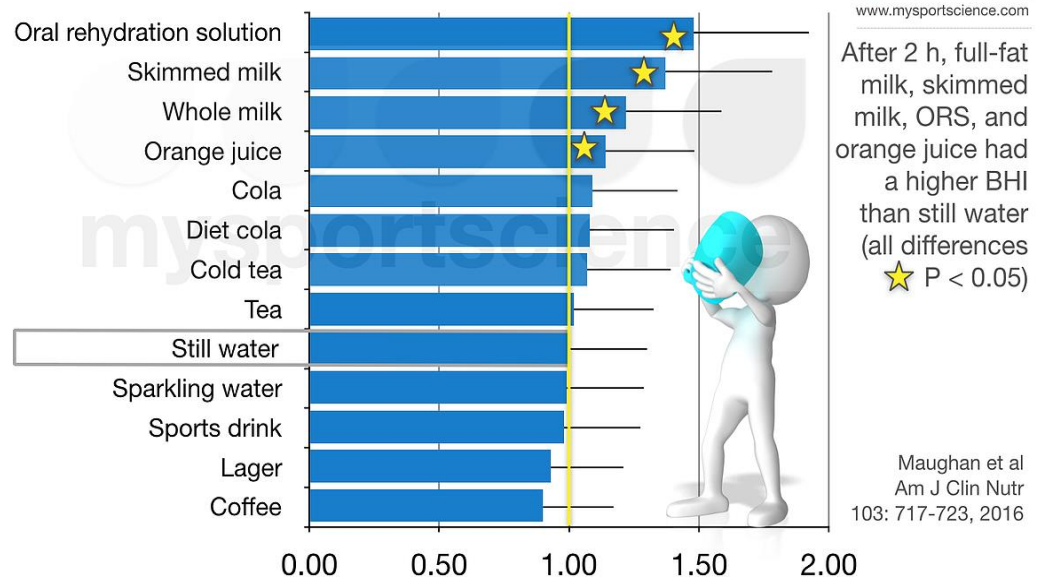
Comparing Beverages

Professor Ron Maughan and colleagues (R. J. Maughan et al., 2016) set out to compare a number of different drinks and capture the hydrating properties in what they called the beverage hydration index (BHI). This is discussed in (A. E. Jeukendrup, 2016b). Essentially, the index compares how much of a drink is retained 2 hours after consumption compared to the same amount of water. The higher the index the more fluid is retained in the body. They compared 13 beverages. Seventy two volunteers consumed 1 litre of each of these drinks. For the next 2 hours urine was collected. 2 hours is a practical time because it is probably similar to normal drink consumption patterns (as opposed to 4 hours which was used in many previous studies) (Jeukendrup, 2018, <https://bit.ly/2exXoVU>).

Figure 1: Beverage hydration index is a measure of how quickly these drinks can rehydrate in the hours after dehydration.

Beverage Hydration Index

The higher the value, the better fluid is retained in the body



Source: Jeukendrup, 2016b, <https://goo.gl/Q6nnJV>

The results demonstrated that some drinks had better hydrating properties than water. Perhaps not surprising is the fact that oral rehydration solutions scored the highest value.

These heavily researched drinks deliver fluid fast and the high electrolyte content is responsible for fluid retention (but are not very palatable). But skimmed milk, whole milk, and orange juice also scored well. These drinks are higher in calories and have more ingredients that may slow down gastric emptying and absorption but result in an overall greater fluid retention

The other effects that may be somewhat surprising to some was that beer (lager), coffee and tea had scores that were very similar to water. They certainly did not display the dehydrating properties that are often talked about. The difference between beer, coffee, tea and water was not statistically significant. It is likely that the dehydrating properties of alcohol and caffeine were counterbalanced by the fluid retaining properties of the other ingredients. It is also possible that alcohol and caffeine in very small amounts do not have diuretic effects. The early studies that demonstrated these properties were done with much larger amounts of alcohol or caffeine (Jeukendrup, 2018, <https://bit.ly/2exXoVU>).

We can further learn from this study that a number of beverages were pretty similar to water (sports drinks, tea, cola, diet cola). So although some drinks are better than others at retaining fluids, most drinks will contribute to daily fluid requirements (Jeukendrup, 2018, <https://bit.ly/2exXoVU>).

The volume consumed remains the most important factor. More important than the type of beverage.

Intravenous Administration of Fluids

Rehydration can also be achieved through the administration of fluid intravenously instead of orally. When there is a medical indication this method might be applied through qualified personnel. However, drinking may still be the preferred option. One study compared oral and intravenous rehydration after a 4% reduction in body mass and demonstrated that restoration of plasma volume, plasma osmolality, plasma sodium concentration, and fluid regulatory hormones were similar regardless of the route of fluid administration. There were also no cardiovascular, thermoregulatory, or performance advantages of intravenous versus oral fluid administration during exercise in the heat (Kenefick et al., 2007). So, in most conditions, oral fluid administration remains the most practical (and ethical) solution. There are times, however, when oral intake of fluids is neither possible nor practical (trauma, nausea, vomiting) and under those circumstances, medical staff may decide that intravenous fluid administration is the preferred route for rapid rehydration.

3.1.3 Glycogen Restoration

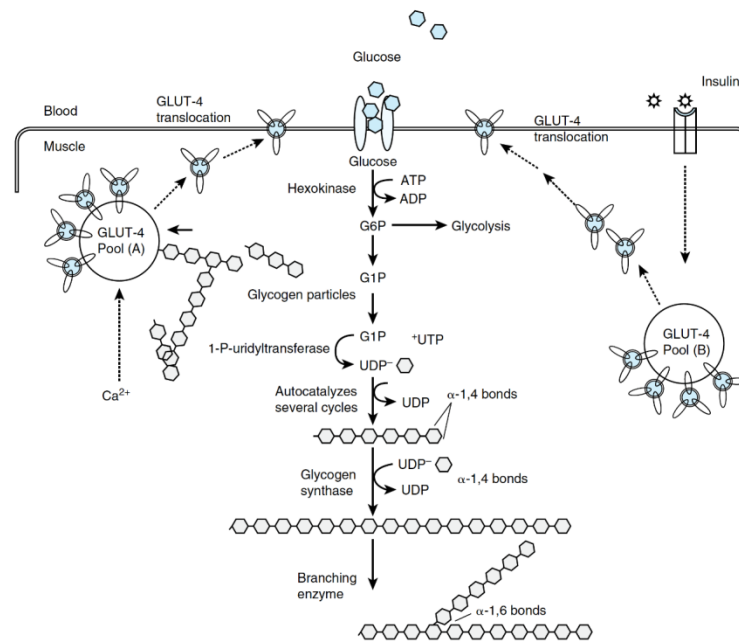
Since muscle and liver glycogen stores are directly related to fatigue (low stores may result in early onset of fatigue), it is important to start replenishing glycogen stores as soon as possible after exercise (hard training or match where glycogen stores are depleted or emptied to a major degree). Replenishment of liver and muscle glycogen can be achieved simply by ingesting carbohydrate. When glycogen stores are depleted, this process takes at least 24 hours even in well-trained individuals. Especially if there is less than 24 hours to recover, it is important to optimise glycogen synthesis. In this section and the next, we will discuss the best ways to maximise glycogen resynthesis after exercise. We will address practical questions like: what is the optimal amount of carbohydrate? What is the best type of carbohydrate? What is the best timing of intake? and so on. Before we look at the practical side, however, we must understand the underlying mechanisms and factors that influence glycogen synthesis. Therefore, in the next sections we will study the regulation of glycogen synthesis and discuss the factors that affect the process.

Regulation of Glycogen Synthesis

Before glycogen can be stored in the muscle, glucose must be taken up by the muscle. "Glucose uptake in the muscle is through facilitated diffusion by the glucose transporter GLUT4" (Jeukendrup & Gleeson, 2018). Most glucose transported across the sarcolemma will make use of this GLUT4 transport system. "GLUT4 is normally stored in intracellular vesicles but can translocate to the cell membrane, merge with the cell membrane, and allow increased transport of glucose into the cell" (Jeukendrup & Gleeson, 2018).

(See Figure 2). There are two types of signals that will trigger the translocation of GLUT4: muscle contraction (through Ca^{2+} ions) and insulin (secreted when glucose is ingested) (Jeukendrup & Gleeson, 2018).

Figure 2: Mechanisms of glucose transport into the muscle and the synthesis of glycogen



Source: adapted from Jentjens and Jeukendrup, 2003.

Once glucose enters the cell it is immediately phosphorylated to glucose-6-phosphate (G6P) by the enzyme hexokinase. G6P is then converted to glucose-1-phosphate (G1P), which combines with uridine triphosphate to form uridine diphosphate (UDP)-glucose. "This UDP-glucose can be considered an activated glucose molecule. It is a carrier of glucose units and takes the glucose molecule to the terminal glucose residue of a pre-existing glycogen molecule. The UDP-glucose then forms an α -1,4 glycosidic bond" (Jeukendrup & Gleeson, 2018).

The enzyme that is responsible for this step is a key enzyme in the glycogen synthesis process: glycogen synthase. If this was the only process, glycogen would be one long straight chain of glucose molecules. However, glycogen is a heavily branched structure. "Branch points (α -1,6 glycosidic bond), are therefore introduced into the glycogen structure by a branching enzyme. When the length of a chain is about 12 glucose residues long, the branching enzyme detaches a chain about 7 residues long and reattaches it to a neighbouring chain by an α -1,6 glycosidic bond" (Jeukendrup & Gleeson, 2018).

Branching results in the formation of a large but compact glycogen molecule.

The rate of glycogen synthesis depends on several factors (Jeukendrup & Gleeson, 2018):

1. The availability of glucose;
2. The transport of glucose into the cell, which in turn depends on:
 - a. Prior exercise (exercise stimulates glucose uptake for 1–2 hours post-exercise and increases insulin sensitivity),
 - b. Insulin concentration (high insulin stimulates glucose uptake), and

- c. Muscle glycogen content (low muscle glycogen stimulates glucose uptake); and
3. "The activity of enzymes (in particular glycogen synthase), which also depends on insulin concentration (high insulin stimulates glycogen synthesis)". (Jeukendrup & Gleeson, 2018).

"As a result of the changing activity of these enzymes and the effectiveness of these transport mechanisms, two phases can be distinguished in the process of glycogen synthesis after exercise" (Jeukendrup & Gleeson, 2018).

1. The initial insulin-independent, or rapid phase and
2. The insulin-dependent, or slow phase

Rapid Phase

The rate-limiting enzyme for glycogen resynthesis after exercise, glycogen synthase, exists in an inactive D-form and an active I-form. More glycogen synthase is present in the active I-form when muscle glycogen concentrations are low. As glycogen stores are replenished, more glycogen synthase is transformed back into the D-form. Exercise activates glycogen synthase (immediately after exercise, as much as 80% of all glycogen synthase may be in the active I-form), but glycogen can be formed only if the substrate (UDP-glucose) is available. Another important factor in glycogen resynthesis, therefore, is the availability of glucose, which is mainly dependent on glucose transport across the sarcolemma. During exercise and in the first hour after exercise, an abundance of GLUT4 is available at the cell membrane, and glucose uptake into the muscle is facilitated. This exercise-induced effect on glucose transport, however, lasts only a few hours in the absence of insulin. The increase in the permeability of the sarcolemma for glucose after exercise seems to be directly related to the amount of glycogen in the muscle. When muscle glycogen concentrations are very low, the enhanced glucose uptake may last longer. With high muscle glycogen concentrations, the effect is rapidly reversed (Jeukendrup & Gleeson, 2018).

Slow phase

When the effect of the exercise-induced increase in glucose transport wears off, glycogen resynthesis occurs at a much slower rate. The rate at which glycogen synthesis occurs

during the slow phase depends mainly on the circulating insulin concentration. This will increase GLUT4 translocation to the cell membrane and increases glucose transport into the muscle cell. In addition, muscle contraction increases insulin sensitivity, an effect that lasts for several hours. This increase in insulin sensitivity after exercise is likely an important factor during the slow phase of glycogen synthesis, when virtually all glucose transport is insulin-dependent. Compared to the initial rapid phase, during the slow phase the glycogen synthase activity is reduced as glycogen concentrations increase

A high rate of glycogen synthesis in the hours after exercise depends in first instance on the availability of substrate. In the absence of carbohydrate ingestion, glycogen resynthesis rates are extremely low, despite increased insulin sensitivity, increased glycogen synthase activity, and increased permeability of the sarcolemma to glucose (Ivy, 1991). Although muscle glycogen concentrations are unlikely to be completely restored to pre-exercise levels within 24 hours, all methods of carbohydrate supplementation that maximize glycogen restoration may benefit performance.

Five main factors have been recognized as potentially important in promoting restoration of muscle glycogen stores

1. timing of carbohydrate intake
 2. rate of carbohydrate ingestion
 3. the type of carbohydrate ingested
 4. the ingestion of protein and carbohydrate after exercise
- the intake of caffeine. (Jeukendrup & Gleeson, 2018).

In the next sections we will discuss each of these factors in a bit more detail.

3.1.4 Optimising Glycogen Resynthesis

Timing

“The timing of carbohydrate intake has an important effect on the rate of muscle glycogen synthesis in the hours after exercise (Ivy, Lee, Brozinick, & Reed, 1988)” (Jeukendrup & Gleeson, 2018).

Carbohydrate intake immediately after (within 30 min after) is more effective than delaying intake by 2 hours. “When carbohydrate intake is delayed until 2 hours after exercise, muscle glycogen concentration after 4 hours is 45% lower compared with ingestion of the same amount of carbohydrate immediately after exercise (Ivy et al., 1988). Average glycogen resynthesis rates in the 2 hours after ingestion are 3 to 4 mmol/kg ww/h when carbohydrate is ingested after 2 hours and 5 to 6 mmol/kg ww/h when it is ingested immediately after exercise” (Jeukendrup & Gleeson, 2018).

Clearly, when carbohydrate intake is delayed until after the “insulin independent phase”, less glucose is taken up and stored as glycogen partly because post-exercise GLUT4 transporters slowly return from the membrane to their intracellular storage sites.

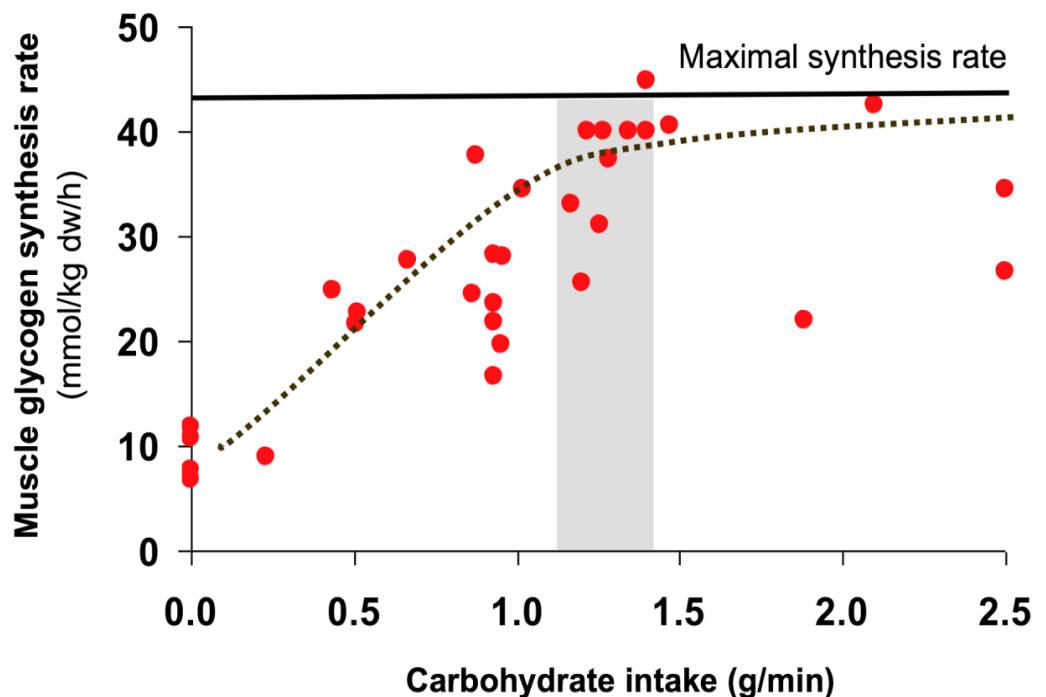
The frequency of meals (many smaller meals or fewer larger meals) does not seem to affect glycogen synthesis (Burke L. M. et al., 1996) and perhaps this is related to the fact that meals do accumulate in the stomach before being absorbed (this will even out the delivery). It is also possible that, on the one hand, larger meals would result in greater delivery and glycogen synthesis; but on the one hand, smaller meals will maintain higher levels of insulin throughout the recovery period. These effects may balance the net outcome.

Amount

When no carbohydrate is ingested after exercise, the rate of muscle glycogen synthesis is extremely low (1 to 2 mmol/kg ww/h). The ingestion of carbohydrate, especially in the first hours after exercise, results in enhanced muscle glycogen restoration, and glycogen is generally synthesized at a rate between 4.5 and 11 mmol/kg ww/h. Glycogen synthesis rates from a large number of studies have been plotted against carbohydrate intake in figure 3. It is clear that an increase in intake results in an increase in synthesis. However, at very high intake of around 1.4 g/min (almost 90 grams per hour), there does not seem to be any further benefit. Therefore, the advice is often to ingest between 70-90 grams per hour for the first hours after exercise. (Ivy et al., 1988) To avoid confusion: this is not

important after every training. This is only relevant when there is serious glycogen depletion and there is little recovery time.

Figure 3: Muscle glycogen synthesis as a function of carbohydrate intake after exercise



Source: Redrawn from (Jentjens & Jeukendrup, 2003).

Types of Carbohydrate

Ingestion of different types of carbohydrate has different effects on glycogen synthesis. Blom, Høstmark, Vaage, Kardel, and Maehlum (1987) demonstrated that fructose ingestion resulted in lower rates of muscle glycogen synthesis after exercise compared with glucose or sucrose ingestion. There are probably 2 main reasons for this. First, fructose must be converted to glucose in the liver before it can be used for glycogen synthesis in the muscle; this process takes a little time. Second, when fructose is absorbed, it will pass through the liver and when liver glycogen is low, fructose will be preferentially used to restore liver glycogen first. Another study showed that fructose and galactose result in more glycogen synthesis in the liver post exercise than glucose (Decombaz, 2011). When glucose is ingested, more glucose will escape from the liver and will be transported to the muscle. Other studies confirmed that glycogen synthesis from fructose occurs at only 50% of the rate of glycogen synthesis from glucose.

In the study by Blom et al. (1987), sucrose intake resulted in similar muscle glycogen levels 4 hours after exercise when compared to those levels after glucose intake.

Because the delivery of carbohydrate seems to be a factor and because combinations of multiple transportable carbohydrates such as glucose and fructose have been shown to increase absorption and delivery to the muscle during exercise, it is possible that these carbohydrate mixtures can also increase muscle glycogen synthesis after exercise. But it was recently observed that a combination of glucose and fructose ingested at relatively high rates did not improve glycogen synthesis compared with the ingestion of glucose only (Wallis et al., 2008). It is possible that fructose is preferentially stored in the liver post-exercise and therefore” (Jeukendrup A., & Gleeson, 2018, <https://bit.ly/2FsrRXA>).

less reaches the muscle. Nevertheless, muscle glycogen synthesis was similar to glucose-fructose compared with glucose.

Protein

Certain amino acids have a potent effect on insulin secretion. This raised the question whether adding amino acids or proteins to a carbohydrate solution could further enhance glycogen synthesis. Zawadzki, Yaspelkis III, and Ivy (1992) compared glycogen resynthesis rates after ingestion of carbohydrate, protein, or carbohydrate plus protein. Unsurprisingly, little glycogen was stored when just protein was ingested. Glycogen storage increased when carbohydrate was ingested, but when carbohydrate was ingested together with protein, insulin concentrations and glycogen synthesis rates were the highest.

These results were reproduced by van Loon, Kruijshoop, Verhagen, Saris, and Wagenmakers, 2000). Instead of protein, they used protein hydrolysate that had been shown to result in a large insulin response. In both studies protein was added to the carbohydrate and thus extra calories were also provided. Therefore, van Loon et al. (van Loon et al., 2000) added one extra trial that had a larger amount of carbohydrate but the same amount of calories as the carbohydrate-protein drink. Despite the fact that the carbohydrate plus protein drink resulted in the largest insulin response, glycogen resynthesis was the highest with the isoenergetic amount of carbohydrate. Taken together, these results suggest that insulin is an important factor, but the main limiting factor is the availability of carbohydrate.

In a follow up study, the larger amount of carbohydrate used in the study by van Loon et al. (van Loon et al., 2000) was compared to the same amount of carbohydrate with added protein. In this study, no further effect of the protein was observed. This means that when carbohydrate intake is high/optimal, protein will have no beneficial effect.

There may be a role for protein in situations where higher carbohydrate intakes are not practical, not possible, or not desirable. Protein ingestion post-exercise will of course also help stimulate protein synthesis.

Form of Carbohydrate

The food form in which carbohydrate is provided may also have an effect. A liquid carbohydrate drink (or carbohydrate-protein shake), may have different effects than a meal or a carbohydrate containing energy bar.

“Few studies have investigated the effect of liquid versus solid carbohydrate foods on glycogen synthesis in the early hours after exercise”. (Jeukendrup & Gleeson, 2018). Keizer Kuipers, van Kranenburg and Geurten (1987) compared liquid and solid carbohydrate meals and concluded that there was no difference in glycogen synthesis. The critical reader, however, would notice that the solid meal in that study contained slightly more carbohydrate than the liquid meal did, and differences in fat and protein content between the two meals were substantial (Jeukendrup & Gleeson, 2018).

It is likely that meals that contain fat, protein, and fibre (which have all been shown to delay gastric emptying and absorption) will result in lower rates, carbohydrate absorption, and a lower insulin response. These factors should slow down muscle glycogen synthesis. Evidence for this comes from studies that compared food with different glycemic indices.

Glycemic Index

The glycemic index (GI) refers to the increase in blood glucose and insulin in response to a standard amount of food, and is determined by measuring the area under the glucose curve. The GI measurements are usually based on the ingestion of 50 g of carbohydrate and measurements of blood glucose over a 2-hour period. The greater the glucose response, the greater the area under the curve is, the greater the GI of food is. Foods are generally divided into 3 categories: low-GI foods, moderate-GI foods, and high-GI foods. “Low-GI foods have a GI of 55 or less, moderate-GI foods have a GI between 56 and 70, and high-GI foods have a GI of 71 or higher” (Jeukendrup & Gleeson, 2018). Apples or lentils, for example, result in a slow and small rise of blood glucose concentration, whereas white bread or potatoes result in a rapid rise in blood glucose concentration. The apples and the lentils, therefore, are classified as low-GI foods, and bread and potatoes are classified as high-GI foods (Jeukendrup & Gleeson, 2018).

Studies have shown that when the same amount of carbohydrate is ingested in the form of high glycemic index foods, this will further stimulate glycogen synthesis over 24 hours compared with low glycemic index foods (Burke, Collier, & Hargreaves, 1993). It is likely that most of this effect is due to the quicker delivery of carbohydrate in the first couple of hours after exercise when glycogen synthesis rates are very high. It is also possible that poor absorption of low glycemic index carbohydrates reduces the efficacy.

So, in theory high glycemic index carbohydrate sources are preferred. However, the usefulness of the glycemic index as a tool should be questioned for a number of reasons:

- First the glycemic index for any given food varies considerably between individuals; so, a value from a table may or may not apply to you.
- The glycemic index of foods is also sometimes confusing. In general, foods with large amounts of refined sugar (simple carbohydrates) have a high glycemic index, and sugars with high fibre content and complex carbohydrates have a lower glycemic index. Some complex carbohydrates (starch), however, can have a high glycemic index.
- Athletes eat meals, not just sources of carbohydrate, and meals combine a number of different foods. Adding relatively small amounts of fat to a high- glycemic index carbohydrate can lower the glycemic index of the food substantially.
- Glycemic index is expressed per 50 grams of carbohydrate in a food. This means in some cases that unrealistic amounts of food have to be eaten to get to 50 grams. Take carrots as an example, one would have to eat almost 1kg of carrots to get to 50 grams of carbohydrate. The glycemic index, then, becomes a purely theoretical concept, not a practical one.

The glycemic load (GL) is a relatively new method which was proposed to assess the effect of carbohydrate consumption as it takes the glycemic index into account but is a little more practical. GL takes the glycemic index value and multiplies it by the actual amount of carbohydrate in a serving. A GL is low if it is between 1 and 10, medium if it is between 11 and 19, and high if it is 20 or higher. Foods that have a low GL almost always have a low GI. Foods with an intermediate or high GL range from a very low to a very high GI. The GL is a more useful concept but is not often applied. Most people still refer to the glycemic index.

“This index must be interpreted and used with caution. It can probably be a useful tool if its limitations and pitfalls are well understood” (Jeukendrup & Gleeson, 2018).

Caffeine

“The co-ingestion of caffeine with carbohydrate during exercise increased glucose delivery to the muscle and oxidation” (Yeo, Jentjens, Wallis, & Jeukendrup, 2005). (Jeukendrup & Gleeson, 2018). If caffeine can increase the delivery of glucose during exercise, it might do the same following exercise, potentially increasing muscle glycogen synthesis. In a study by Pedersen et al. (Pedersen et al., 2008), caffeine was added to a carbohydrate drink and given to subjects during a 4-hour recovery period from exhaustive glycogen-depleting exercise. In this study, caffeine (a large amount 8 mg/kg) improved glycogen synthesis. However, a follow-up study by Beelen et al. did not confirm this finding. In this study co-ingestion of caffeine did not further enhance post-exercise muscle glycogen synthesis (Pedersen et al., 2008). The difference between the two studies was that in

the latter, subjects received recommended amounts of carbohydrate after exercise (1.2 g/kg/h) whereas in the former, carbohydrate intakes were lower. So, it is possible that if enough carbohydrate is ingested, even large amounts of caffeine will not have an effect (Jeukendrup A., & Gleeson, 2018, <https://bit.ly/2qTprHq>).

Creatine

Several studies have demonstrated that creatine supplementation (typically 20 grams of creatine monohydrate for 5 days) can improve glycogen restoration post exercise (Derave et al., 2003; Nelson, Arnall, Kokkonen, Day, & Evans, 2001; Robinson, Sewell, Hultman, & Greenhaff, 1999). Creatine appears to “sensitise” the muscle after exercise for glucose uptake, most likely because of an effect on GLUT4 transporters. There are other potential benefits of creatine that will be discussed elsewhere. One of the side effects of creatine is a 1-2 kg of weight gain (fluid retention) and this needs to be considered when using the supplement.