2.1 An introduction to Metabolism in Football

Energy for Football

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 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.

Establishing a basic understanding of the systems which provide energy for football activities will provide the foundations on which basic and more advanced concepts of nutrition can be built. In this unit, the key energy systems associated with football activities discussed in module 1 will be categorized into: (1) sprints using the ATP-phosphocreatine (ATP-PCr) system; (2) high-speed running dependent on glycolysis; and (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 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).

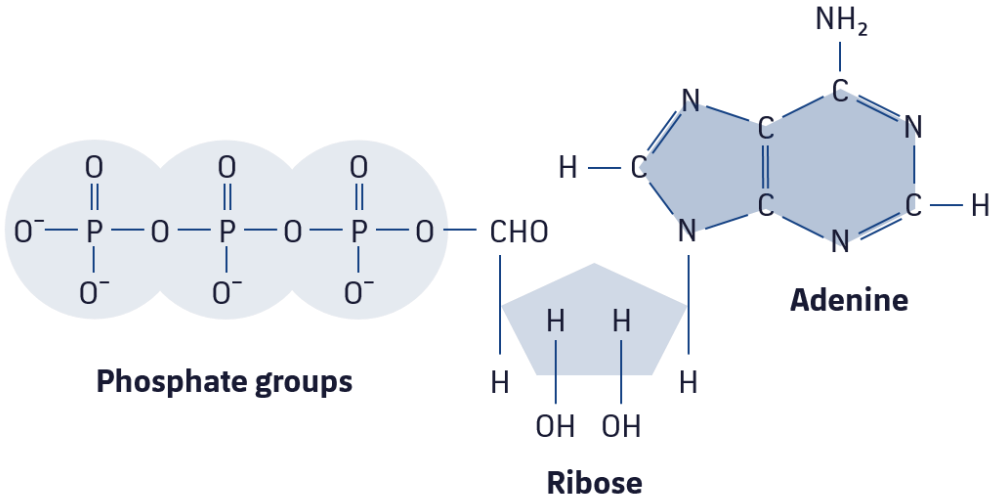
KEY POINT

Metabolism is the process of converting food into energy.

ATP: The Energy Currency for Football

The process of muscle contraction, a pre-requisite for football performance, is ultimately dependent on the degradation of one organic molecule, 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. Because of these low concentrations, ATP can only provide energy to perform an intense effort for approximately 2 seconds before its depletion. 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



$ATP + H_2O <----> ADP + P_i + \alpha H^+ + 7.3kcal$

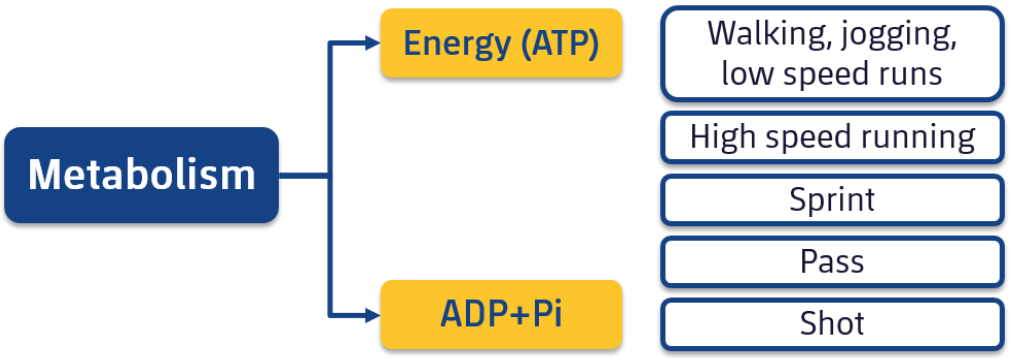
Source: Prepared by the author

Stores of ATP can act independently as an immediate source of energy. The ATP resynthesis process is possible because players have energetic stores that support the ADP in the ATP formation process. Energy must be provided to players via the foods they eat. After being consumed, the food is used or stored in the body to be available to release its energy when ATP is formed from ADP. 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



Source: Prepared by the author

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) and (3) aerobic system (for glucose, glycogen, fat and protein 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 is different and this influences the rates of ATP resynthesis. This is a very important feature of the energetic stores, due to the fact that 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 force-time curve.

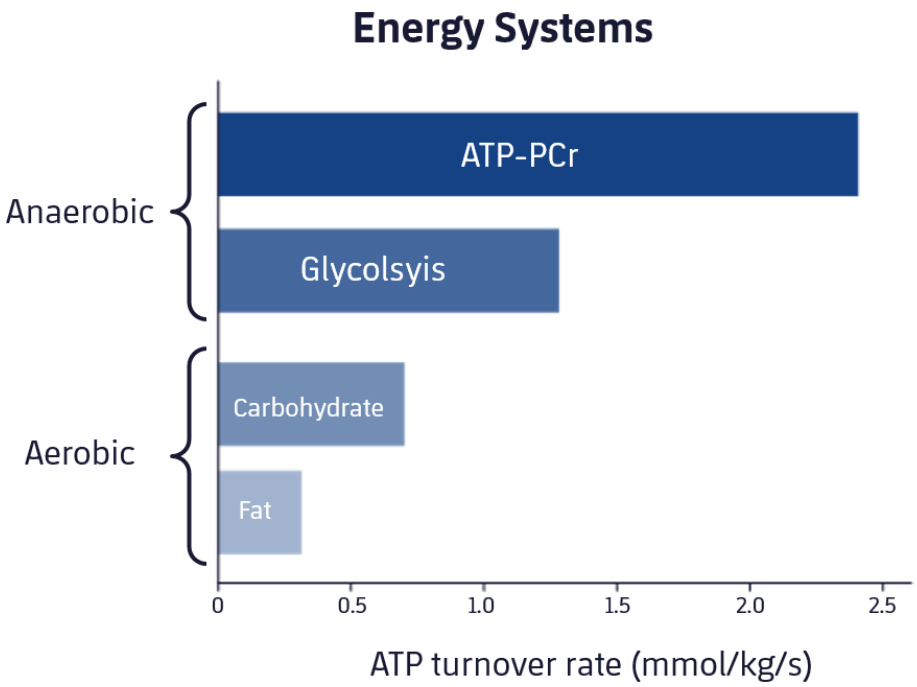
In football, it is important to generate appropriate force production in relation to the power of passes, accuracy of shots and an appropriate response to ongoing game events. The breakdown of ATP at high rates leads to failure in cellular functioning and muscle fatigue. To this end, football players have two main objectives from an energy point of view: (1) to rapidly use ATP, and (2) to rapidly regenerate ATP. Players can achieve this through

the metabolism of available energy pools (fuel sources) to sustain performance. A desirable outcome of appropriate 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



Redrawn by author. **Source:** (Baker, 2010)

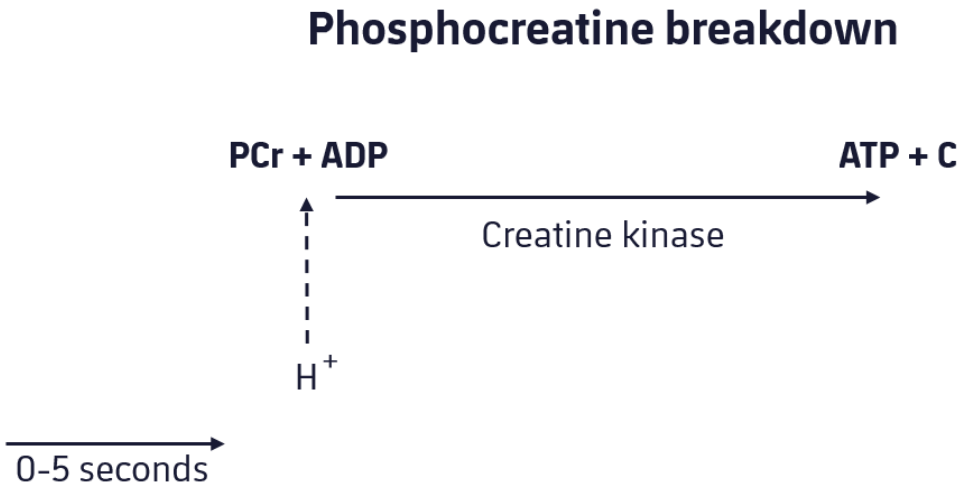
SPRINTING

All those activities which require the player to generate force quickly during football, such as a 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 first 5 seconds of maximal muscle contractions (Figure 3).

Figure 4: Energy demands during the first seconds of a maximal activity. PCr breakdown process and H^+ buffering



Source: Robergs, 2001.

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 & 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, Mohr et al. 2006). Using estimated values for re-synthesis 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.

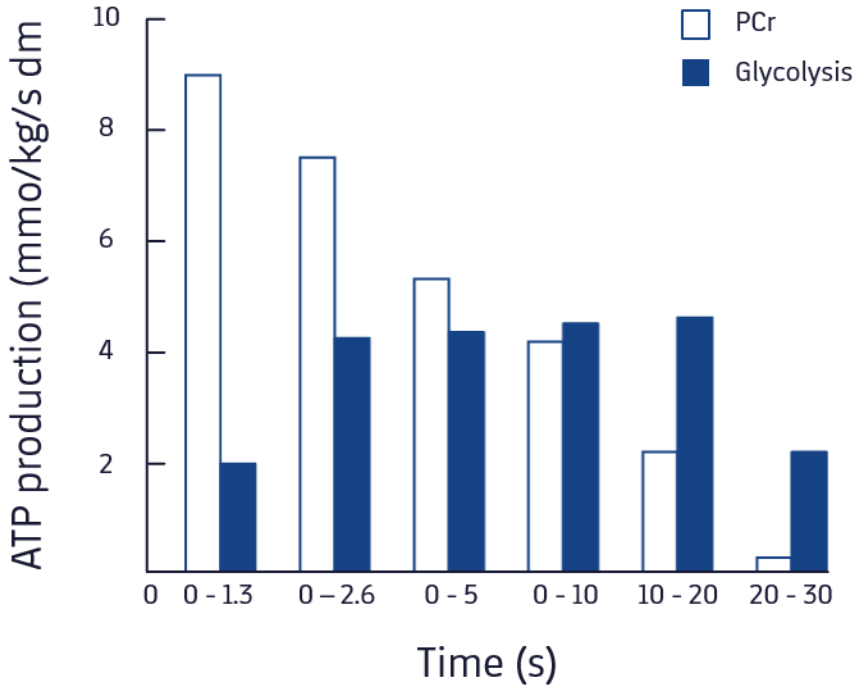
High-intensity activities are noted to produce H^+, the accumulation of which increases the acidity within the cell and has been implicated in fatigue (Module 1). Russell and Kingsley (2012) demonstrated that blood pH and buffering capacity are reduced throughout a football match and such metabolic perturbations 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 3), (Lindinger, Kowalchuk et al. 2005). Bishop, Edge 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 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 muscle contractibility (Metzger and Moss 1990)and to inhibit glycolytic activity (Hollidge-Horvat, Parolin 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 (Course 4).

DID YOU KNOW?

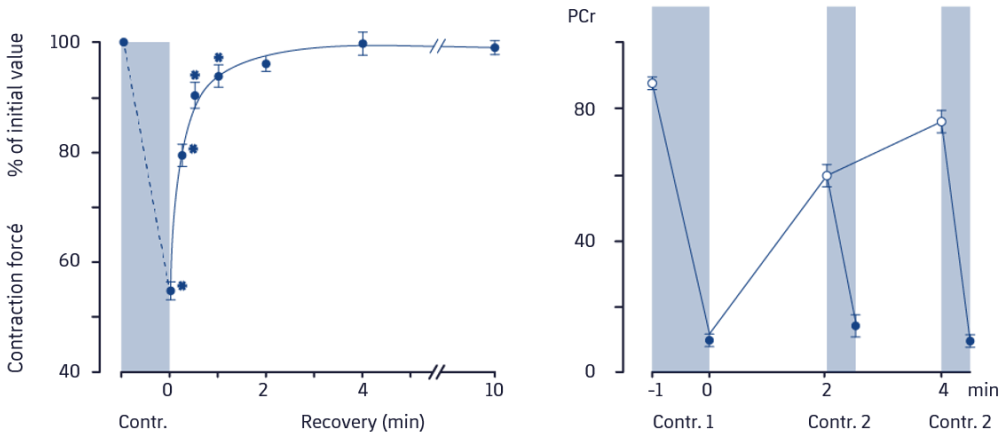
Mitochondria are specialized structures with an inner and outer membrane and are considered the "powerhouses" of cells. The mitochondria are the sites of energy metabolism where nutrients and oxygen are used to generate ATP.

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



Source: Hultman & Sjoholm, 1983

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



Source: (SAHLIN, TONKONOGI et al. 1998)

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 (Figure 6a). 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 (Figure 6b).

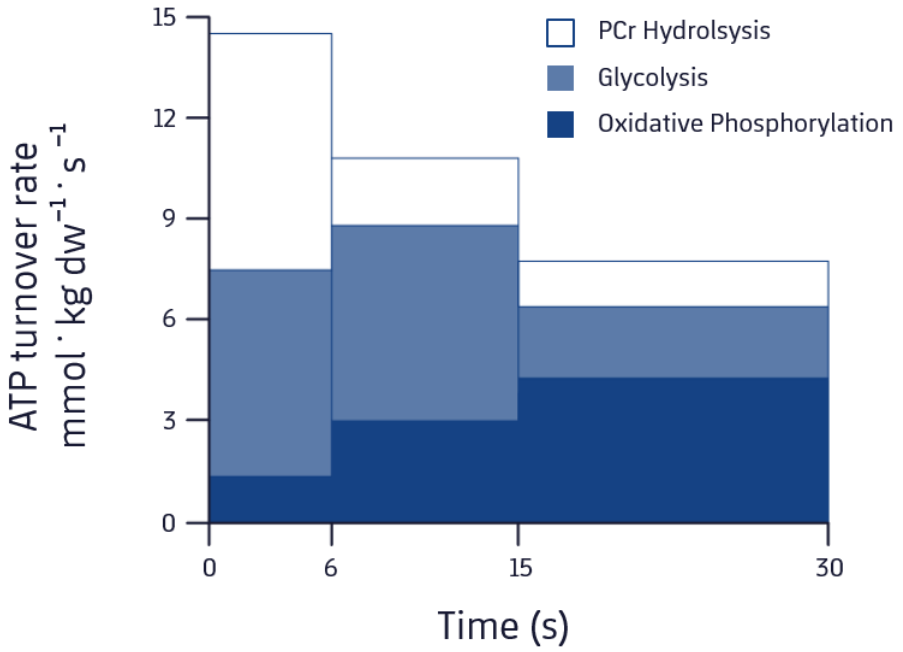
Importantly, higher rates of PCr resynthesis will be achieved in players with better aerobic capacities (VO_2 max). A higher mitochondrial density, especially in type IIa fast fibres, will also speed resynthesis of PCr. In practical terms, the ability of the player to recover quickly from an intense 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 (Course 4).

HIGH SPEED RUNINNG

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 second bouts of maximal isokinetic cycling



Source: (Parolin, Chesley et al. 1999)

Glycolysis involves the breakdown of carbohydrate derived either from glucose or glycogen (the storage form of glucose, unit 2). 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 end 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, fats and proteins 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 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 matches, with individual player values reaching 12 mmol/L (Krustrup et al., 2006). These findings indicate that the glycolysis rate 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. During a friendly match between two non-professional teams, muscle lactate rose fourfold (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).

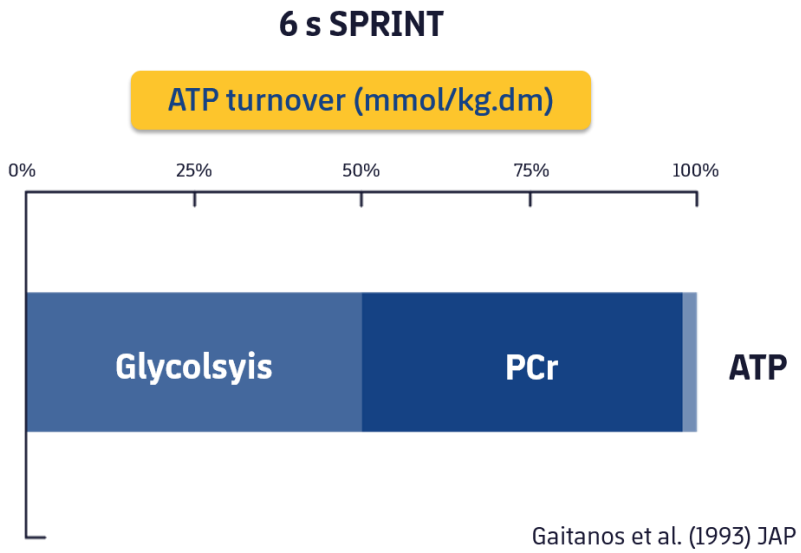
An interesting finding was that muscle lactate was not correlated with blood lactate (Figure. X). A scattered relationship, with a low correlation coefficient, has also been observed between muscle and blood lactate when players performed repeated intense exercise (Yo-Yo intermittent recovery test) (Krustrup 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 (Figure. X).

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.

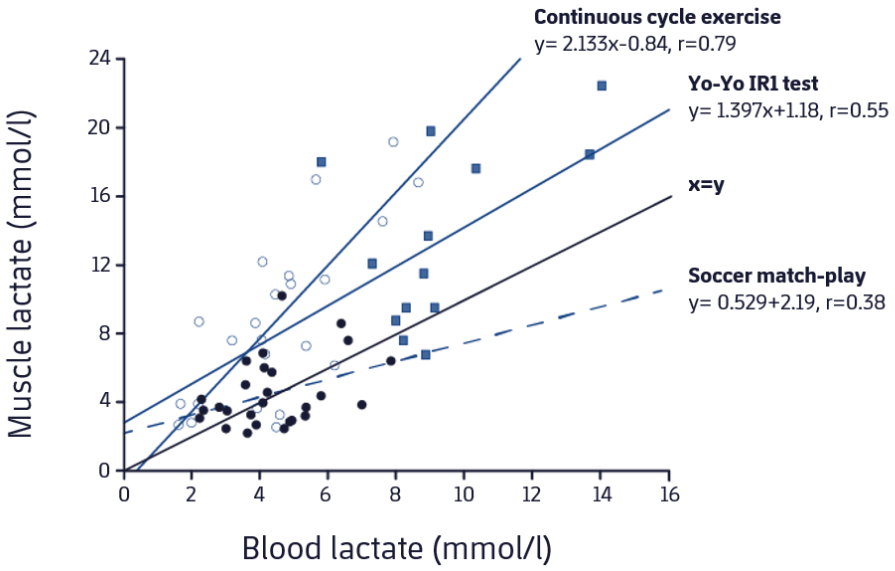
During a match, the glycolytic energy system is extremely important, as it provides energy at very high rates. As an example of how important glycolysis is in supporting high-intensity running, even in a 6-s sprint, glycogen will contribute approximately 50% to ATP turnover within the muscle (Gaitanos, Williams et al. 1993). Based on (1) numerous studies using short-term maximal exercise performed in the laboratory, (2) the finding of high blood lactate and moderate muscle lactate concentrations during matches, and (3) the fact 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



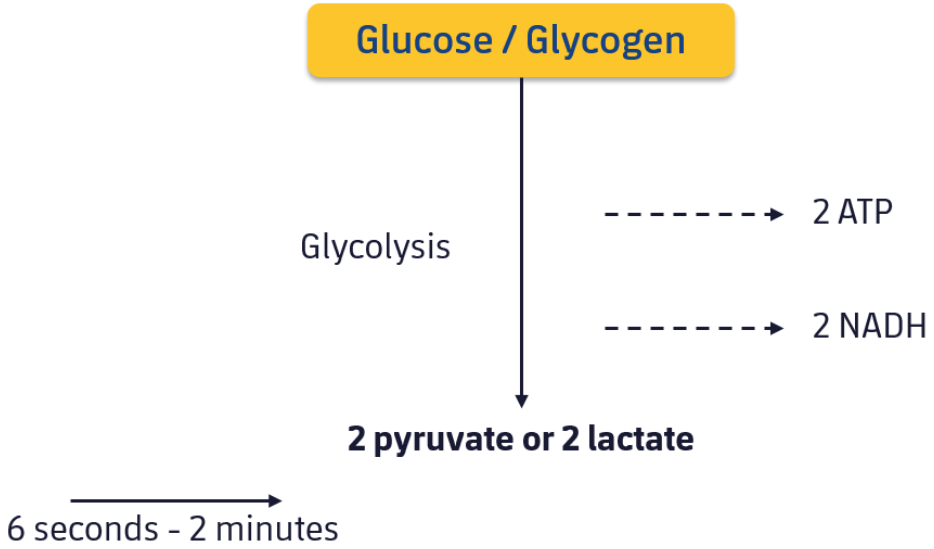
Source: Prepared by the author.

Figure 9: Blood lactate vs Muscle lactate levels in different exercise protocols



Source: Retrieved from Krustrup (2004). 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).

Figure 10: Glycolytic pathway

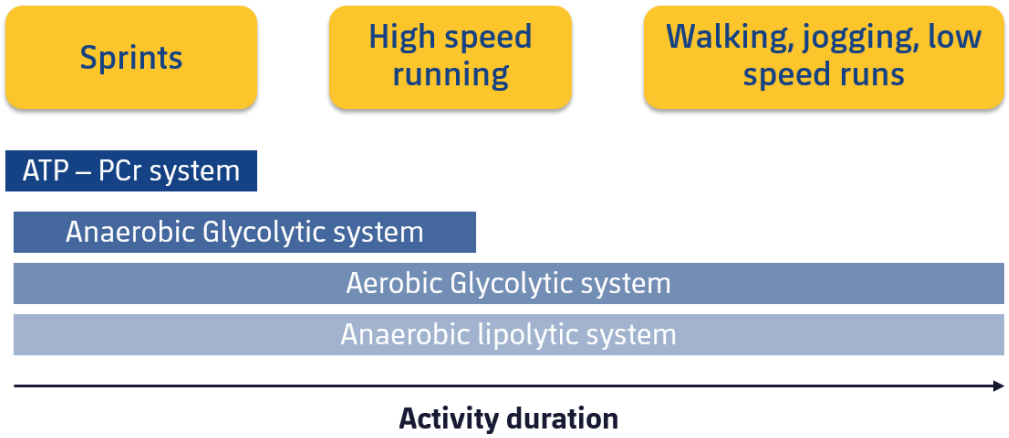


Source: Prepared by the author.

WALKING, JOGGING, LOW-SPEED RUNNING

The energy for low-intensity activities (standing still, walking and low speed running) during football will be provided almost exclusively by aerobic metabolism. The process of aerobic metabolism is complex and a detailed and complete discussion is beyond the scope of this course. However, in short; aerobic energy is produced in the specialized organelles called mitochondria by using 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) and beta-oxidation (fat sources). Protein can also be broken down and used as a substrate for aerobic metabolism. 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 (~147 vs. 38 ATP) 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 their bodies utilize different nutrients during a football match. This information is fundamental to inform our nutritional advice to the player (Unit 2).

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



Source: Prepared by the author.

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.