

1

Energy sources for muscular activity

Learning outcomes

After studying this chapter, you should be able to:

- outline the key energy sources for exercise;
- distinguish between anaerobic and aerobic sources of energy;
- describe the essential structure of ATP;
- draw and explain the components of the energy continuum;
- describe the role of PCr in ATP synthesis;
- explain how PCr is resynthesized;
- describe the involvement of carbohydrates and fats as energy sources for exercise;
- explain reasons why an athlete is unable to sprint a marathon;
- describe the amounts and sources of energy in the body and their rates of energy formation;
- discuss how amino acids can be used as an energy source during exercise.

This chapter presents a brief overview of the energy sources used by muscles in order to engage in various activities. It is a 'taster' that will (hopefully) encourage you to delve a bit more deeply into the basic biochemistry of the macronutrients which provide energy, as well as to gain an understanding of the likely regulation of the processes which produce energy. From this perspective, this chapter examines the

energy-yielding processes from a superficial level in addressing issues of energy for sprinting and for more prolonged events.

Key words

adenosine	fatty acid
diphosphate (ADP)	glycogen
aerobic	glycogenolysis
anaerobic	glycolysis
anaerobic alactic	lipid
anaerobic glycolytic	lipolysis
anaerobic glycolysis	mitochondria
anaerobic lactic	oxidation
adenosine	PCr
triphosphate (ATP)	(phosphocreatine)
carbohydrate	phosphorylation
CK (creatine kinase)	protein
creatine	protein degradation
dephosphorylation	protein synthesis
energy continuum	

1.1 Adenosine triphosphate: the energy currency

In order for our muscles to contract and provide movement, energy is required. Such energy is

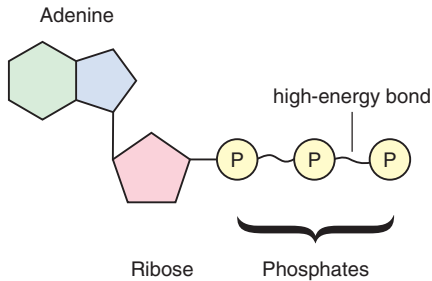


Figure 1.1 Adenosine triphosphate (ATP)

provided by **adenosine triphosphate (ATP)** and is the only energy capable of being used for muscle contraction in humans. Figure 1.1 provides the structure of an ATP molecule. As you can see from this diagram, ATP consists of a base (adenine) attached to a sugar (ribose), to which is attached three phosphate molecules. The phosphates are attached by ‘high energy’ bonds which, when removed, provide energy.



The process is reversible, which means that ATP may be re-formed from **adenosine diphosphate (ADP)** as long as there is sufficient energy to restore the missing phosphate molecule on to the ADP. The latter can be achieved by **phosphocreatine (PCr)** or by processes such as **anaerobic glycolysis**, and **aerobic** processes.

The stores of ATP in muscle tissue are rather limited, so there is a constant need to resynthesize it for survival, let alone movement. The amount of ATP in a muscle cell amounts to 25 mM/kg dry muscle or about 40–50 g in total, which is sufficient to enable high intense activity for around 2–4 seconds if it is the only useable source of energy available. This is not a great amount – hence the importance of resynthesis of ATP at rates sufficient to enable appropriate levels of exercise to ensue, i.e. fast rates of resynthesis for sprinting and slower rates for prolonged exercise.

1.2 Energy continuum

The major energy sources for exercise are dependent on the intensity and duration of the

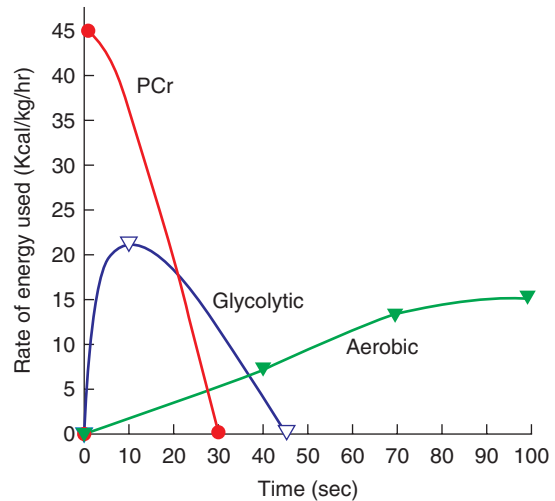


Figure 1.2 Energy continuum

activity. Examination of Figure 1.2 highlights that there appears to be three such sources, i.e. PCr, glycolytic and aerobic. These energy-producing processes predominate exercise from 1–10 seconds, 10–60 seconds and beyond 60 seconds respectively.

Another way of expressing the **energy continuum** is represented in Figure 1.3, which shows the major energy sources for running events of varying distances. Note that short, highly intense sprinting bouts lasting 1–10 seconds use PCr predominantly, while events such as the 400 metres mainly use anaerobic glycolysis, and thereafter aerobic metabolism predominates.

1.3 Energy supply for muscle contraction

ATP is not stored to a great degree in muscle cells. Therefore, once muscle contraction starts, the regeneration of ATP must occur rapidly. There are three primary sources of ATP; these, in order of their utilization, are PCr, anaerobic glycolysis and aerobic processes.

Energy from ATP derives from cleaving the terminal phosphate of the ATP molecule. The resulting molecule is adenosine diphosphate (ADP). Phosphocreatine converts ADP back to ATP by donating its phosphate in the presence of the enzyme **creatine kinase (CK)**, and

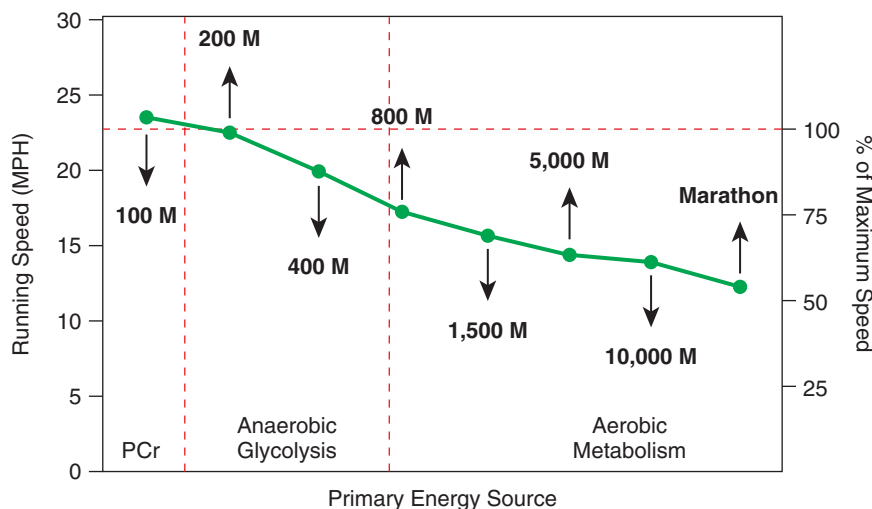
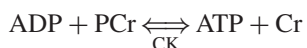


Figure 1.3 Primary energy sources for different running distances

in turn the PCr forms **creatine** (Cr), i.e. the **dephosphorylated** form of PCr.



The reaction of PCr with ADP to form ATP is very rapid, but is short-lived since the cell does not store high amounts of PCr (the muscle concentration of PCr is about 80 mM/kg dry muscle or 120 g in total). However, during short, high-intensity contractions, PCr serves as the major source of energy. This form of energy generation is often called **anaerobic alactic**, because it neither produces lactic acid nor requires oxygen. It is of paramount importance in sports requiring bursts of speed or power, such as sprints of 1–10 seconds.

Figure 1.4 provides a schematic to show the synthesis of ATP from ADP using PCr at the muscle crossbridge, and also the regeneration of PCr from Cr by ATP at the mitochondria.

Thus, Cr is formed from PCr during intense bouts of exercise, while Cr is re-phosphorylated to PCr by ATP produced in the mitochondria during aerobic recovery. Oxygen is needed for recovery of PCr, as can be seen in Figure 1.5, which clearly demonstrates that recovery of exercise-depleted PCr only happens when the blood supply to the exercising muscle is not occluded, i.e. there

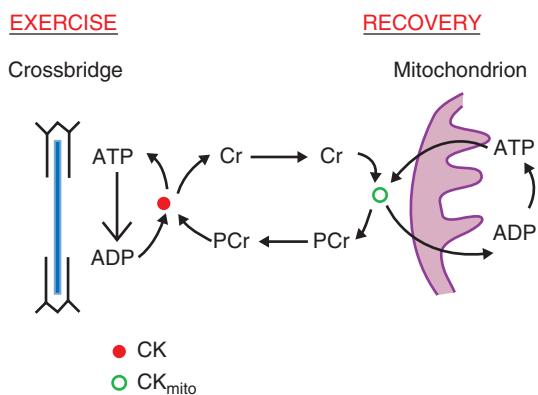


Figure 1.4 PCr shuttle

is an intact blood supply taking oxygen to the cells. If the blood supply is occluded (e.g. via a tourniquet), then PCr resynthesis fails. As a consequence, you should appreciate the need for a low level (so called active) recovery in between bouts of intense exercise.

The enzyme CK, which regulates PCr activity, exists in a number of forms known as isoforms (this will be dealt with later). Note that not only is there a CK which favours the formation of ATP from PCr, but there is also another form, CK_{mito}, which is present at the mitochondria and favours the synthesis of PCr from Cr using ATP.

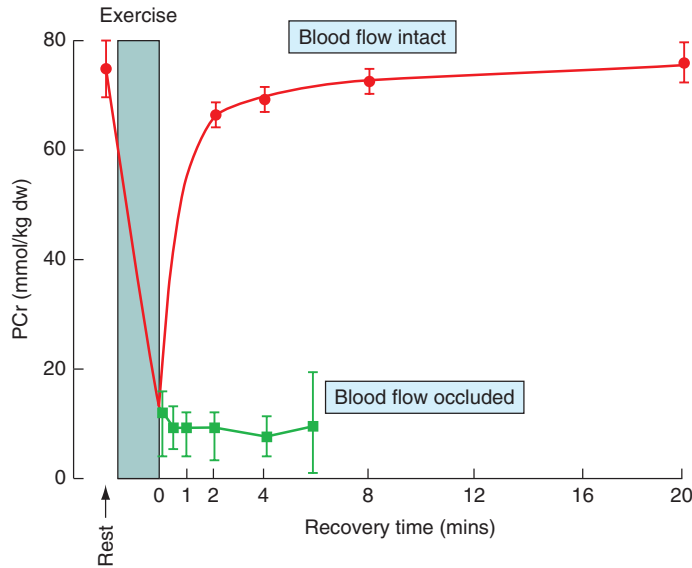


Figure 1.5 Resynthesis of PCr after exercise with and without an occluded blood supply (adapted from Hultman *et al.*, 1990)

You should also note from Figure 1.5 that there is a rapid loss of PCr during intense exercise and that it is rapidly recovered (this may even be depleted if the exercise is sufficiently intense or prolonged). Indeed, nearly 75% of PCr is resynthesized within the first minute of recovery and the rest over the next 3–5 minutes. The graph is biphasic, i.e. rapid restoration at first, then a second, slower phase.

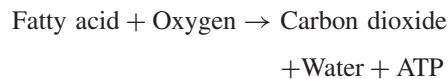
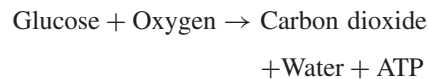
As soon as muscle contraction starts, the process of anaerobic glycolysis also begins. Anaerobic glycolysis does not contribute as large an amount of energy as PCr in the short term, but its contribution is likely to predominate from 10–60 seconds.

During glycolysis, locally stored muscle **glycogen**, and possibly some blood-borne glucose, supply the substrate for energy generation. **Glycolysis** takes place in the cytoplasm, where no oxygen is required, so the process is called anaerobic. It may also be called ‘**anaerobic lactic**’, since lactic acid is formed as the end product. Sufficient lactic acid formation can lower the pH of the cell (i.e. make it more acid) to the extent that further energy production may be reduced.

The major substrate for **anaerobic glycolysis** (see below equation) is glycogen, so prior hard exercise without adequate repletion of glycogen will limit further high-intensity short-term work.



Exercise beyond 60 seconds requires mainly aerobic energy sources, such as the complete **oxidation** of glucose or **fatty acids** to carbon dioxide and water. These processes necessitate oxygen and take place in the **mitochondria** of the cells. The equations below illustrate the essence of aerobic metabolic reactions:



We shall see more detail about these processes in Chapters 5 and 6.

Aerobic activities invariably occur at lower exercise intensities (which are those lasting

Energy expenditure
(kcal.kg⁻¹.min⁻¹)

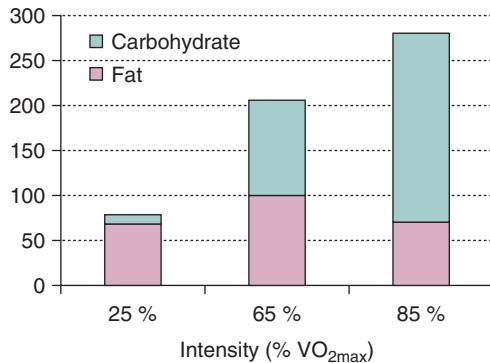


Figure 1.6 Carbohydrate and fat use at three exercise intensities (adapted from Romijn *et al.*, 1993)

longer than one minute), and the contributions of **carbohydrate** and fat at these levels of intensity can be realized in Figure 1.6. Note that fats contribute a greater percentage (and amount) of energy at 25% VO_{2max} (i.e. walking pace), around 50% of the energy at 65% VO_{2max} (i.e. steady state pace), and around 25% of the energy at 85% VO_{2max} (i.e. an intense aerobic bout with some significant anaerobic energy involved).

1.4 Energy systems and running speed

Based on world record times, humans can maintain maximum sprinting speed for approximately 200 m. The average speeds for the 100 m and 200 m world records are similar, at 22.4 mph and 21.6 mph respectively. However, with increasing distances, average speeds decline. The average speed for the marathon world record is 12.1 mph, which is 55% of the world sprint record. This is remarkable, since the marathon distance is more than 200 times the length of a 200 m race.

Although natural selection plays a crucial role in elite sprinting and marathon performance, the energy systems must also be highly trained and exercise-specific to be successful. For example,

the energy needed to maintain an average sprinting speed of 22 mph for 200 m or less, and that required for an average running speed of 12.1 mph for the marathon, are acquired by two very different systems (the predominant energy systems required for running at different speeds can be seen in Figure 1.3). The primary energy source for sprinting distances up to 100 m is PCr. From 100 m to 400 m, anaerobic glycolysis is the primary energy source. For distances longer than 800 m, athletes rely primarily on aerobic metabolism.

The rate of glycogen and fat utilization varies according to the relative running speed. Although the rate of glycogen utilization is low while running a marathon, the duration of the event increases the possibility of depleting glycogen stores. In contrast, the rate of glycogen utilization is substantially higher during a 5,000 m run, but glycogen depletion is not a concern because of the shorter duration of the event.

Maximum maintainable speed decreases by approximately 7 mph as running distance increases from 200 m to 1500 m. However, as the distance increases from 1500 m to 42.2 km, maximum maintainable speed only drops by an additional 3.5 mph. On average, a healthy, fit, non-elite, male athlete can be expected to sprint at an average speed of 16–18 mph for 100–200 m and at approximately 6–8 mph for a marathon (see Figure 1.7).

1.5 Why can't a marathon be sprinted?

Figure 1.7 clearly demonstrates the inability to sustain high running velocities for a protracted duration. So why is an athlete unable to keep up higher running speeds over a marathon distance? The different energy sources have already been noted above, but what it is necessary to understand is that each of these energy sources resynthesizes ATP at varying rates. Table 1.1 highlights the likely rates of ATP production, and you should note the hierarchy.

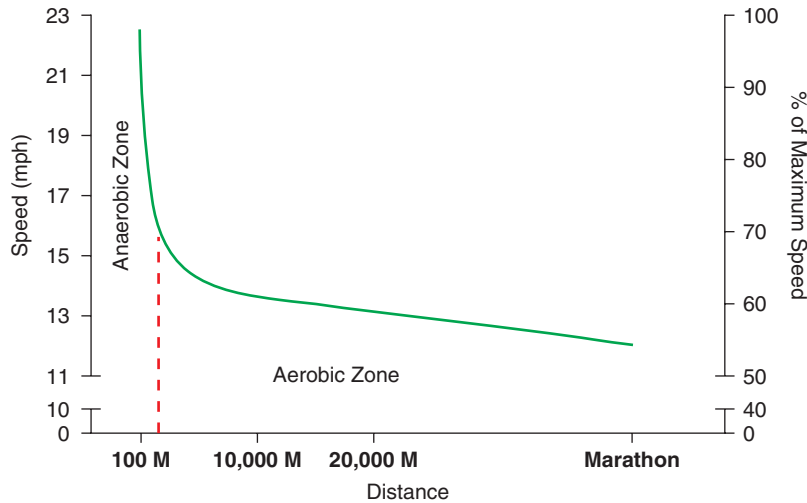


Figure 1.7 Sustainable running speed and distance run

Table 1.1 Maximum rates of energy production

Process	Maximum power
PCr → ATP	9 mM/kg/s
CHO → lactate + ATP	4 mM/kg/s
CHO → CO ₂ + H ₂ O + ATP	2 mM/kg/s
Fat → CO ₂ + H ₂ O + ATP	1 mM/kg/s

The PCr system is the most rapid of these ATP-producing systems. A calculated rate of 9 mM/kg dry muscle/s is more than twice as fast as ATP generation from anaerobic glycolysis which in turn is twice as fast as aerobic oxidation of carbohydrates. Furthermore, the aerobic breakdown of carbohydrates produces ATP at twice the rate of fats (i.e. 2 mM/kg/s vs. 1 mM/kg/s). It thus seems that energy processes in the cytoplasm produce ATP at a faster rate than those which require oxidation via the mitochondria, and that carbohydrates produce ATP quicker than fats.

In later chapters, we will see that whereas PCr generation of ATP is a single reaction, anaerobic glycolysis entails ten reactions, aerobic breakdown of glucose necessitates around 26 reactions (if the TCA cycle is used twice), and somewhere in the

region of 90–100 reactions are required for complete fatty acid oxidation. No wonder, that there are varying rates for ATP production.

Since the muscle stores of PCr are rather limited, and the end product of the rapid ATP generation from anaerobic glycolysis produces lactic acid, it would appear that it is not possible for an athlete to keep running at a sprint pace when undertaking a marathon – they would either run out of PCr, or the pH of their muscles would be significantly reduced due to lactic acid production. In addition, there are also limited stores of muscle and liver carbohydrate (glycogen) which would seem to be problematic as a source of energy for a complete marathon, so the need to employ fatty acids is important in energy production. Fatty acids produce the slowest rates of ATP synthesis – hence the fact that when these stores are engaged, running speeds are lowered.

1.6 Energy sources and muscle

Table 1.2 highlights a number of key points in relation to energy sources for muscle. These include:

1. the total amount of the energy source, from which it is quite apparent that the faster

- ATP-producing sources are limited (notably PCr and glycogen for anaerobic glycolysis);
- the likely duration for which these energy sources will last if they are the only source of ATP production;
 - the maximal rates by which they can produce ATP.

1.7 Can muscle use protein for energy?

So far there has been little or no mention of using **proteins** for energy. Muscles are made of protein in the main, but can muscle protein provide energy? The answer is, to a limited extent, yes. A major difference between carbohydrates and fats is that they are essentially made up of carbon, hydrogen and oxygen only, whereas protein molecules also contain an amino group, (i.e. a nitrogen). The end result of carbohydrate and fat oxidation is the generation of carbon dioxide and water, whereas oxidation of proteins requires the removal of nitrogen.

Figure 1.8 illustrates the fact that amino acids (the basic structural component of proteins) can, after the removal of the nitrogen (which ends up as urea), be converted to carbohydrates,

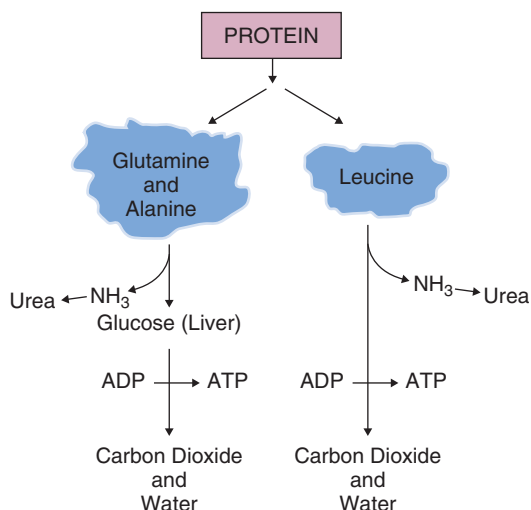


Figure 1.8 Likely use of amino acids for energy

which can then be oxidized. During prolonged exercise, the amino acids alanine and glutamine are converted to glucose in the liver, and the glucose is then oxidized by muscle. In addition, the muscle also has a limited capacity to oxidize the amino acid leucine. In total, amino acids usually accounts for 5% of the energy needed by muscle.

Table 1.2 Energy sources available to working muscle including amounts and likely duration before depletion

	ATP	PCr	Anaerobic glycolysis	Carbohydrate oxidation	Fatty acid oxidation
Total amount	40 g	120 g	350 g of CHO	500 g of CHO	15,000 g of fatty acids
Duration of exercise before depleted stores		4–6 s	1–2 min	1–2 h	>6 h
Max rate of ATP synthesis (mM/kg/s)		9	4	2	1

1.8 Key points

- Adenosine triphosphate (ATP) is the useable form of energy for muscle contraction.
- Phosphocreatine (PCr), anaerobic glycolysis and aerobic processes enable ATP to be resynthesized during exercise.
- High intensity bouts of exercise demand a faster rate of ATP generation if the activity is to proceed and this is achieved by the faster 'anaerobic' sources, i.e. PCr and anaerobic glycolysis.
- Low to moderate bouts of exercise use aerobic energy processes such as complete oxidation of carbohydrates and fats.
- ATP and PCr content are limited in muscle and hence the reduced capability to engage in very intense levels of activity for prolonged periods.
- Anaerobic glycolysis results in lactic acid formation which is considered by some research to contribute to fatigue.
- Carbohydrate sources of energy (glycogen) are limited in comparison with fat sources.
- Amino acids from protein breakdown can contribute to energy production in a limited manner.