2.1 An introduction to metabolism in football

Introduction

As described in module 1, football performance is characterized by bursts of very intense activity interspersed with periods of recovery at relatively low exercise intensities. For the locomotive activity involved in football, the immediate and only source of energy that allows muscles to generate movement is adenosine triphosphate (ATP). Metabolism in football simply refers to the process of converting the foods, which a player eats into energy.

Players have only a limited amount of available energy (ATP), which is rapidly used during football activity. Therefore, to continuously provide the energy needed during a football match, ATP must be continually regenerated. The player achieves this through a combination of three main energy systems: (1) phosphocreatine breakdown, (2) glycolysis, (3) aerobic metabolism. Phosphocreatine breakdown and glycolysis can occur without the use of oxygen and, thus, they are referred to as “anaerobic” energy systems. On the contrary, the formation of ATP using oxygen (oxidative phosphorylation) is referred to as an “aerobic” energy system.

The aim of this unit is to establish a basic understanding of the systems that provide energy for football activities. This knowledge will provide the foundation on which basic and more advanced concepts of sports nutrition can be built. In this unit, the energy systems will be attached to three main football activities and intensities discussed in module 1.

(1) Sprints using the ATP-phosphocreatine (ATP-PCr) system.
(2) High-speed running dependent on glycolysis.
(3) Low to moderate intensity activities relying on aerobic metabolism.

To avoid misunderstandings about the function of “aerobic” and “anaerobic” energy systems, it is important to recognize that they work in concert, not in isolation. For example, during a sprint, the high rate of energy production in the muscle is provided by anaerobic energy systems, whilst, simultaneously, physiological functions of the heart and other organs are supported by energy derived from ongoing aerobic metabolism (Williams and Rollo, 2015).

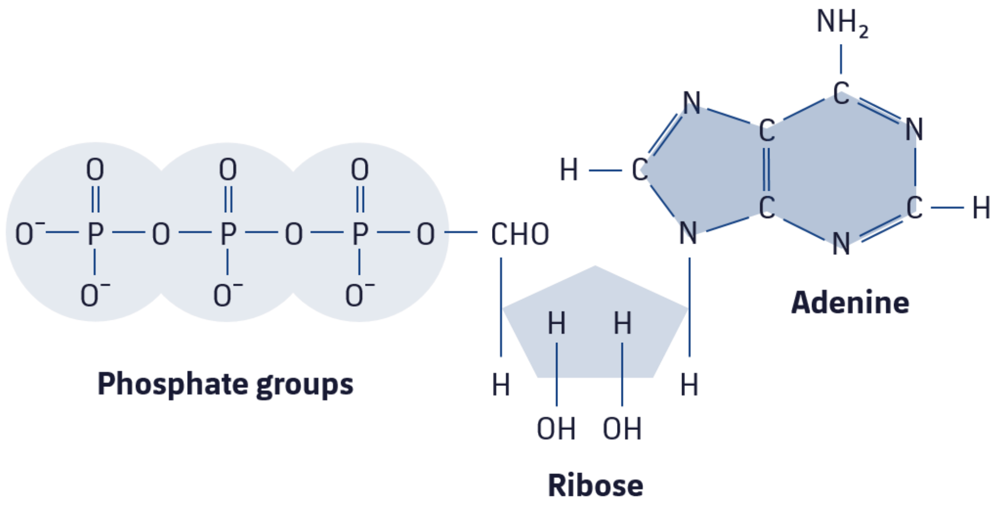
Key point

> Metabolism is the process of converting food into energy.

ATP: The energy currency for football

The process of muscle contraction, a prerequisite for football performance, is ultimately dependent on the degradation of one organic molecule, adenosine triphosphate (ATP). Energy is released from the breakdown of ATP. A phosphate group is removed, energy is released, and adenosine diphosphate (ADP) is produced. The breakdown of ATP produces a high amount of energy but the stores of ATP in muscle tissues are limited. For this reason, the players' ability to sustain all the energy required for football demanding activities depends on the capacity of their skeletal muscles to rapidly replenish the ATP. The process of ATP resynthesis relies on the re-formation of ATP from adenosine diphosphate (ADP) and a phosphate group (figure 1).

Figure 1. ATP molecule structure and energy liberation



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Hydrolysis (adding water) of ATP to produce energy:

ATP $\rightarrow$ ADP + P_i + energy

Phosphorylation (adding a phosphate) of ADP to reform ATP

$ATP \leftarrow ADP + P_i + energy$

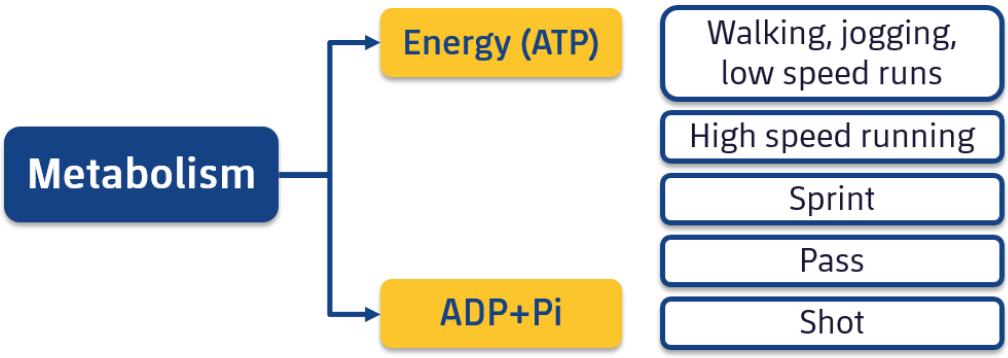
The key concept to understand is that ATP is continually used and regenerated. Stores of ATP act as an immediate source of energy. However, the intramuscular stores of ATP are relatively small (~5 mmol/kg wet muscle). Therefore, metabolic pathways must be activated to sustain the rate at which ATP is used. At 75 % of $\dot{V}O_{2max}$ (the approximate oxygen uptake during a football match (module 1)) ATP is utilised at a rate of 3.7 mmol/kg/second.

The ATP resynthesis process is possible because players have energetic stores that support the ATP formation process (phosphorylation). Central to the importance of sports nutrition is that this energy is provided to the players via the foods and beverages in their diet. After being consumed, food is used or stored in the body to be available to release its energy in response to exercise. Specifically, these energy stores include creatine (Cr) (which is stored as phosphocreatine [PCr]), glucose (which is stored as glycogen) and lipids (which are stored as triglycerides [TG]).

Did you know?

Muscles are made up of small fibres called myofibrils. Myofibrils consist of smaller protein filaments called actin and myosin. Filaments "slide" in between each other to shorten the muscle, causing it to contract.

Figure 2. The energy for all football specific activities is provided by ATP. The resynthesis of ATP is maintained by metabolism



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Metabolic systems

The main metabolic pathways that use the energy stores to drive ATP resynthesis are:

(1) ATP-PCr (phosphagen) energy system,
(2) glycolytic system (for glucose and glycogen metabolism),
(3) aerobic system (for glucose, glycogen and fat metabolism).

Each energy system requires different enzymes and steps in the metabolic processes, which influences the rate at which ATP can be resynthesised.

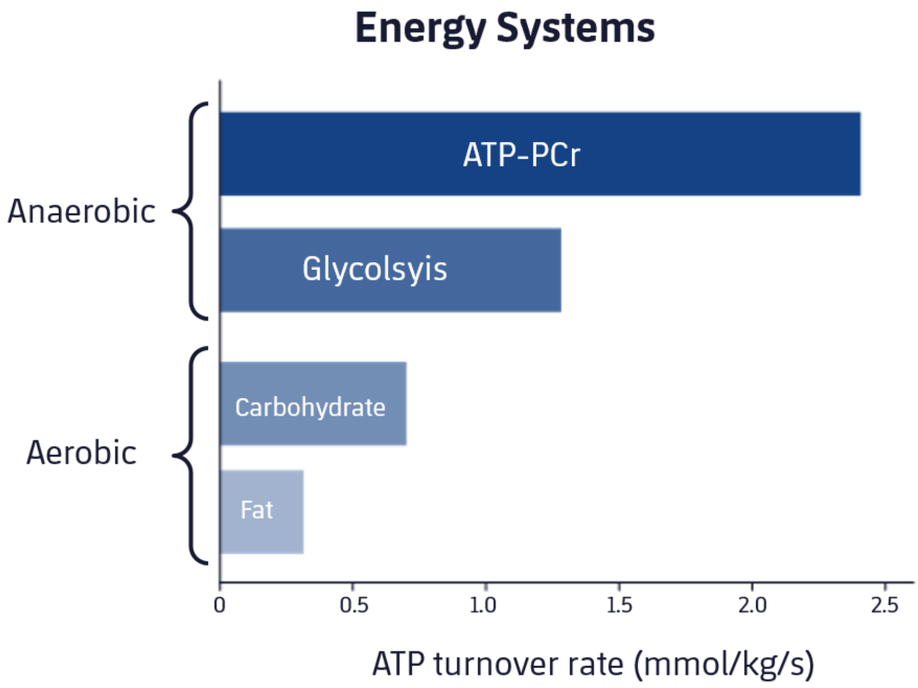
As PCr, glycogen and triglycerides have different structures, their rate of degradation are different and this influences the rates of ATP resynthesis. This is a very important feature of the energetic stores, because the rate of ATP resynthesis determines the rate of force production that can be sustained in the player's skeletal muscle (figure 2). The faster the rate of ATP resynthesis, the higher the rate of force production per unit of time. The relationship between the force produced by the muscle and the time necessary to do so is called the force-time curve.

In football, it is important for the muscle to generate appropriate force in relation to the weight of passes, accuracy of shots and respond appropriately to ongoing dynamic events for the duration of the match. Players can achieve this through the metabolism of available energy pools (fuel sources) to sustain performance. A goal of sports nutrition strategies is to ensure that the player has adequate energy pools available to resynthesise ATP at the rates required to support football performance.

Did you know?

Enzymes are biological catalysts which facilitate chemical reactions in the body. Enzymes act on substrates. The enzyme converts the substrates into different molecules known as products. The energy systems require specific enzymes to catalyse individual steps in the energy pathway.

Figure 3. The rate of ATP turnover from the anaerobic and aerobic energy systems



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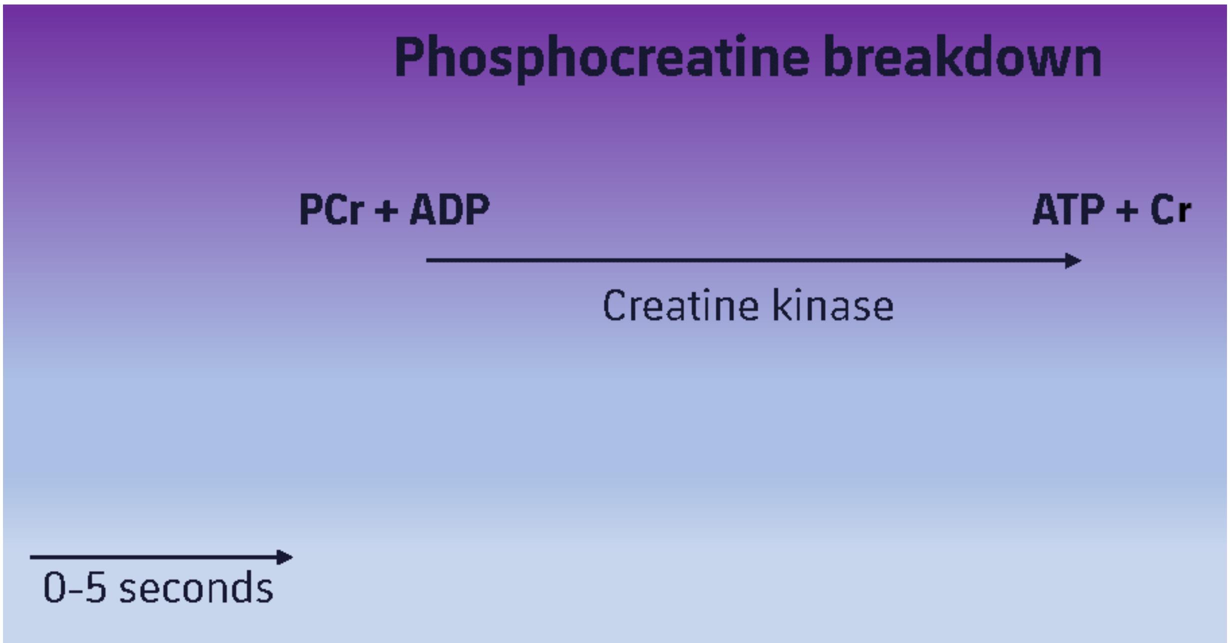
Sprinting

All those activities that require the player to generate force quickly during football, such as sprinting, jumping or shooting, are dependent on the ATP-PCr system. The ATP-PCr is the simplest and most rapid system to regenerate ATP, as it only requires a single enzymatic step.

In the initial stages of a sprint in football, the energy will be provided instantaneously by the ATP-PCr system without the use of oxygen. As previously stated, ATP can act independently as an immediate source of energy. This is the ATP-PCr system contribution of ATP. The splitting of the high-energy phosphate of the ATP present in the cell provides immediate energy in the initial stages of muscle contraction (Gastin, 2001). The PCr section of the ATP-PCr system splits the high-energy phosphate of PCr and donates it to ADP, to then reform the ATP.

During the first seconds of a high-intensity muscle contraction, ATP is resynthesised at very high rates by PCr breakdown. This is a consequence of two important factors: (1) PCr is stored in the cytosol of the cell, very close to the sites of energy utilization; and (2) The PCr breakdown process requires only one enzymatic step. Therefore, this way of providing energy to the muscle is simple and quick. The breakdown of PCr is catalysed by the enzyme creatine kinase (CK), which is activated by an accumulation of ADP in the muscle cell. The ATP-PCr system is capable of regenerating ATP at twice the rate of ATP resynthesis from glycolysis. Thus, the ATP-PCr is the predominant system of ATP resynthesis during the initial seconds of maximal muscle contractions (figure 4).

Figure 4. PCr breakdown process to meet energy demands during the first seconds of a maximal activity



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A limitation of the PCr energy system is that, just like ATP, the intramuscular store of PCr is small, limiting the amount of energy that can be produced from PCr breakdown. Resting levels of PCr can be completely depleted at the end of high-intensity exhaustive exercise (Gastin, 2001). The rate of PCr breakdown is increased by approximately 28 % after only 1.3 seconds of muscle contraction and by 45 % after 2.6 seconds (figure 5) (Hultman and Sjöholm, 1983). Accordingly, approximately 70 % of ATP production is supplied by the degradation of PCr during the first 3 seconds as a player sprints for a ball. The degradation of PCr has been reported to follow a biphasic response, with a rapid phase lasting approximately 10 seconds (during which 70 % of the PCr is degraded) and a slow phase lasting approximately 20 seconds (where the remaining 30 % is degraded). Fast-twitch muscle fibres have been reported to contain 15-20 % more PCr in comparison to slow-twitch fibres (Söderlund and Hultman, 1991).

Did you know?

Muscle fibres can be classified into different "types". A type 1 muscle fibre is considered "slow", whereas type 2 muscle fibres are considered "fast". This is because type 1 fibres have a higher oxidative capacity and type 2 fibres have a higher glycolytic capacity.

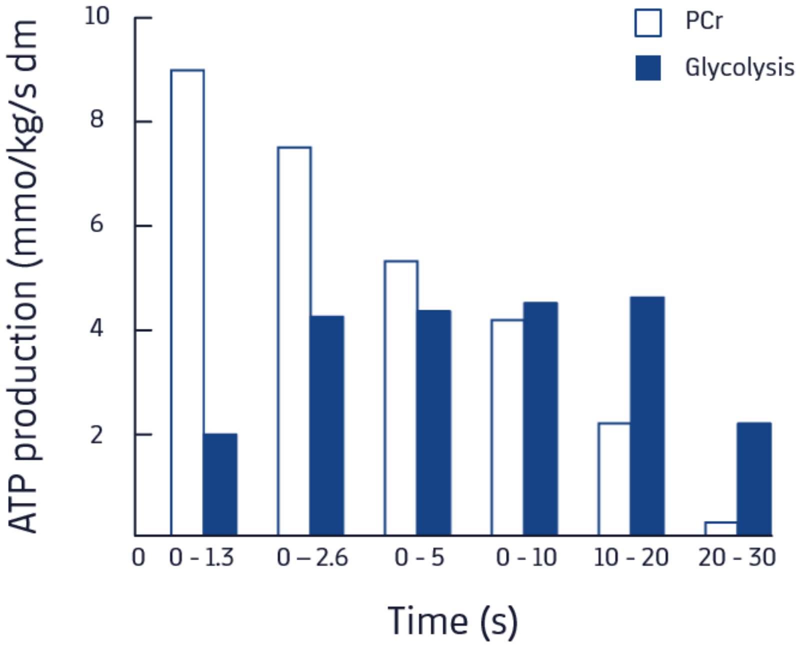
Measurements of PCr taken from muscle biopsies obtained after intense exercise periods during a football match have shown values around 75 % of the level at rest. However, this figure is likely to be significantly lower during the match, as these values were obtained from biopsies taken 15–30 seconds after match activities, during which a substantial re-synthesis of PCr would have certainly occurred (Krustrup et al., 2006). Using estimated values for resynthesis of PCr, PCr levels may be expected to be below 30 % of resting concentrations during parts of a match, when a number of intense bouts are performed with only short recovery periods between them.

High-intensity activities are noted to produce H^+, the accumulation of which increases the acidity within the cell and has been implicated in fatigue (module 1). Russell and Kingsley (2012) demonstrated that blood pH and buffering capacity are reduced throughout a football match and such metabolic perturbations are even more pronounced during the extra-time period (Harper et al., 2016). Keeping this in mind, the ATP-PCr energy system has an additional benefit for high-intensity football performance, since it has the ability to buffer the accumulation of hydrogen ions (H^+). The reaction of PCr breakdown involves the absorption of H^+ (figure 4) (Lindinger et al., 2005). Bishop et al. (2004) suggested that the ability to buffer H^+ is an important attribute for maintaining performance during brief, repeated sprints. Furthermore, the buffering capacity of the muscle (alongside aerobic fitness) is a strong predictor of repeated sprint performance. Importantly, despite the fact that muscle pH has not been established as a direct cause of fatigue during brief, high-intensity exercise (module 1), a low muscle pH has been shown to reduce the contractile properties (Metzger and Moss, 1990) and inhibit glycolytic activity (Hollidge-Horvat et al., 1999; Spriet, 1991). To this end, the buffering capacity of the muscle is likely to have implications for energy production and associated football performance. For example, professional players have been shown to have superior buffering capacity of H^+ in comparison to amateur football players (Rampinini et al., 2009). This is likely a consequence of accumulated match/training physiological adaptations and potentially enhanced nutrition strategies employed by professional versus amateur teams (Football Nutrition Skills Course).

Did you know?

Mitochondria are specialized structures with an inner and outer membrane and are considered the "powerhouses" of cells. The mitochondria are the sites of energy metabolism where nutrients and oxygen are used to generate ATP.

Figure 5. Rate of ATP production and metabolic dependence at the beginning of muscle contraction

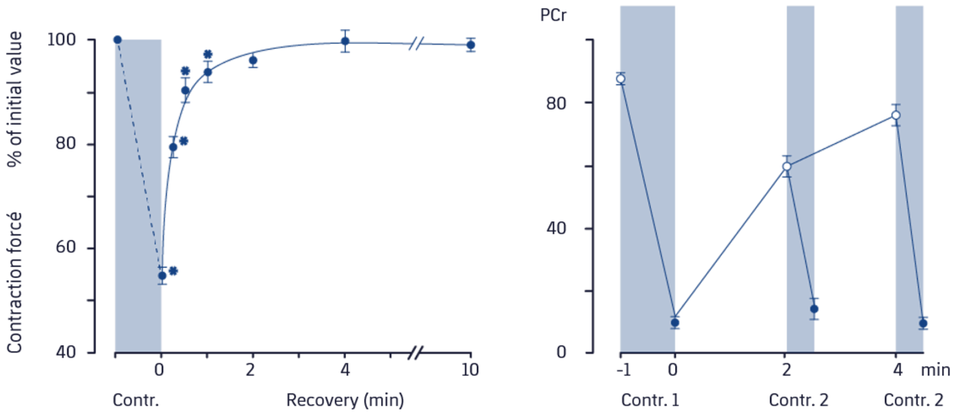


Source: Hultman and Sjoholm, 1983, https://lc.cx/iOYB_K

Figure 6. PCr breakdown and recovery (graphic a). The influence of repeated contractions on PCr concentrations and the ability to generate force (graphic b)

Graphic a

Graphic b



Source: Sahlin et al., 1998, https://lc.cx/edYeGK

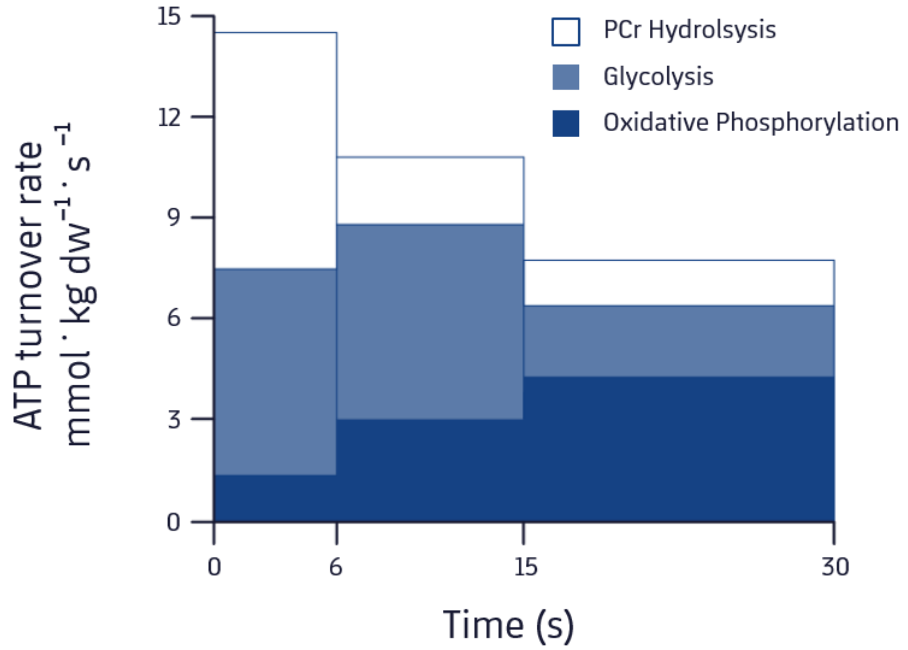
The resynthesis of PCr occurs thanks to the contribution of energy produced by ongoing aerobic metabolism. Approximately 50 % of PCr stores are recovered within 30 seconds of recovery and fully restored in 2 to 4 minutes of recovery (graphic a). Active recovery rather than complete inactivity appears to speed the recovery of PCr stores. During a football match, players usually achieve this by performing lower-intensity running to regain their tactical positions following a high-intensity effort/sprint. However, this is not always possible due to the “flow” of the game. Insufficient recovery time will impair the ability to generate energy through the PCr energy pathway and impair the player’s repeated high-intensity running performance (graphic b).

Importantly, higher rates of PCr resynthesis will be achieved in players with better aerobic capacities ($\dot{V}O_2$ max). A higher mitochondrial density, especially in type IIa fast fibres, will also speed resynthesis of PCr. In practical terms, the ability of the player to recover quickly from an intense effort offers a clear performance advantage, if they are ready to “sprint again” before an opposing player. High-intensity repeated sprint performance may also be improved with dietary supplementation with creatine monohydrate to increase the muscle energy store of PCr (Football Nutrition Skills Course).

High speed running

Given the relatively limited reserve of PCr, other systems must help to maintain a supply of energy for the intense activities during a match. For high-speed running (approximately 15-18 km/h) between 6 seconds and 2 minutes, ATP will be generated predominantly through glycolysis. It is important to note that the energy systems do not work exclusively but on a continuum. The relative contribution of the energy system will change depending on the intensity and duration of exercise (figure 7).

Figure 7. Relative contribution of ATP-PCr, glycolysis, and aerobic metabolism (carbohydrate and fat) to ATP resynthesis during a 30 seconds bout of maximal isokinetic cycling



Source: Parolin et al., 1999, https://lc.cx/_u7Pdr

Glycolysis involves the breakdown of carbohydrate derived either from glucose or from glycogen (the storage form of glucose). A rapid sequence of reactions breaks down molecules of glucose into two molecules of pyruvate or two molecules of lactate, with a net gain of two ATP and the formation of two molecules of NADH from NAD+. This process occurs within the muscle fibre and proceeds quickly without the use of oxygen (anaerobic energy system). If the oxidation of pyruvate continues to the tricarboxylic acid cycle (TCA) cycle to form carbon dioxide and water (see aerobic metabolism below), the net yield of ATP is much higher (38 ATP per molecule of glucose).

Did you know?

NAD and FAD are "carriers," they transport hydrogens and their associated electrons to be used later in the generation of ATP in the mitochondria.

Although the energy yield of glycolysis is small, the readily available store of carbohydrate (glycogen, glucose) and the rapid rate of glycolysis are essential for the repeated intense exercise performed during a football match. For the glycolysis reaction to proceed, the NADH formed by the glycolytic reaction must be reformed back to NAD+ at an equal rate. To achieve this, the product of glycolysis, pyruvate, has two main fates.

(1) Pyruvate enters the mitochondria. Pyruvate is converted into Acetyl CoA, which enters the tricarboxylic acid cycle. The tricarboxylic acid cycle (also known as the Krebs cycle) completes the oxidation (removal of hydrogen) of carbohydrates and fats using energy carriers (NAD, FAD). Carbon dioxide is also produced at this stage. The removal of the hydrogens is important as they contain the potential energy in food molecules. It is this energy that can be passed to the final stages of aerobic metabolism, the electron transport chain. The electron transport chain occurs in the mitochondria and powers the regeneration of ATP from ADP. The net gain is 38 ATP molecules per mol of glucose. This process is called aerobic glycolysis, as it requires oxygen. The oxygen is used at the last stage of the electron transport chain to produce water.

(2) Pyruvate may be converted to lactate. This process is often called anaerobic glycolysis, as it does not require oxygen. If the intensity of exercise remains high and the demand for energy is great, the rate of pyruvate production will exceed that which can be used by the mitochondria and lactate will accumulate within the muscle.

At rest, blood lactate concentrations may range from 0.5-1.0 mmol/L, depending on prior activity. “Average blood lactate concentrations of 2–10 mmol/L have been observed during football games, with individual player values above 12 mmol/L (Krustrup et al., 2006)” (Bangsbo, 2014, https://lc.cx/lefEFe).

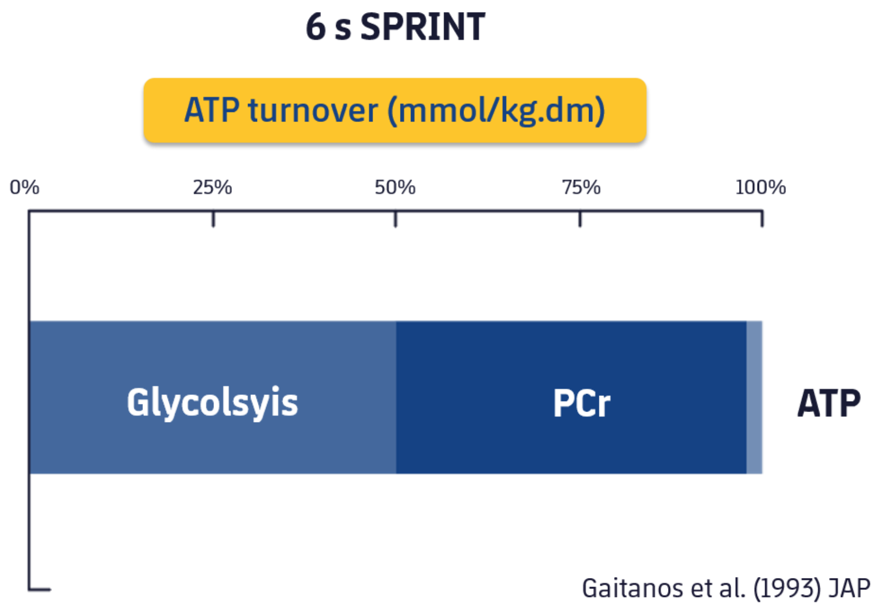
These findings indicate that the rate of glycolysis in the muscle is high during a match. However, muscle lactate (a direct marker of lactate production) has only been measured in one football specific study (Bangsbo, 2014).

“In a friendly game between two non-professional teams, muscle lactate rose four-fold (to around 15 mmol/kg d.w.) compared to resting values after intense periods in both halves, with the highest value being 35 mmol/kg d.w. (Krustrup et al., 2006). Such values are less than one-third of the concentrations observed during non-football specific short-term intermittent exhaustive exercise (Krustrup et al., 2003)” (Bangsbo, 2014, https://lc.cx/lefEFe).

“An interesting observation is that muscle lactate was not correlated with blood lactate. A scattered relationship, with a low correlation coefficient, has also been observed between muscle and blood lactate when players performed repeated intense exercise (Yo-Yo intermittent recovery test) (Krustrup et al., 2003). This is in contrast to continuous exercise where a strong positive correlation is seen between the blood lactate concentrations and the muscle lactate concentrations. These differences between intermittent and continuous exercise are probably due to different turnover rates of muscle and blood lactate during the two types of exercise, with the rate of lactate clearance being significantly higher in muscle than in blood (Bangsbo, Johansen, Graham & Saltin, 1993). This means that, during the intermittent football exercise, the blood lactate level may be high even though the concentration of lactate in the muscle is relatively low. The relationship between muscle and blood lactate will also be heavily influenced by activities performed immediately prior to sampling (Bangsbo et al., 1991; Krustrup & Bangsbo, 2001). Thus, the high blood lactate concentrations often seen in football (Bangsbo, 1994; Ekblom, 1986; Krustrup et al., 2006) may not represent high lactate production in a single action during the game, but rather reflect the response to an accumulated number of high-intensity activities. This is important to consider when interpreting blood lactate concentrations as a measure of muscle lactate production" (Bangsbo et al., 2006, p. 667).

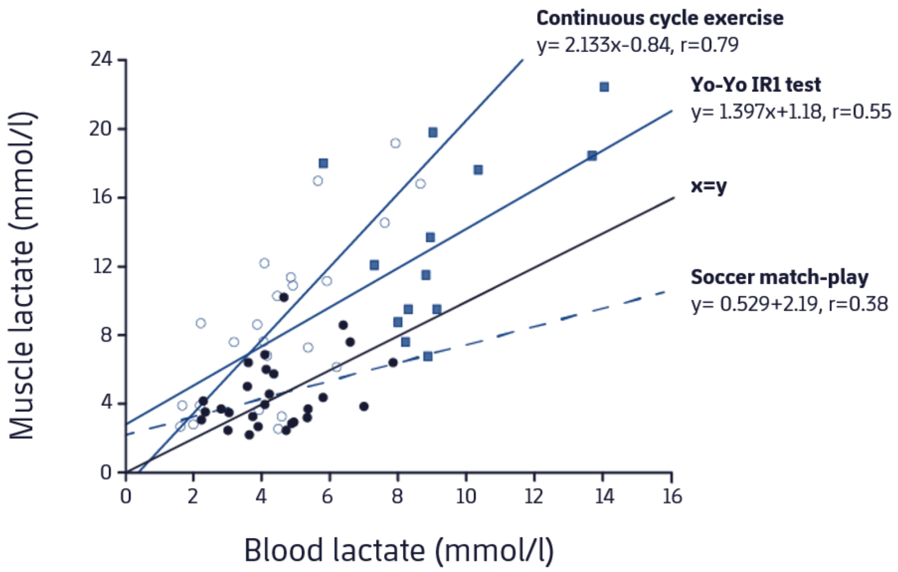
During a match, the glycolytic energy system is extremely important, as it provides energy at very high rates. As an example of how important glycolysis is in supporting high-intensity running, even in a 6-s sprint, glycogen will contribute approximately 50 % to ATP turnover within the muscle (Gaitanos et al., 1993). Therefore, based on the finding of high blood lactate and moderate muscle lactate concentrations during matches, and the fact that glycogen stores are significantly depleted during a match, it can be concluded that glycolysis is an important energy system for football performance.

Figure 8. Contribution of the ATP-PCr and glycolytic energy systems to ATP generation during a 6 second all out sprint



Source: adapted from Gaitanos et al., 1993.

Figure 9. Blood lactate vs. muscle lactate levels in different exercise protocols

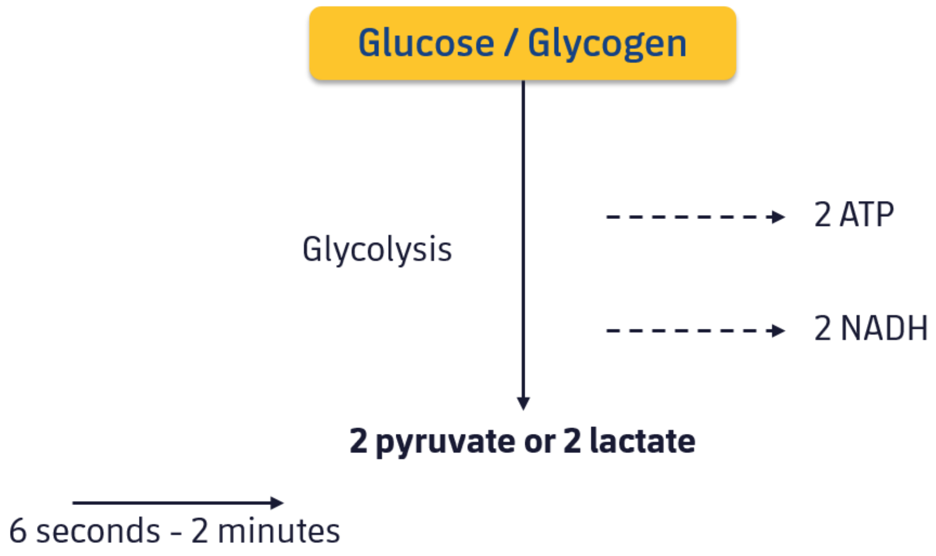


Source: Bangsbo et al., 2006, p. 668

"Individual relationship between muscle lactate, expressed in mmol/l cell water, and blood lactate, during a football match (filled circles; data from the present study), at exhaustion in the Yo-Yo intermittent level 1 recovery test (filled squares; data from

Krustrup et al., 2003) as well as after 20 min of continuous cycle exercise at 80 % of maximal oxygen uptake (open circles)" (Bangsbo et al., 2006, p. 668).

Figure 10. Glycolytic pathway



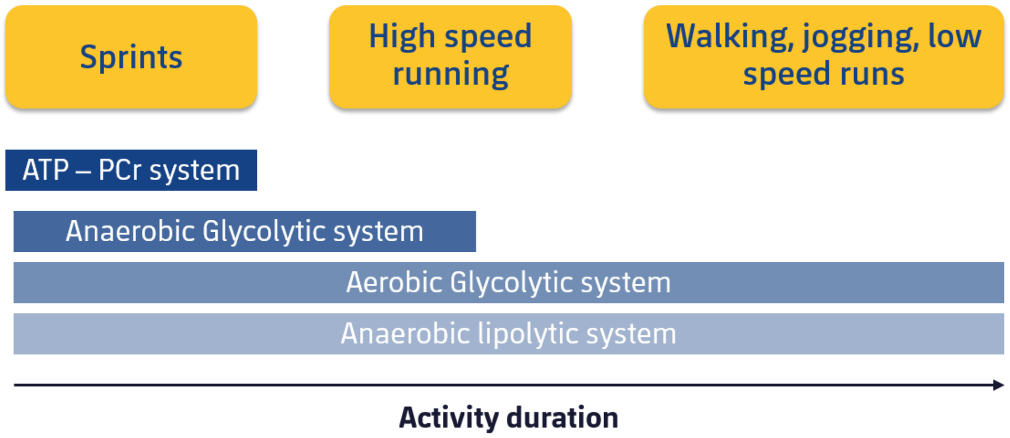
Source: own elaboration.

Walking, jogging, low-speed running

The energy for low-intensity activities: standing still (recovering from high intensity actions), walking and low speed running, will be provided almost exclusively by aerobic metabolism. The process of aerobic metabolism is complex and a detailed and complete description is beyond the scope of this course. Aerobic energy is produced by specialised organelles called mitochondria with the use of oxygen, which is transported to the muscle via the blood. The main substrates used for aerobic metabolism are formed either through glycolysis (using carbohydrate sources: pyruvate as previously discussed) and beta-oxidation (fat sources). Protein can also be broken down and used as a substrate for aerobic metabolism. However, the contribution of protein to energy production during football is negligible in comparison to both carbohydrate and fat.

Aerobic metabolism makes an increasing contribution to total energy provision as the duration of the training or match progresses. Acetyl-CoA is the product of both pyruvate conversion in the mitochondria and fatty acid oxidation. Acetyl CoA enters the TCA cycle, generating hydrogen atoms to be passed along the electron transport chain. The high concentration gradient of hydrogen between the inner and outer membranes of the mitochondria generates a force that is used to drive ATP synthesis. The oxidation of fatty acids provides more ATP per molecule than glucose, but requires more oxygen than the oxidation of glucose. Importantly, the relative contribution of these fuels during exercise will depend on several factors, including the pre-exercise carbohydrate stores, the exercise intensity and duration, and the training status of the player (Unit 2). The large aerobic component of football results in a large utilization of the available energy pools (carbohydrate and fat) by the exercising muscle. Thus, it is important to understand how the players' body stores energy and how these different energy pools are harvested during a football match.

Figure 11. Summary of the energy systems involved in the key football activities



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Unit 1. Summary

- Metabolism is the process of converting food into energy.
- Energy systems work in concert to generate ATP to support football specific movements.
- Short intense activities, sprints and jumps are dependent on the ATP-PCr energy system.
- Repeated sprints are dependent upon the recovery of PCr stores in muscles.

- Longer sprints and high intensity running will have a greater reliance on glycolysis to provide energy.

- Aerobic metabolism will support low Intensity activities (walking and low speed running) as well as the replenishment of PCr stores during periods of recovery.

2. 1 Fuels for football

The large aerobic component of football results in a large energy requirement. The energy expenditure for an outfield player is approximately 1300–1600 kcal (Bangsbo et al., 1991). Carbohydrate contributes 60 %-70 % to the total energy supply (Ferrauti et al., 2006). These additional energy requirements of football are additional to daily living energy needs. Therefore, the total MD energy expenditure on match day has been estimated at ~3500 kcal.

The main sources of fuel (substrates) that the player's body uses to produce energy are carbohydrates and fats. Both carbohydrates and fats enter the body as food and, following digestion and absorption, are either stored for later use or used immediately in metabolism. Therefore, it is the player's nutrition, which is fundamental in supporting performance by providing the appropriate fuels to produce the energy required for training and matches throughout the season. Although proteins can be used as fuel, they are not considered an important energy substrate for football (Coyle et al., 1997). The current unit will focus on the storage and metabolism of carbohydrate and fat as the main energy substrates and discuss those factors that influence their use during football training and matches.

Did you know?

The substrates for energy production in football are made from the digestion and absorption of foods.

Fats

Fat is stored in the body in the form of triglyceride, which is composed of three fatty acids attached to a molecule of glycerol. Fatty acids consist of chains of carbon atoms with hydrogen atoms attached.

Fat is stored in different locations in the body. The assessment of the quantity of body fat will be covered in module 3. Fats are stored in the player's body as subcutaneous adipose tissue (under the skin), visceral fat (around major organs) and intramuscular triglyceride (IMTG) (in muscle). The store of IMTG in the muscle is important as it places fat in close proximity to the mitochondria (site of oxidative energy production in the muscle).

Did you know?

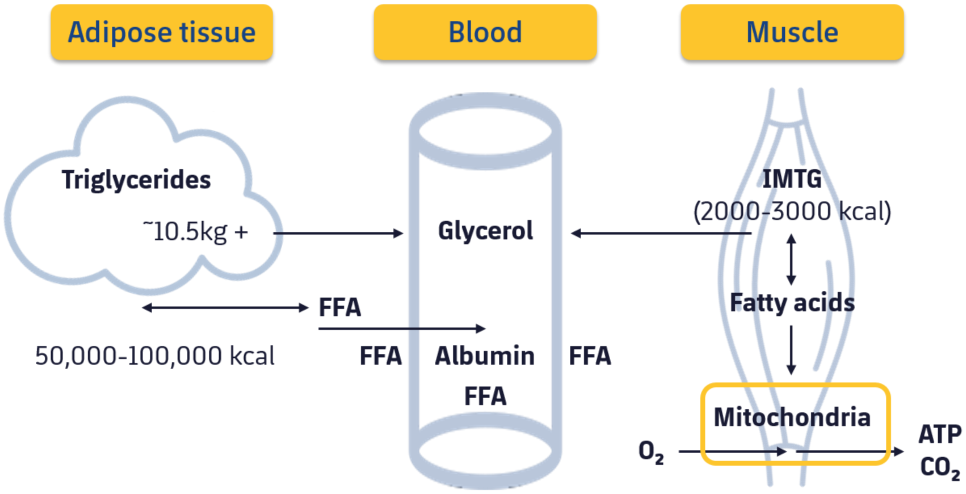
Common sources of dietary fat include oils, spreads, animal fats, dairy products, nuts and seeds.

A player's body has a huge capacity to store fat. For a lean 70 kg player with 10 % body fat, the quantity of adipose tissue is approximately 7000 g, which could yield approximately 63,000 kcals. In addition, up to 300 g of fat can be stored in muscles (intramuscular triglyceride), with a potential yield of 2700 kcal. This provides an almost limitless energy supply. Fats can be mobilized as an energy source during exercise through the action of hormone sensitive lipase, splitting fat into glycerol and three fatty acids. Nearly all free fatty acids are transported in the blood, loosely bound to albumin, to the working muscles. There is more stored energy per gram of fat (9 kcal) than carbohydrate (4 kcal/g). However, although fat provides an abundant energy supply and yields more energy than carbohydrate on a per gram basis, it is important to understand that the rate of energy production resulting from the breakdown of fat is much slower than that of carbohydrate. Therefore, fat oxidation cannot keep up with the high energy demand of the match activities, such as high-speed running and sprinting. As exercise intensity increases, there is an increased reliance on carbohydrates for energy production.

Fat is transported into the muscle during football exercise via a fat specific transport protein. The fat transport protein (FAT/CD36) translocates to both the muscle membrane and mitochondrial membrane during exercise. In the muscle, fatty acids are activated by acyl-CoA synthetase, forming fatty acyl-CoA. The fatty acyl-CoA is then transported to the mitochondria for beta oxidation and energy production (figure 2) (Turcotte et al., 1991).

In comparison to the other energy systems (Unit 1), the player's ability to convert their body fat stores into energy during training and games is slow. Therefore, players must rely on carbohydrate metabolism for high-intensity exercise. If the store of carbohydrate is low, then the intensity of play will be reduced to a level that can be supported predominantly by the metabolism of fat. In endurance events such as the marathon, this is commonly referred to as "hitting the wall". In football, players are at risk of low carbohydrate stores in the final stages of a 90-min game and in the extra-time period, especially with inadequate sports nutrition strategies.

Figure 12. Fat storage, transport and use in the players' body



Source: own elaboration.

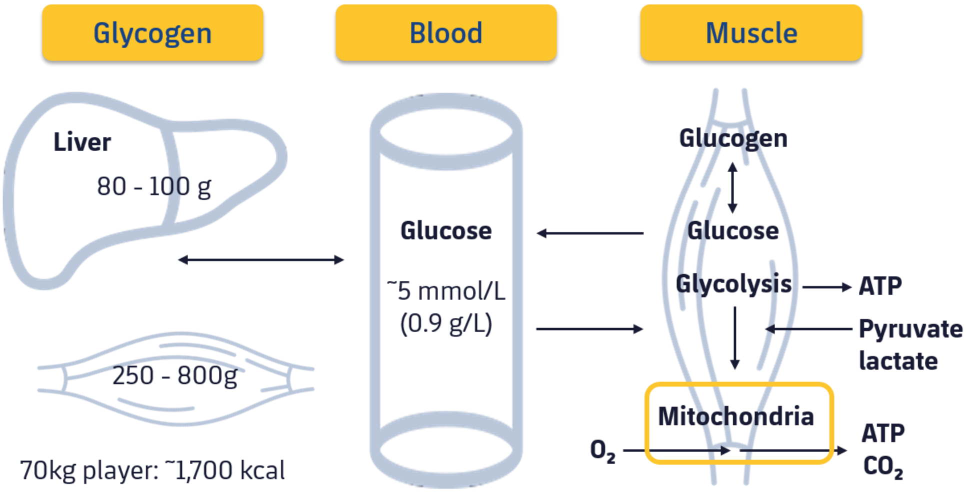
Did you know?

Hormones are chemical messengers secreted directly into the blood, which transports them to the tissues of players' bodies to exert their functions. There are many types of hormones that regulate different bodily functions. Insulin, a hormone secreted by the pancreas, promotes the uptake of carbohydrate (glucose) into muscles for immediate use or storage. Glucagon is a hormone also secreted by the pancreas that promotes the breakdown of stored carbohydrate and fats.

Carbohydrates

Carbohydrates are stored in the body in the form of glycogen (a condensed matrix of glucose molecules). The two main body stores of glycogen are located in the liver and skeletal muscle (figure 2). In a 70 kg player, approximately 80-100 g of glycogen is stored in the liver, 300-800 g in the muscle, there is also a small but significant reservoir of glycogen in the brain. Blood glucose also provides a store of carbohydrate, which is tightly regulated to 0.9 g per litre of blood in healthy players.

Figure 13. Carbohydrate storage, transport and use in the player's body



Source: own elaboration.

Did you know?

Well-known sources of dietary carbohydrate include bread, rice, potatoes and pasta. However, fruits and even many dairy products also contribute to total carbohydrate intake.

The player's body store of glycogen is generally sufficient to cover the amount of carbohydrate used by the body in a single day (Flatt, 1995). However, this will depend on the physical activity performed. Thus, depending on the diet and the pattern of physical activity performed, muscle glycogen reserves in the player's body will vary (Coyle et al., 1997). Because a high rate of carbohydrate oxidation is required to sustain intense exercise for prolonged periods, insufficient carbohydrate intake in a player's diet can easily deplete glycogen stores and the player may experience premature fatigue during a match (Coyle et al., 1997).

The carbohydrates that we ingest are absorbed as monosaccharides (single sugars) in the intestinal cells after the action of the digestive enzymes (amylases, disaccharidases). Once in the circulation, glucose is transported to the liver and made available to the whole body. Glucose transport into cells is facilitated by a group of specialized glucose transporter proteins (GLUTs). At rest, the ingestion of carbohydrates stimulates the release of insulin. The action of insulin stimulates a series of intracellular signalling cascades that ultimately result in the translocation of glucose transporter protein type 4 (GLUT4) to the plasma membrane. During football, GLUT4 will also translocate to the cell membrane, driven through muscle contraction, increasing the uptake of available blood glucose into the muscle (Richter and Hargreaves, 2013).

Did you know?

Translocation simply means a change in location. For example, when a protein in the cell moves location to the cell membrane.

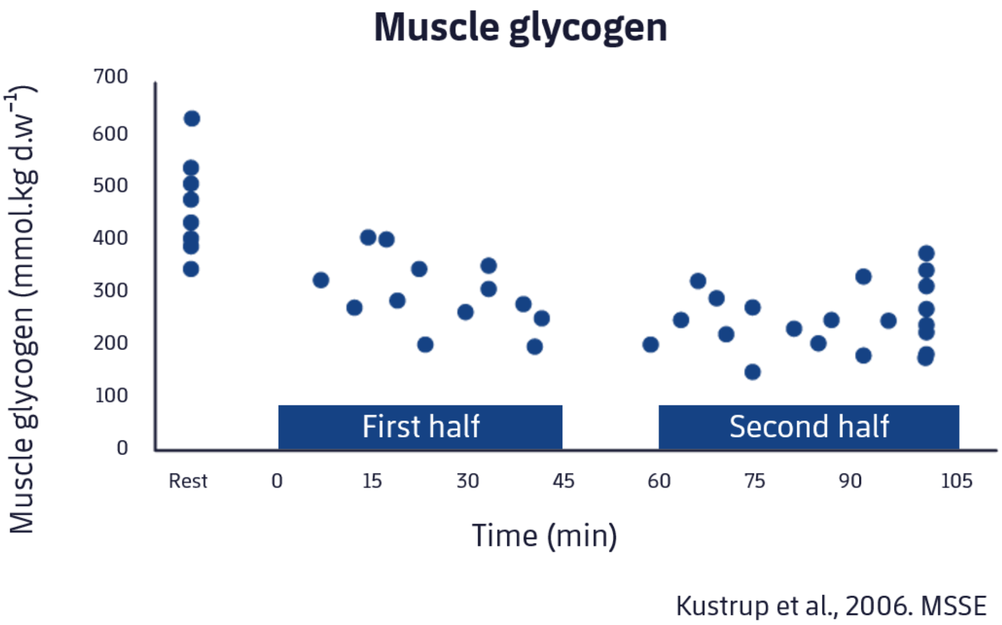
As glucose crosses the cell membrane, it is converted to glucose-6-Phosphate, which prevents it from leaving the cell. If the energy demand of the cell is high, glucose-6-Phosphate enters glycolysis. However, if the energy demand is low, then the glucose-6-Phosphate is arranged and stored as bundles of glucose units (glycogen). The formation of glycogen is driven by the action of a key enzyme, glycogen synthase. This process allows the accumulation of glycogen in the liver and muscle. Glycogen can be rapidly broken down by another enzyme (glycogen phosphorylase) in a process called glycogenolysis. This process results in the sequential release of the individual glucose units, which can then enter glycolysis for energy production.

The key point regarding the use of carbohydrates for energy production in football is that the player's body store of carbohydrates is finite. In a 6-s sprint, glycogen will contribute approximately 50 % to ATP turnover within the muscle (Gaitanos et al., 1993). Thus, the repeated sprint activity during a football game result in a net reduction in muscle glycogen concentrations (figure 3). Low muscle glycogen concentrations have been associated with impaired performance, as measured by distance covered at high intensity toward the latter stages of a match (Bendiksen et al., 2012). Therefore, nutrition priorities are to ensure the player begins exercise with "full" stores of glycogen. This can be achieved by eating sufficient quantities of carbohydrate in the hours before exercise, as well as providing carbohydrate before and during the game. The ingestion of carbohydrate acutely around the match occasion will block the release of hepatic glycogen, support energy production in the muscle and may have a "central" stimulatory effect.

Did you know?

A "central" effect refers to an impact on the central nervous system, which is made up of the brain and spinal cord.

Figure 14. Muscle glycogen concentrations at rest and during the first and second half of a football match



Source: Kustrup et al., 2006. p 1168.

Proteins

To be used as a fuel for energy production, proteins must be broken down into amino acids. Skeletal muscle can directly metabolize certain amino acids (the 'building blocks' of proteins), valine, leucine, isoleucine, to produce ATP. These amino acids are modified and their carbon structure can be used to form acetyl-CoA or various intermediates of the TCA cycle for oxidative metabolism. The amino acid alanine can also be converted into glucose in the liver in a process called gluconeogenesis. The glucose can be subsequently returned to the muscle and used for energy metabolism.

Did you know?

Common sources of dietary protein include meat, dairy products and eggs. Plant based proteins can also contribute significantly to a player's protein intake.

Protein will contribute between 3 and 10 % of the total energy, depending on the duration of exercise and the availability of carbohydrate as a substrate. Given the typical duration of football training and matches (60-90 minutes), the contribution of amino acids as a fuel for energy production in the muscle will be negligible.

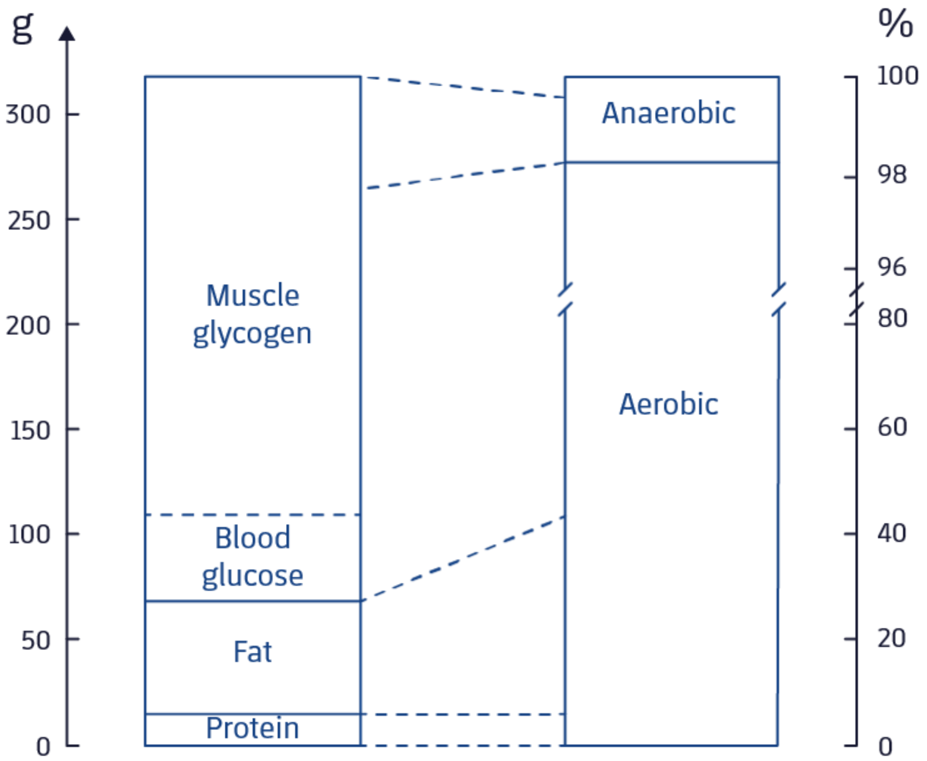
Did you know?

Amino acids are the 'building blocks' of proteins. There are 20 different amino acids which can be classified as essential or non-essential. The non-essential amino acids are those which can be made by the body. The essential amino acids are those which cannot be made by the body, thus must be ingested in the players' diet.

Fuel utilisation during a football game

To provide nutritional strategies for a football player, it is important to understand the energy demands and to know which substrates are utilized during a match. To achieve this, studies have biopsied players' leg muscles before, during and after matches to gain insight into the relative use of different substrates. The estimated relative aerobic and anaerobic energy turnover and the corresponding substrate utilisation during a match is displayed in figure 15. The specific use of carbohydrate and fat as substrates during a football match are discussed below.

Figure 15. Estimated relative aerobic and anaerobic energy turnover and the corresponding substrate utilization during a football match



Source: Bangsbo, 1994a, https://doi.org/10.1080/02640414.1994.12059272

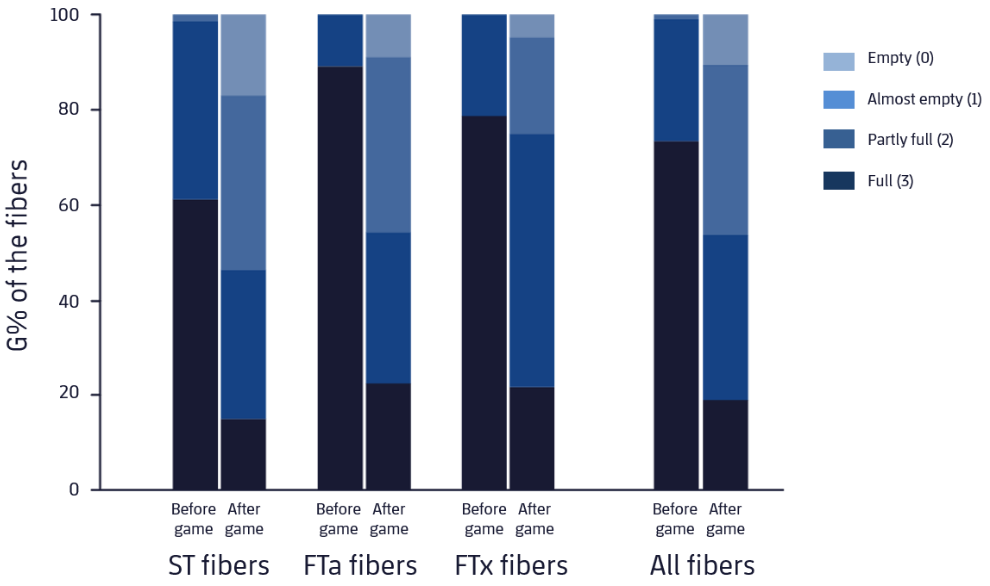
Carbohydrates

Carbohydrates are significantly utilised during a match. The majority of carbohydrate oxidation is contributed by muscle glycogen. Liver glycogen will make a smaller contribution to overall carbohydrate oxidation, but will depend on the glycogen status of the player.

Muscle glycogen is an important substrate for the football player as evident from the various studies where glycogen has been measured. Saltin (1973) observed that muscle glycogen stores were almost depleted at halftime when pre-match levels were low (~45 mmol/kg w.w.). In that study, some players who started the match with normal muscle glycogen levels (~100 mmol/kg w.w.) still had rather high values at halftime, but were below 10 mmol/kg w.w. at the end of the game. Others have found glycogen concentrations to be 40–65 mmol/kg w.w. after the game (Smaros, 1980; Jacobs et al., 1982; Krustrup et al., 2006), indicating that muscle glycogen stores are not always depleted by the end of a football match. However, analyses of single muscle fibres after a game have revealed that a significant number of fibres are depleted or partly depleted at 90 minutes. Again, this is a main reason for fatigue to occur toward the end of a game (Krustrup et al., 2006)" (Bangsbo, 2014, https://lc.cx/lefEFe).

"The analysis of top level football has revealed the ability to maintain high-intensity running and levels of skill proficiency, especially in the final stages of a match, are key attributes of a top class player and successful team (Mohr et al., 2003). Thus, the preservation of muscle glycogen and blood glucose concentrations may be important in supporting the physical demands of football and also other factors which contribute to football performance such as agility, timing, skills and decision making. Although the exact mechanisms are still to be determined, carbohydrate ingestion before and during intermittent running can delay fatigue and improve performance" (Rollo, 2014, https://lc.cx/NGpMir).

Figure 16. Relative glycogen content in slow twitch and fast twitch fibres as well as all fibres before and immediately after a soccer match. Values are means (N = 10)



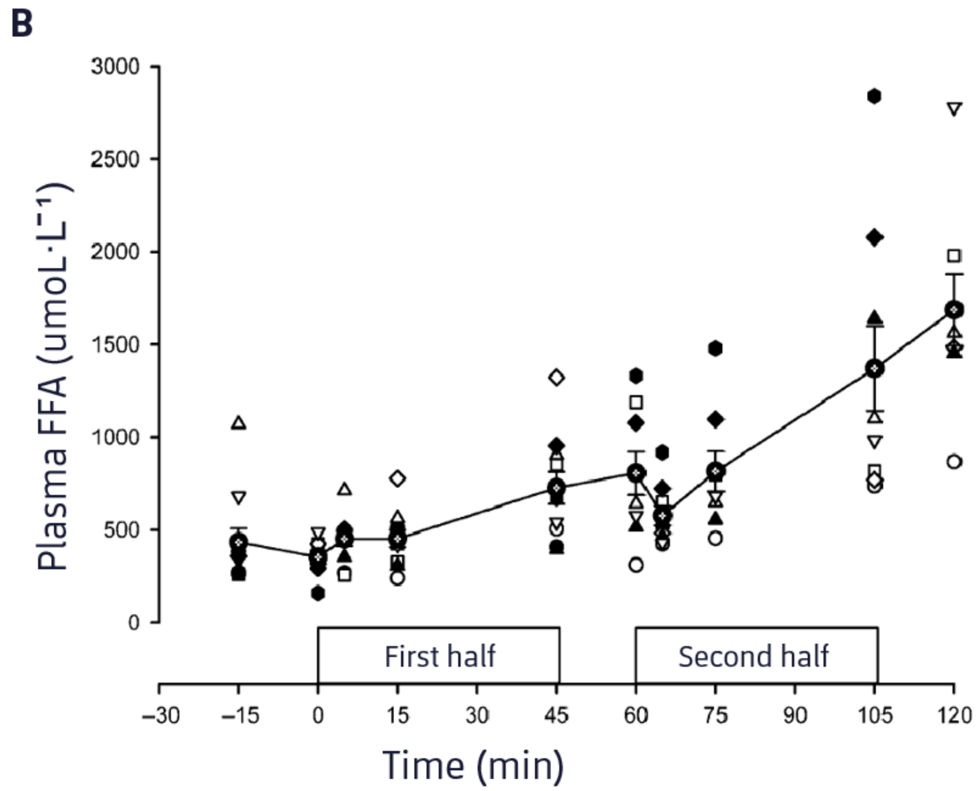
Source: Krustrup et al., 2006, https://lc.cx/K1FXr2

Fat

"Free fatty acid (FFA) concentration in the blood increases during a game, more so during the second half (Bangsbo, 1994; Krustrup et al., 2006) [figure 17]. Frequent rest and low-intensity periods of a game allow for significant blood flow to adipose tissue, which promotes release of FFA. This effect is also illustrated by the finding of high FFA concentrations at halftime and after the game. The suggestion of a high rate of lipolysis during a game is supported by observations of elevated levels of glycerol. The increase in glycerol reported during football is smaller than that reported during continuous endurance type exercise. This difference could potentially reflect a high turnover of glycerol, with it being used as gluconeogenic precursor in the liver (Bangsbo, 1994). Hormonal changes may play a major role in the progressive increase in the FFA concentrations. Specifically, insulin concentrations are lowered, and catecholamine levels are progressively elevated during a match (Bangsbo, 1994), stimulating a high rate of lipolysis and thus the release of FFA into the blood (Galbo, 1983). The effect is reinforced by lowered lactate levels toward the end of a game, leading to less suppression of fatty acid mobilisation from adipose tissue (Bülow & Madsen, 1981; Galbo, 1992; Bangsbo, 1994; Krustrup et al., 2006). The changes in FFA during a match may cause higher uptake and oxidation of FFA by contracting muscles" (Bangsbo, 2014, https://lc.cx/lefEFe).

This may be particularly evident during recovery periods in a game and in the second-half. The elevation in fat use is likely a compensatory mechanism for the progressive lowering of muscle glycogen and used to maintain the blood glucose concentration (critical for the function of the central nervous system). However, it should be emphasized, that should the footballer wish to maintain high intensity efforts, the 'switch' to fat oxidation as a greater contributor to energy production is not ideal. Thus, strategies to enable increased carbohydrate availability should be encouraged.

Figure 17. Plasma FFA concentrations before, during, and after a football match. Data are means as well as individual values



Source: Krustrup et al., 2006, https://lc.cx/K1FXr2

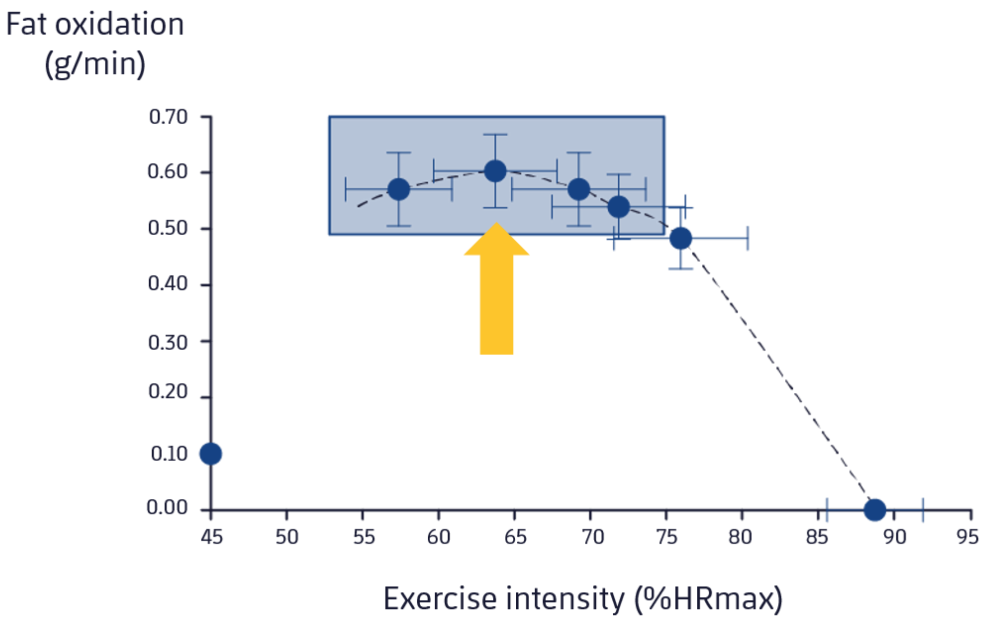
Factors affecting fuel utilisation during football

Factors affecting the metabolism of fat and carbohydrate at rest and during exercise are summarized in figure 18 and discussed below.

Intensity

When players are at rest, fatty acids are the main fuel used by muscles for energy metabolism. As the player begins to exercise, the energy demand is increased. Even during low intensity running, metabolism is significantly higher in comparison to metabolism at rest. Fat oxidation is increased alongside exercise intensity, up to a point. As the intensity of exercise gradually increases, such as when players transition from a slow to high intensity run, fat oxidation will begin to decline. As players achieve maximal exercise intensities (such as during sprints), fat oxidation will be negligible (figure 18). In contrast, carbohydrate metabolism increases as the exercise intensity increases.

Figure 18. Fat oxidation as a function of activity intensity in players



Source: Adapted from Achten et al., 2002.

The term *lipolysis* refers to the process of breaking down adipose tissue into free fatty acids. Lipolysis is dependent upon the concentrations of specific hormones, which promote or inhibit the process. The hormone adrenaline (epinephrine) will stimulate lipolysis, whilst the hormone insulin will inhibit lipolysis.

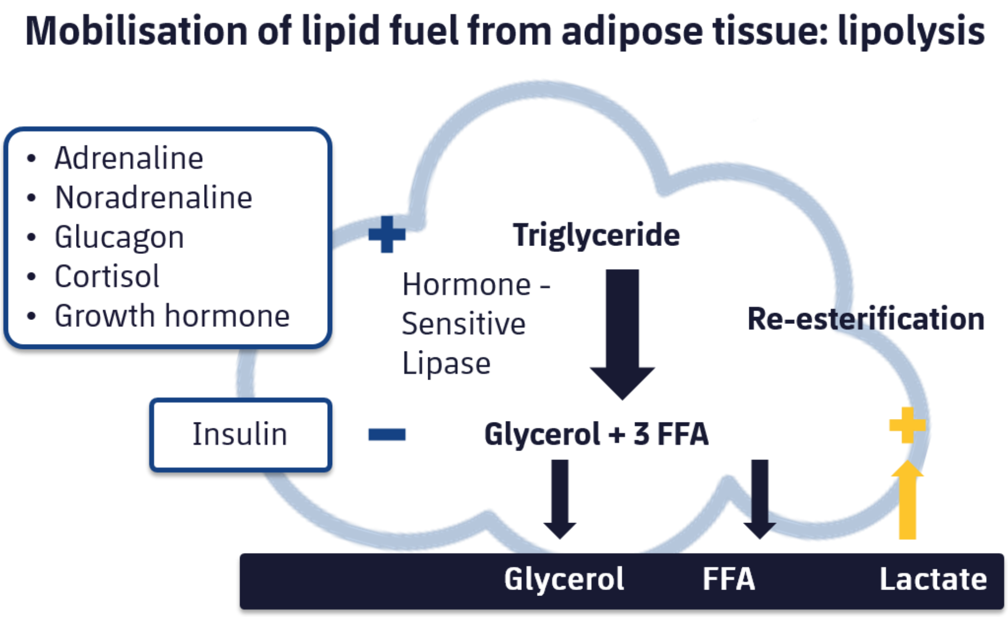
If a player undergoes a prolonged fast (or similarly, in the absence of food overnight), most of their resting energy requirements are met by the oxidation of fatty acids, mobilized from adipose tissue. As players begin football exercise, the rate of lipolysis and corresponding fatty acid appearance in the circulation is increased.

Did you know?

A "fast" is the abstinence from food, drink or both for a period of time. For example, all players engage in a daily overnight "fast" for 7-10 hours as they sleep. This is where the word "breakfast" originates. It simply means the first meal to "break" the "fasting period".

During moderate-intensity exercise, lipolysis increases approximately threefold, mainly because of the action of adrenaline (Jeukendrup, 2003). In addition, during moderate-intensity exercise, the blood flow to adipose tissue is doubled resulting in an increased delivery of fatty acids to the muscle. During the first 15 minutes of training or match play, it is usual for plasma fatty acid concentrations to decline. This is because the rate of fatty acid uptake by the working muscle is greater than the mobilization of fatty acids through lipolysis. However, after approximately 15 minutes, the rate of lipolysis exceeds the rate at which fatty acids can be taken up by the muscle, and fatty acid concentrations in the blood will rise (Jeukendrup, 2002).

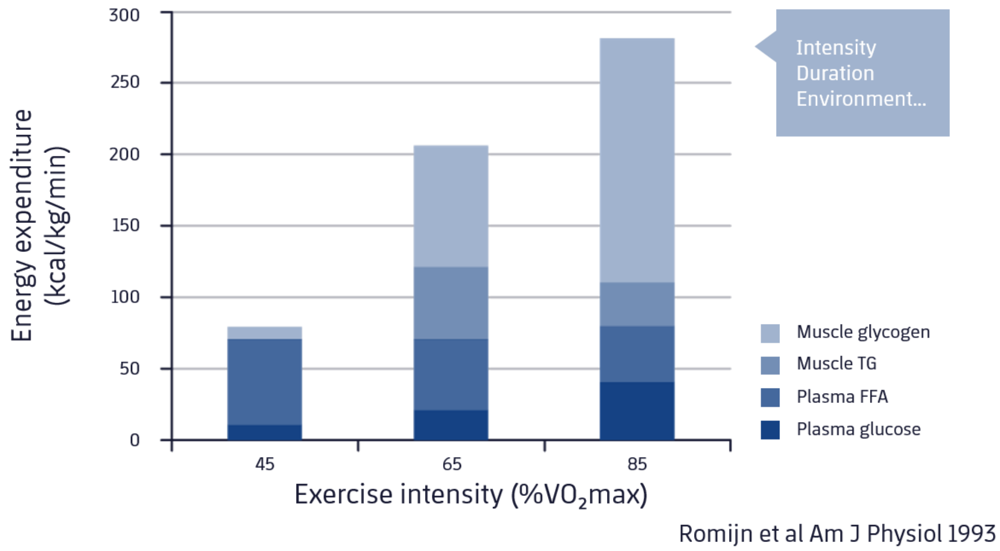
Figure 19. Fat metabolism under exercise-imposed conditions



Source: own elaboration.

Fat metabolism at varying exercise intensities has been investigated under controlled laboratory conditions. Romijn et al. (1993) investigated fat metabolism at three different exercise intensities. The data from Romijn et al. (1993) suggests that lipolysis increases from rest to exercise and from 25 % to 65 % $\dot{V}O_{2max}$. However, at 85 % $\dot{V}O_{2max}$, there is no further increase of lipolysis, and lipolytic rates are similar to those at 65 % $\dot{V}O_{2max}$. As players exercise at intensities above 95 % of $\dot{V}O_{2max}$, carbohydrates and PCr will be exclusively used to produce energy (without the use of fatty acids). Liver glycogen breakdown will also be increased at the onset of exercise. The output of glucose from the liver will increase with exercise intensity. The available glucose will then be transported to and taken up by the active muscle. Here, it is important to note that muscle glycogen becomes the most important energy source when the exercise intensity increases above approximately 50 % of $\dot{V}O_{2max}$ (high-speed running) (Jeukendrup, 2003). This is important, as remember, mean oxygen uptake values reported during a football match are approximately 70 % of $\dot{V}O_{2max}$.

Figure 20. Substrate oxidation at different exercise intensities



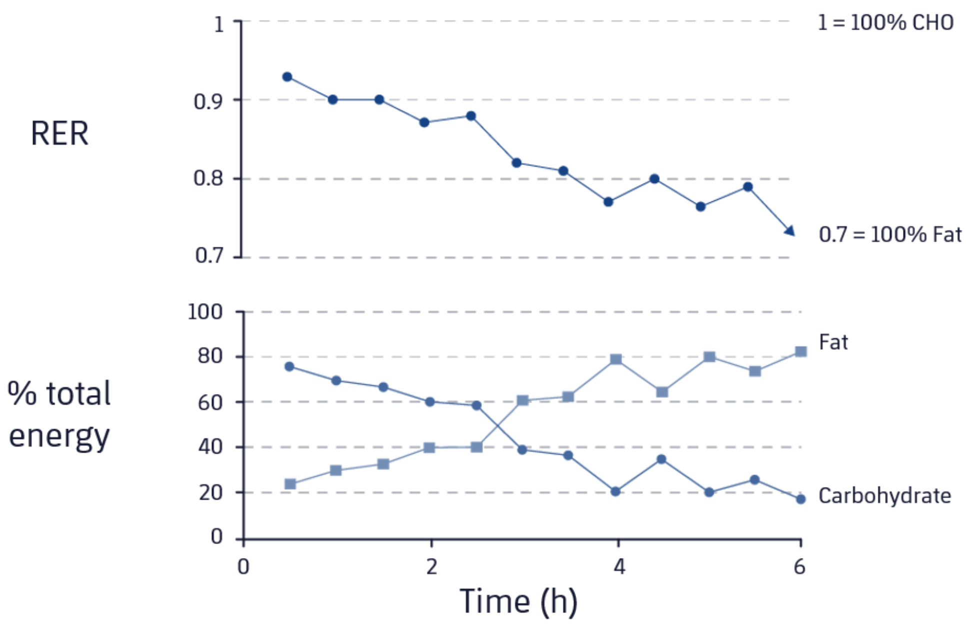
Source: own elaboration based on Romijn et al., 1993.

Duration

The duration of training or match play also affects the use of carbohydrate and fat to produce energy. At constant exercise intensities, fat oxidation increases, and carbohydrate oxidation decreases as the exercise duration increases. The increase in fat oxidation during football matches and training is likely a consequence of the gradual reduction in muscle glycogen stores. Typical fat oxidation rates during football are likely to range between 0.2 and 1.0 g/min. Values of fat oxidation greater than 1.0 g/min during exercise have been reported, but typically only during endurance sports that require prolonged physical efforts (greater than 3 hours) (Jeukendrup, 2003). Fat oxidation rates in football players will be covered in detail in Macronutrients and Fluid for Football course. Figure 18 shows how substrate oxidation changes over time at constant exercise intensity. As discussed, the reduction in muscle glycogen is believed to be responsible for the development of fatigue (Module 1). To reiterate, this is because when muscle glycogen concentrations reach very low levels, the rates of glycolysis cannot be maintained at the rate necessary to maintain ATP resynthesis required for higher intensity exercise. Therefore, to maintain the output, fat must have an increasing contribution to total energy expenditure. However, once glycogen stores are depleted, a player simply cannot maintain the same work rate as before. Please note, in the graph, it takes approximately 3 hours for fat to become the predominant energy source during continuous exercise in well fed individuals.

Figure 21. Substrate oxidation is dependent on exercise duration

Substrate utilisation: exercise duration



Source: own elaboration.

Key point

As the duration of football exercise increases, the player is at greater risk of fatigue and not being able to sustain high-intensity efforts.

Trainning status

The completion of regular football exercise (training and matches) results in adaptations that promote the ability to use fat during exercise as well as to increase maximal rates of fat oxidation. Players with a maintained or greater "training status" (maximal oxygen uptake) have an increased number and better functioning mitochondria within muscles. Therefore, these players have an improved ability to use the available fat stores, such as the intramuscular triglyceride. Other endurance adaptations, such as the capillarization of the muscle, may also aid the transport of fatty acids to the working muscle during football exercise. Increased fat oxidation has been shown to improve with endurance type training. Therefore, increases in maximal rates of fat metabolism parallels changes in training status (Purdom et al., 2018).

It is important to note that even within a group of well-trained players, the ability to utilize fat as a fuel will vary significantly. For example, in football players (n.= 283), the rates of maximal fat oxidation have been reported to range from 0.17 to 1.1 g of fat per minute. The maximal oxygen uptake is just one factor which accounts for the ability to utilize fat during exercise between players (Randell et al., 2017).

Environment

Football is played in diverse environmental conditions, including extremes of heat and hypoxia (low partial pressure of oxygen). The change in environmental conditions in which a player exercises can influence substrate utilization (Jeukendrup, 2003).

Playing in the heat ($\geq$27 °C), is associated with an increase in muscle glycogen utilization. The increased use of glycogen in the heat is likely due to a number of mechanisms including:

- an elevation in muscle temperature, which in turn increases activity of key enzymes involved in carbohydrate metabolism;

- increased adrenaline, which increases muscle glycogenolysis.

There is less information on how substrate use changes during football activity in cold environments ($\leq$15 °C). The relative contribution of carbohydrate to energy production may increase, though it is likely that there is negligible change with moderate cold exposure. However, in extreme cold, players will shiver as a mechanism to increase heat production. The consequence of shivering will increase the rate of glucose metabolism and hepatic glucose outputs. This consideration may apply to substitutes who do not start the game, but the shift in substrate use *per se* will unlikely influence performance (Jeukendrup, 2002).

Playing at altitude ($\geq$500 m above sea level) may also affect substrate utilization at rest and during exercise. Studies have shown that acclimation to altitude may reduce fatty acid uptake in the legs and increase glucose uptake, both at rest and during exercise (Roberts et al., 1996). It is also important to note that a player's appetite will be suppressed at altitude (Wasse et al., 2012). Therefore, care should be taken to ensure players are eating sufficient dietary carbohydrate and overall energy in their diet. Specific nutrition considerations for football players at altitude will be discussed in later courses.

Figure 20. Factors affecting the use of carbohydrate and fat during exercise

Factors affecting substrate utilization during exercise
Changes are extpressed as the relative (%) and absolute (for example, kj/min) contributions to energy expenditure (EE) for both carbohydrate (CHO) and fat. ▲ indicates an increase or a higher amount; ▼ indicates a decrease or a lower amount.

	CHO contribution to EE		Fat contribution to EE	
	Relative	Absolute	Relative	Absolute
Exercise intensity ▲	▲	▲	▼	▲*, ▼†
Exercise duration ▲	▼	▼	▲	▲
CHO feeding before exercise	▲	▲	▼	▼
CHO-rich diet	▲	▲	▼	▼
Endurance training	▼	▼	▲	▲
Hot conditions	▲	▲	▼	▼
Cold conditions	▲	▲	▼	▼
Altitude ▲	▲	▲	▼	▼
Gender (women compared with men)	▼	▼	▲	▲

* Up to about 65% VO_{2max}.

† Higher tan about 65% VO_{2max}.

Source: Jeukendrup, 2003, p. 1272.

Summary

- The large aerobic component of football requires a large utilisation of fuel (carbohydrate and fat) by the exercising muscle to produce energy.
- Fats are stored in the form of triglycerides (TG). The metabolism of fat provides more energy than carbohydrate, but at a slower rate.
- Fat metabolism supports low and moderate intensity running as well as the recovery between high intensity efforts.

- Carbohydrates are stored in the body in the form of glycogen. The metabolism of carbohydrates provides energy at a faster rate than fat.

- Carbohydrate metabolism supports moderate to high speed running and sprints.

- The player's body store of carbohydrate is finite. Muscle glycogen concentrations are gradually depleted during football activity.

- The main factors affecting substrate oxidation during football exercise are intensity, duration, training status and environmental conditions.

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