

2.2 Nutrition for Football

The large aerobic component of football results in a large energy requirement. 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, Jeukendrup, Wagenmakers, & Saris, 1997). The current unit will focus on the storage and metabolism of carbohydrate and fat as the main energy substrates and discuss those factors which influence their use during football training and matches.

DID YOU KNOW

The substrates for energy production in football are those products of food digestion and absorption which energy systems use to produce energy.

FATS

Fat is stored in the body in the form of triglyceride, which is comprised 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) (Figure 1). The store of IMTG directly 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?

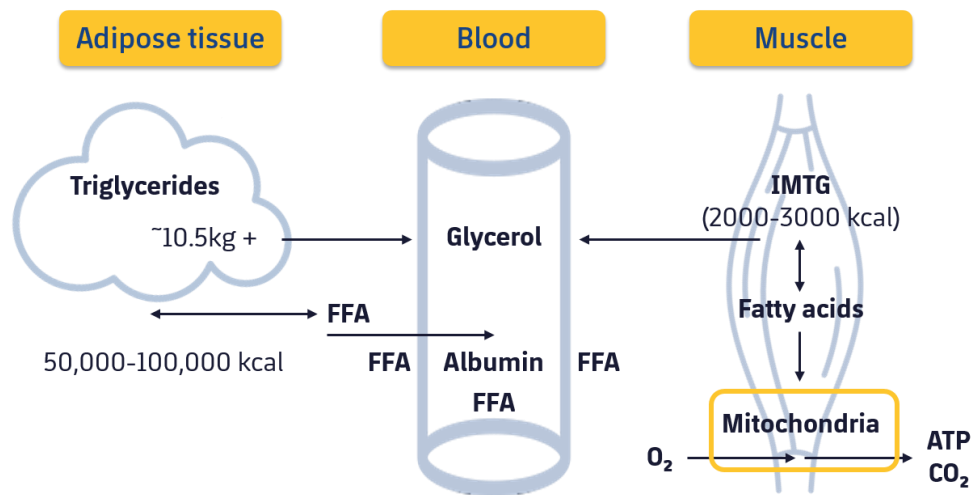
Common sources of dietary fat include oils, spreads, animal fats, dairy products, nuts and seeds.

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 by 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 and transport and use in the players' body



Source: Prepared by the author

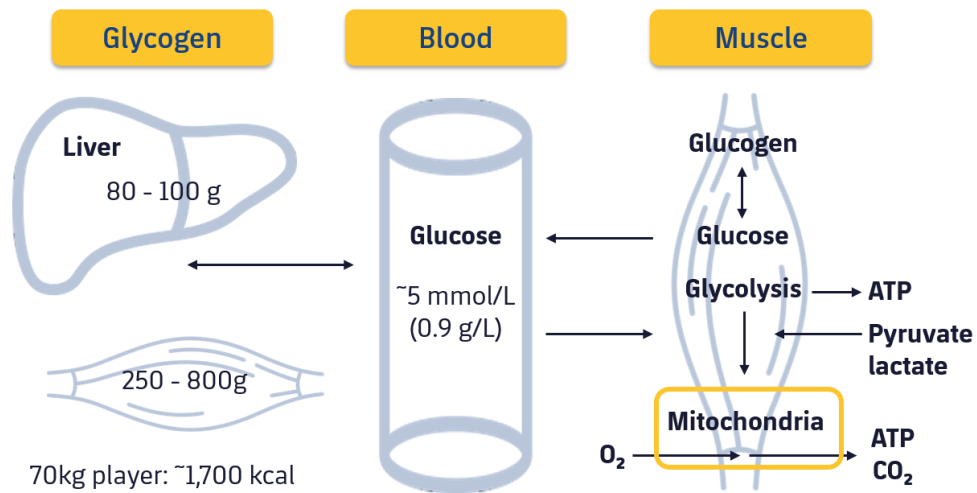
DID YOU KNOW

Hormones are chemical messengers that are secreted directly into the blood, which carries them to the tissues of players' bodies to exert their functions. There are many types of hormones that act on different aspects of bodily functions. Insulin is a hormone secreted by the pancreas that promotes the uptake of carbohydrate (glucose) into the muscle for use or to store. 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 long chain 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: Prepared by the author

DID YOU KNOW?

Common, 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, 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, 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 (Chicharro and Vaquero 2006).

DID YOU KNOW?

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

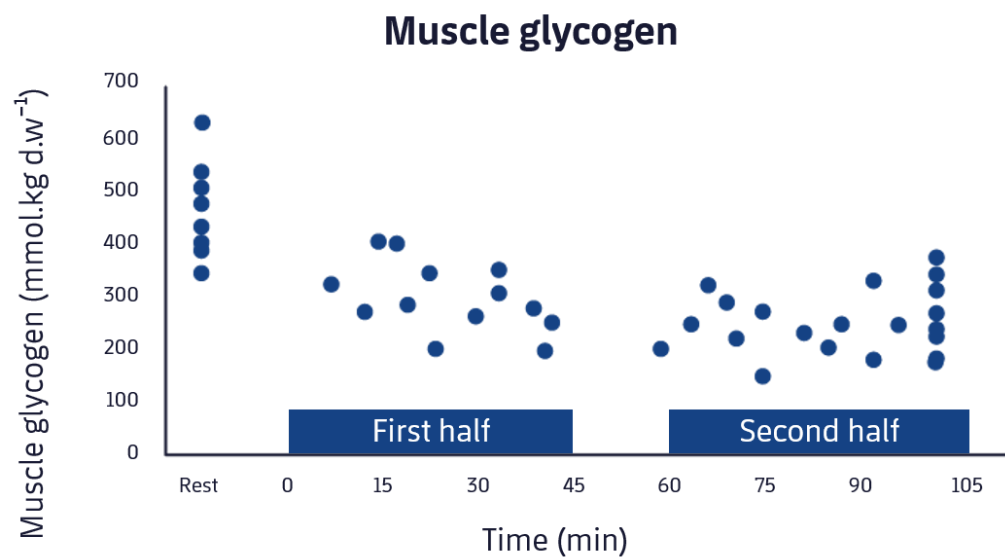
As glucose crosses the cell membrane, it is converted to glucose-6-Phosphate which prevents it from leaving the cell. If the energy demand of the cell is high, glucose-6-Phosphate enters glycolysis. However, if the energy demand is low, then the glucose-6-Phosphate is arranged and stored as long chains 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, Williams et al. 1993). Thus, the repeated sprint activity during a football game results 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, Bischoff 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 also 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



Kustrup et al., 2006. MSSE

Source: Prepared by the author.

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.

FACTORS AFFECTING FUEL UTILIZATION DURING FOOTBALL

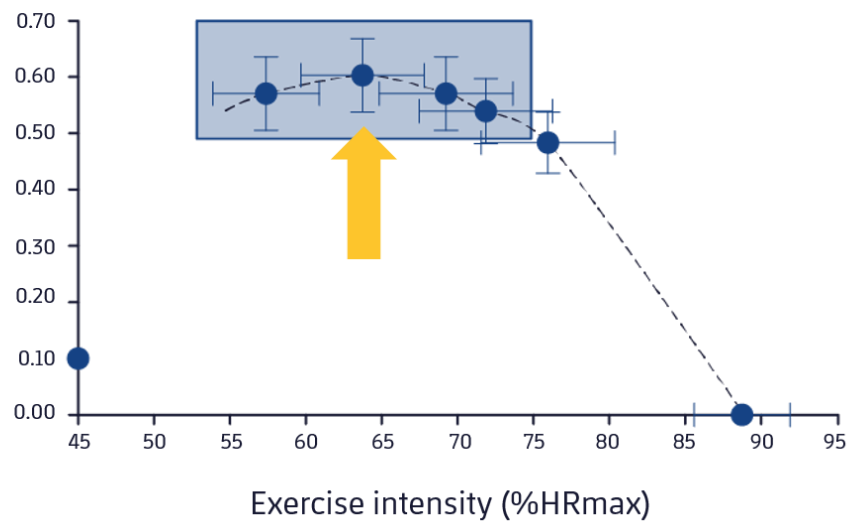
Factors affecting the metabolism of fat and carbohydrate at rest and during exercise are summarized in Figure 19 and discussed below.

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 4). In contrast, carbohydrate metabolism increases as the exercise intensity increases.

Figure 15: Fat oxidation as a function of activity in players

Fat oxidation
(g/min)



Source: Retrieved from Achten, Gleeson 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

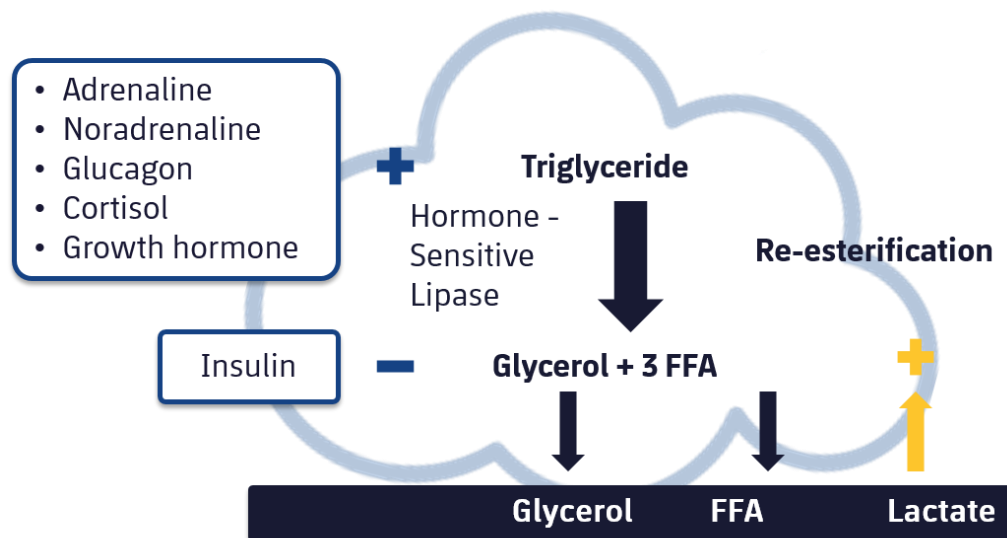
A "fast" is the abstinence from food, drink or both for a period of time. For example, all players engage in a daily overnight "fast" for 7-10 hours as they sleep. This is where the word "breakfast" originates. It simply means the first meal to "break" the "fasting period".

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 min 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 that which fatty acids can be taken up by the muscle and fatty acid concentrations in the blood will rise (Jeukendrup 2002) (Figure 50).

Figure 16: Fat metabolism under exercise-imposed conditions

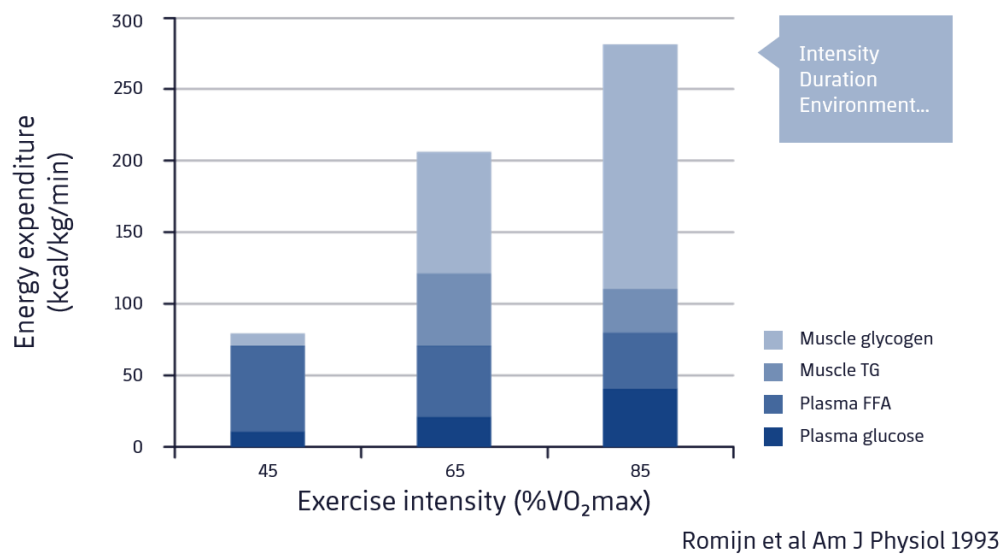
Mobilisation of lipid fuel from adipose tissue: lipolysis



Source: Prepared by the author.

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 (Figure 6). The data from Romijn et al. (1993) suggests that lipolysis increases from rest to exercise and from 25% to 65% VO_2 max. However, at 85% VO_2 max, there is no further increase of lipolysis, and lipolytic rates are similar to those at 65% VO_2 max. As players exercise at intensities above 95% of VO_2 max, 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 VO_2 max (High-speed running) (Jeukendrup 2003). This is important as mean oxygen uptake values reported during a football match are approximately 70% of VO_2 max.

Figure 17: Substrate oxidation at different exercise intensities



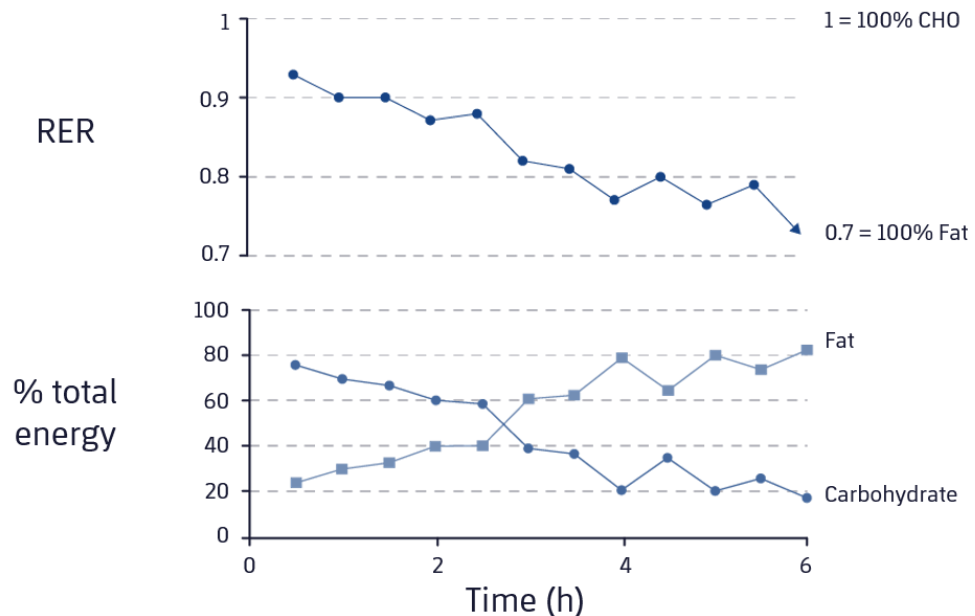
Source: Romijn, Coyle et al. (1993)

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). 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). 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 as high as possible, 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.

Figure 18: Substrate oxidation is dependent on exercise duration

Substrate utilisation: exercise duration



Source: prepared by the author.

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.

TRAINING 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, and therefore, increases in maximal rates of fat metabolism parallels changes in training status (Purdom, Kravitz 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, Rollo 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 ($\geq 27^{\circ}\text{C}$), 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 ($\leq 15^{\circ}\text{C}$). 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 (≥ 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, Butterfield et al. 1996). It is also important to note that a player's appetite will be suppressed at altitude (Wasse, Sunderland 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 19: Factors affecting the use of carbohydrate and fat during exercise

Factors affecting substrate utilization during exercise

Changes are expressed 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.

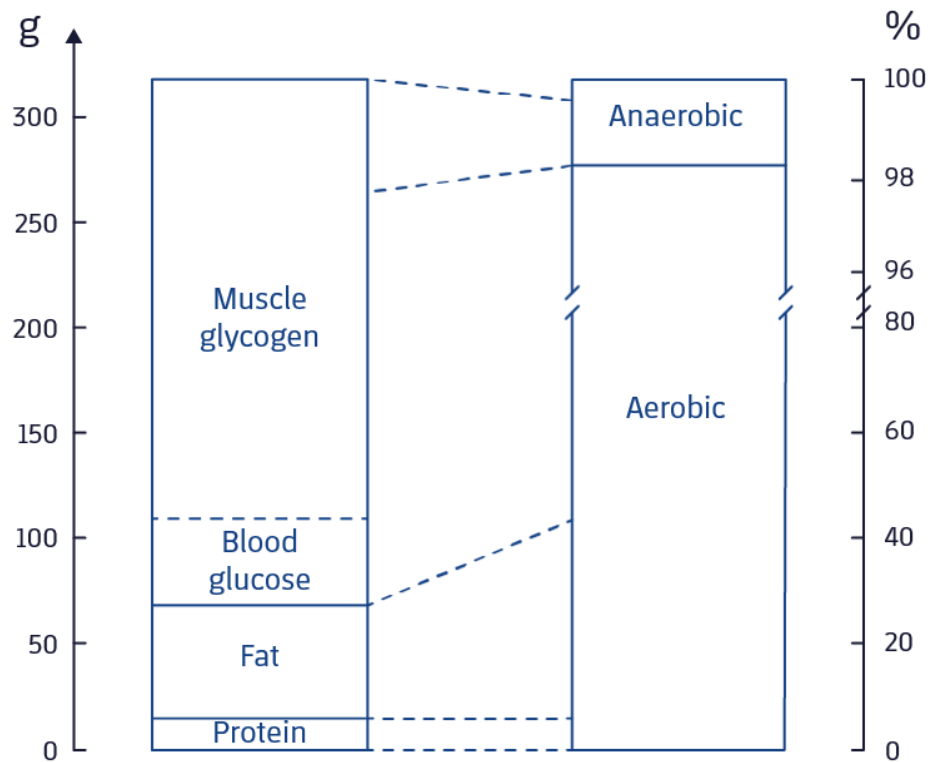
	CHO contribution to EE		Fat contribution to EE	
	Relative	Absolute	Relative	Absolute
Exercise intensity ▲	▲	▲	▼	▲*, ▼†
Exercise duration ▲	▼	▼	▲	▲
CHO feeding before exercise	▲	▲	▼	▼
CHO-rich diet	▲	▲	▼	▼
Endurance training	▼	▼	▲	▲
Hot conditions	▲	▲	▼	▼
Cold conditions	▲	▲	▼	▼
Altitude ▲	▲	▲	▼	▼
Gender (women compared with men)	▼	▼	▲	▲
* Up to about 65% VO_{2max} .				
† Higher than about 65% VO_{2max} .				

Source: Jeukendrup, 2003.

SUBSTRATE 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 muscle before, during and after matches to gain insight on 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 20. The specific use of carbohydrate and fat as substrates during a football match are discussed below:

Figure 20: Estimated relative aerobic and anaerobic energy turnover and the corresponding substrate utilization during a football match



Source: Retrieved from Bangsbo, 1994.

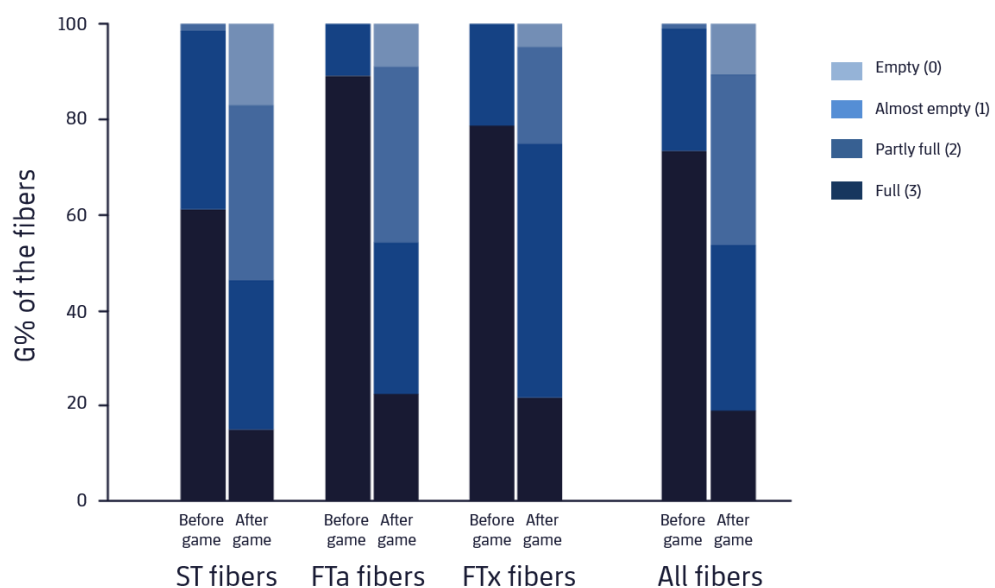
Carbohydrates

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, however will depend on the glycogen status of the player (Bangsbo, 1994).

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 the concentrations to be 40–65 mmol/kg w.w. after the game (Smaros, 1980; Jacobs et al., 1982; Krstrup 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 by that time, which may be one of the reasons why fatigue appears to occur toward the end of a game (Krstrup et al., 2006; Fig. 18).

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 2019)

Figure 21:



Source: Retrieved from Krstrup, 2006. 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).

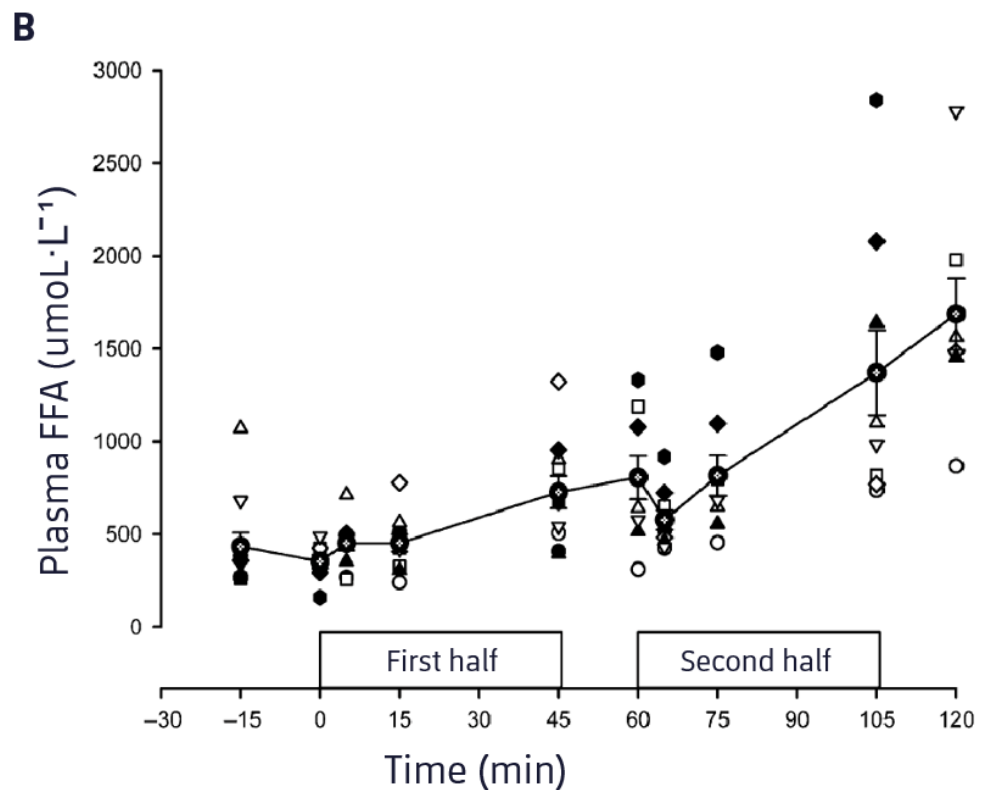
Fat

Free fatty acid (FFA) concentration in the blood increases during a game, more so during the second half (Bangsbo, 1994; Krstrup et al., 2006; Fig. 19). 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; Krstrup et al., 2006). The changes in FFA during a match may cause higher uptake and oxidation of FFA by contracting muscles.

This may be particularly evident during recovery periods in a game and in the second-half (Turcotte, Kiens et al. 1991). The elevation in fat use is likely a compensatory mechanism for the progressive lowering of muscle glycogen and used to maintaining the blood glucose concentration. 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 implemented where possible.

Figure 22: Plasma FFA concentrations before, during, and after a football match. Data are means as well as individual values



Source: Retrieved from Krstrup et al, 2006.

Summary

- The large aerobic component of football results in a large utilization of 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.
- Carbohydrates are stored in the body in the form of glycogen. The metabolism of carbohydrate provides less energy than fat but at a much faster rate.
- The main factors affecting substrate oxidation during football exercise are intensity, duration, training status and environmental conditions.
- The player's body store of carbohydrate is finite. Muscle glycogen concentrations are gradually depleted during football activity.

Disclaimer: Ian Rollo is an employee of the Gatorade Sports Science Institute, a division of PepsiCo, Inc. The views expressed in this course are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

REFERENCES

Achten, J., Gleeson, M., & Jeukendrup, A. E. (2002). The relation between maximal fat oxidation and exercise intensity. *Medicine & Science in Sports & Exercise*, *34*, 92-97

Achten, J., M. Gleeson and A. E. Jeukendrup (2002). "Determination of the exercise intensity that elicits maximal fat oxidation." Med Sci Sports Exerc **34**(1): 92-97.

Bendiksen, M., R. Bischoff, M. B. Randers, M. Mohr, I. Rollo, C. Suetta, J. Bangsbo and P. Krstrup (2012). "The Copenhagen Soccer Test: physiological response and fatigue development." Med Sci Sports Exerc **44**(8): 1595-1603.

Bishop, D., J. Edge and C. Goodman (2004). "Muscle buffer capacity and aerobic fitness are associated with repeated-sprint ability in women." Eur J Appl Physiol **92**(4-5): 540-547.

Chicharro, J. L. and A. F. Vaquero (2006). Fisiologia del ejercicio, Editorial Medica Panamericana Sa de.

Coyle, E. F., Jeukendrup, A. E., Oseto, M.C., Hodgkinson, B. J., & Zderic, T. W. (2001) *Am. J. Physiol. Endocrinol. Metab.* *280*, E391–E398

Coyle, E. F., Jeukendrup, A. E., Wagenmakers, A. J., & Saris, W. H. (August, 1997). Fatty acid oxidation is directly regulated by carbohydrate metabolism during exercise. *American Journal of Physiology*, *273*(2 Pt 1), E268-E275.

Flatt, J. P. (1995). "Use and storage of carbohydrate and fat." Am J Clin Nutr **61**(4 Suppl): 952s-959s.

Febbraio, M. A., Snow, R. J., Stathis, C. G., Hargreaves, M., & Carey, M. F. (1994). *J. Appl. Physiol.* *77*, 2827–2831

Gaitanos, G. C., Williams, C., Boobis, L. H., & Brooks, S. (August, 1993). Human muscle metabolism during intermittent maximal exercise. *Journal of Applied Physiology* (1985), *75*(2), 712-719

Gastin, P. B. (2001). "Energy system interaction and relative contribution during maximal exercise." Sports Med **31**(10): 725-741.

Hargreaves, M., Angus, D., Howlett, K., Conus, N. M. & Febbraio, M. (1996) *J. Appl. Physiol.* *81*, 1594–1597



Harper, L. D., Clifford, T., Briggs, M. A., McNamee, G., West, D. J., Stevenson, E., & Russell, M. (June, 2016). The Effects of 120 Minutes of Simulated Match Play on Indices of Acid-Base Balance in Professional Academy Soccer Players. *The Journal of Strength and Conditioning Research*, 30(6), 1517-1524

Hollidge-Horvat, M. G., M. L. Parolin, D. Wong, N. L. Jones and G. J. Heigenhauser (1999). "Effect of induced metabolic acidosis on human skeletal muscle metabolism during exercise." *Am J Physiol* **277**(4): E647-658.

Hultman, E. and H. Sjöholm (1983). "Energy metabolism and contraction force of human skeletal muscle in situ during electrical stimulation." *J Physiol* **345**: 525-532.

Jeukendrup, A. E. (November, 1999). Dietary fat and physical performance. *Current Opinion in Clinical Nutrition & Metabolic Care*, 2(6), 521-526

Jeukendrup, A. E. (June, 2002). Regulation of fat metabolism in skeletal muscle. *Annals of the New York Academy of Sciences*, 967, 217-235.

Jeukendrup, A. E. (December, 2003). Modulation of carbohydrate and fat utilization by diet, exercise and environment. *Biochemical Society Transactions*, 31(Pt 6), 1270-1273.

Jeukendrup, A. E., Saris, W. H., & Wagenmakers, A. J. (1998). Fat metabolism during exercise: a review. Part I: Fatty acid mobilization and muscle metabolism. *International Journal of Sports Medicine*, 19(4), 231-244.

Jeukendrup, A. E. (2002). "Regulation of fat metabolism in skeletal muscle." *Ann N Y Acad Sci* **967**: 217-235.

Jeukendrup, A. E. (2003). "Modulation of carbohydrate and fat utilization by diet, exercise and environment." *Biochem Soc Trans* **31**(Pt 6): 1270-1273.

Kiens, B., Essen-Gustavsson, B., Christensen, N. J., & Saltin, B. (September, 1993). Skeletal muscle substrate utilization during submaximal exercise in man: effect of endurance training. *The Journal of Physiology*, 469, 459-478.

Kiens, B., Essen-Gustavsson, B., Gad, P., & Lithell, H. (February, 1987). Lipoprotein lipase activity and intramuscular triglyceride stores after long-term high-fat and highcarbohydrate diets in physically trained men. *Clinical Physiology*, 7(1), 1-9.

Kiens, B. & Helge, J.W. (1998) *Proc. Nutr. Soc.* 57, 73–75.

Krustrup, P., M. Mohr, A. Steensberg, J. Bencke, M. Kjaer and J. Bangsbo (2006). "Muscle and blood metabolites during a soccer game: implications for sprint performance." *Med Sci Sports Exerc* **38**(6): 1165-1174.

Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., & Bangsbo, J. (June, 2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Medicine & Science in Sports & Exercise*, **38**(6), 1165-1174.

Lindinger, M. I., J. M. Kowalchuk and G. J. Heigenhauser (2005). "Applying physicochemical principles to skeletal muscle acid-base status." *Am J Physiol Regul Integr Comp Physiol* **289**(3): R891-894; author reply R904-910.

Metzger, J. M. and R. L. Moss (1990). "pH modulation of the kinetics of a Ca²⁺-sensitive cross-bridge state transition in mammalian single skeletal muscle fibres." **428**(1): 751-764.

Parolin, M. L., A. Chesley, M. P. Matsos, L. L. Spriet, N. L. Jones and G. J. F. Heigenhauser (1999). "Regulation of skeletal muscle glycogen phosphorylase and PDH during maximal intermittent exercise." **277**(5): E890-E900.

Purdom, T., Kravitz, L., Dokladny, K., & Mermier, C. (January, 2018). Understanding the factors that effect maximal fat oxidation. *Journal of the International Society of Sports Nutrition*, **15**, 3.

Rampinini, E., Sassi, A., Morelli, A., Mazzoni, S., Fanchini, M., & Coutts, A. J. (December, 2009). Repeated-sprint ability in professional and amateur soccer players. *Applied Physiology, Nutrition, and Metabolism*, **34**(6), 1048-54. doi: 10.1139/H09-111

Randell, R. K., Rollo, I., Roberts, T. J., Dalrymple, K. J., Jeukendrup, A. E., & Carter, J.M. (January, 2017). Maximal Fat Oxidation Rates in an Athletic Population. *Medicine & Science in Sports & Exercise*, **49**(1), 133-140.

Randle, P. J., Hales, C. N., Garland P. B., & Newsholme, E. A. 1963. The glucose-fatty acid cycle: its role in insulin sensitivity and the metabolic disturbances of diabetes mellitus. *The Lancet*, **1**(7285), 785-789.

Randle, P. J., Newsholme, E. A., & Garland, P. B. (December, 1964). Regulation of glucose uptake by muscle: 8. Effects of fatty acids, ketone bodies, and pyruvate, and of alloxandibetosis and starvation, on the uptake and metabolic fate of glucose in rat heart and diaphragm muscles. *Biochemical Journal*, **93**(3), 652-665.

Reed, L. J. (1981). Regulation of mammalian pyruvate dehydrogenase complex by a phosphorylation-dephosphorylation cycle. *Current Topics in Cellular Regulation*, 18, 95-106.

Rennie, M. J. & Winder, W. W. (June, 1976). A sparing effect of increased plasma fatty acids on muscle and liver glycogen content in the exercising rat. *Biochemical Journal*, 156(3), 647-655.

Roberts, A. C., Butterfield, G. E., Cymerman, A., Reeves, J. T., Wolfel, E. E., & Brooks, G. A. (October, 1996). Acclimatization to 4,300-m altitude decreases reliance on fat as a substrate. *Journal of Applied Physiology* (1985), 81(4), 1762-1771.

Romijn, J. A., Coyle, E. F., Sidossis, L. S., Gastaldelli, A., Horowitz, J. F., Endert, E., Wolfe, R. R. (September, 1993). Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity. *American Journal of Physiology*, 265(3 Pt 1), E380-E391.

Romijn, J. A., Coyle, E. F., Sidossis, L. S., Zhang, X. J., & Wolfe, R. R. (December, 1995). Fat oxidation is impaired somewhat during high intensity exercise by limited plasma FFA. *Journal of Applied Physiology*, 79(6), 1939-1945.

Russell, M. & Kingsley, M. (September, 2012). Changes in acid-base balance during simulated soccer match play. *The Journal of Strength & Conditioning Research*, 26(9), 2593-2599.

Saggerson, E. D. & Carpenter, C. A. (July, 1981). Carnitine palmitoyltransferase and carnitine octanoyltransferase activities in liver, kidney cortex, adipocyte, lactating mammary gland, skeletal muscle, and heart. *FEBS Letters*, 129(2), 229-232.

Sahlin, K., Tonkonogi, M., & Söderlund, K. (March, 1998). Energy supply and muscle fatigue in humans. *Acta Physiol Scand*, 162(3), 261-266.

Söderlund, K. & Hultman, E. (December, 1991). ATP and phosphocreatine changes in single human muscle fibers following intense electrical stimulation. *American Journal of Physiology*, 261(6 Pt 1), E737-E741.

Spriet, L. L. (February, 1991). Phosphofructokinase activity and acidosis during short-term tetanic contractions. *Canadian Journal of Physiology and Pharmacology*, 69(2), 298-304.

Spriet, L. L. (1998) Adv. Exp. Med. Biol. 441, 249–261.

Spriet, L. L. (2002) Med. Sci. Sports Exerc. 34, 1477–1484.

Turcotte, L. P., B. Kiens and E. A. Richter (1991). "Saturation kinetics of palmitate uptake in perfused skeletal muscle." FEBS Lett **279**(2): 327-329.

Wasse, L. K., C. Sunderland, J. A. King, R. L. Batterham and D. J. Stensel (2012). "Influence of rest and exercise at a simulated altitude of 4,000 m on appetite, energy intake, and plasma concentrations of acylated ghrelin and peptide YY." J Appl Physiol (1985) **112**(4): 552-559.

Williams, C. and I. Rollo (2015). "Carbohydrate Nutrition and Team Sport Performance." Sports Med **45 Suppl 1**: S13-22.

Wolfe, R. R., Klein, S., Carraro, F., & Weber, J. M. (1990) Am. J. Physiol. 258, E382–E389.