INQUIRY QUESTION
How is energy produced to enable this physical activity?

AU: Please note that all figure & Table calls are not cited in text.
Energy is required for all kinds of bodily processes including growth and development, repair of body tissue, the transport of various substances between cells and, of course, muscle contraction, which enables movement to occur.

**KEY KNOWLEDGE**
- Fuels (both chemical and food) required for resynthesis of ATP at rest and during physical activity including the relative contribution of fuels at varying exercise intensities
- Characteristics of the three energy systems (ATP-CP, anaerobic glycolysis and aerobic systems) for physical activity, including rate of ATP production, the yield of each energy system, fatigue/limiting factors and recovery rates associated with active and passive recoveries
- Interplay of energy systems in relation to the intensity, duration and type of activity

**KEY SKILLS**
- Participate in a variety of physical activities and describe, using correct terminology, the interplay and relative contribution of the energy systems
- Perform, observe, analyse and report on laboratory exercises designed to explore the relationship between the energy systems during physical activity and recovery
- Explain the fatiguing factors associated with the use of the three energy systems under varying conditions

**CHAPTER PREVIEW**

Energy systems and interplay of energy systems
5.1 Adenosine triphosphate (ATP): the body’s energy currency

**KEY CONCEPT** Adenosine triphosphate (ATP) provides energy for muscular contraction.

Adenosine triphosphate (ATP) is a high-energy molecule stored in muscle cells and other parts of the body. It is the energy currency for biological work. The chemical breakdown of ATP to ADP (adenosine diphosphate) produces an immediate source of energy for muscular contraction and other bodily functions and processes.

Adenosine triphosphate (or ATP as it is more commonly referred to) is the chemical energy ‘currency’ of all body cells, including muscle cells. It powers all of the cells metabolic activities, including in the case of muscle cells, the ability to contract. An ATP molecule consists of adenosine and a chain of three inorganic phosphate groups bound together by high-energy chemical bonds (see figure 5.1).

The energy that powers the mechanisms involved in muscular contraction is obtained from the catabolism (breaking down) of ATP. However, the body stores only a very small quantity of this ‘energy currency’ within the cells, enough to power only 1–2 seconds of maximal exercise. As most sporting activities last longer than this, the body must replace or resynthesise ATP on an ongoing basis. Understanding how the body does this is the key to understanding energy systems.

**FIGURE 5.1** An ATP molecule consists of adenosine and a chain of three inorganic phosphate groups bound together by high-energy chemical bonds.

The phosphate ‘tail’ of ATP is the actual ‘power source’ that the cell taps into. Available energy is contained in the bonds between the phosphates and is released when they are broken. Usually only the outer phosphate is removed from ATP to yield energy; when this occurs ATP is converted to adenosine diphosphate (or ADP) and inorganic phosphate (or Pi — free phosphate molecule).

The energy released during the breakdown of ATP to ADP and Pi is used to power cell processes such as the mechanisms involved in muscular contraction. This can be represented by the formula ATP → ADP + Pi + Energy (see figure 5.2).

**FIGURE 5.2** The energy released during the breakdown of ATP to ADP and Pi is used to power cell processes such as the mechanisms involved in muscular contraction.

Replenishing ATP stores

While the breakdown of ATP is required in order to provide the energy that powers the mechanisms involved in muscular contraction, muscular stores of ATP are very limited. It is estimated that the total quantity of ATP in the average human body is
about 0.1 mole or approximately 50–100 grams. Yet estimates put the daily energy requirement of an average person upwards of 100–180 moles of ATP, which is equivalent to 50–75 kilograms of ATP (see figure 5.3).

The limited stores of ATP within the body are used up within about 1–2 seconds of maximal intensity activity. If it were not for the fact that ATP stores are constantly replenished during activity, muscular contraction could not continue. Once intramuscular ATP stores begin to deplete, chemical reactions within the muscle start to replenish ATP stores which, therefore, allows the muscles to keep working.

The replenishment of the limited stores of ATP occurs via a process known as phosphorylation. This is a biochemical process that involves the addition of a phosphate group to an organic compound or molecule. In this particular circumstance it involves the addition of a phosphate group to ADP to form ATP. In other words, ATP is replenished or resynthesised from ADP and Pi. However, this resynthesis requires energy to connect the phosphate group back to ADP to create ATP (ADP + Pi + Energy ↔ ATP). This energy can be obtained from the breakdown of several energy fuels or substrates that are also present within the muscle. These fuels or substrates include creatine phosphate (or phosphocreatine as it is also known), forms of carbohydrates (glycogen), fats and protein. These fuels can provide the energy required for the resynthesis of ATP during physical activity for as long as sufficient stores of the fuels or substrates are available (see figure 5.4).

The energy that is required to enable ATP resynthesis to occur can be released from these energy fuels via three distinct yet closely integrated metabolic pathways or energy systems. If ATP resynthesis occurs via energy systems or pathways that require the presence of oxygen, it is referred to as aerobic metabolism (or oxidative phosphorylation). If it occurs via energy systems or pathways that do not require oxygen then it is referred to as anaerobic metabolism.

**FIGURE 5.3** It is estimated that the total quantity of ATP in the average human body is 50–100 grams; much less than what is required in a 24-hour period.

**FIGURE 5.4** The resynthesis of ATP from ADP and a free phosphate molecule requires energy available from the breakdown of energy fuels.

**Phosphorylation** is a biochemical process that involves the addition of a phosphate group to an organic compound or molecule. It involves the addition of phosphate to ADP to form ATP (ADP + Pi + Energy ↔ ATP).

**Aerobic metabolism** is when ATP resynthesis occurs via energy pathways that require the presence of oxygen.

**Anaerobic metabolism** is when ATP resynthesis occurs via energy pathways that do not require the presence of oxygen.

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**TEST your understanding**

1. Explain what is meant by ‘ATP is the energy currency of the cell’.
2. Draw a diagram to show the basic structure of ATP.
3. Explain how ATP differs from ADP.
4. Define the term ‘phosphorylation’.
5. What is the difference between anaerobic and aerobic metabolism?

**EXAM practice**

6. Outline the role of ATP in producing energy for physical activity.
Several energy fuels or substrates can be used to provide the energy required for the resynthesis of ATP from ADP and Pi. These include creatine phosphate (a chemical fuel) and carbohydrates, fats and protein (food fuels).

**Creatine phosphate**

Creatine phosphate (CP), or phosphocreatine (PC) as it is also known, is a chemical compound that, like ATP, is stored in limited quantities within muscle cells. Also like ATP, creatine phosphate is a high-energy substance capable of storing and releasing energy via the high-energy bond that binds the creatine and phosphate together (see figure 5.5). When this bond is broken, energy is released that enables ATP to be resynthesised from ADP and Pi.

**Creatine in the diet**

Approximately 50 per cent of the creatine stores within our bodies are obtained through the foods we eat, while the other 50 per cent are manufactured in the kidneys and liver. Roughly 95 per cent of the human body’s total creatine is located in skeletal muscle. The rest is located in the brain or heart. Approximately one-third is found within our bodies in its free form as creatine, while the remainder is bound with phosphate to form creatine phosphate.

**Carbohydrates**

Carbohydrates are found in many of the foods we eat. Traditionally, carbohydrates have been generally divided into two groups:
1. simple carbohydrates or sugars, composed of one or two glucose molecules (monosaccharides and disaccharides)
2. complex carbohydrates or starches, made up of many hundreds of glucose molecules (polysaccharides).

**Glycaemic index**

The glycaemic index (GI) is a ranking of carbohydrates on a scale from 0 to 100 according to the extent to which they raise blood-glucose levels after eating. Foods with a high glycaemic index (70 and above) are those that are rapidly digested and absorbed and result in a rapid increase in blood-glucose levels. Foods that have a high glycaemic index include sugar, potatoes, watermelon, many breakfast cereals (e.g. Corn Flakes), most white rices (e.g. jasmine) and white bread (see figure 5.6(a)).

Foods with a low glycaemic index, by virtue of their slow digestion and absorption, produce gradual rises in blood-glucose and insulin levels, and have proven benefits for health. Foods that have a low glycaemic index (55 or less) include most fruits and vegetables (except potatoes and watermelon), grainy breads, pasta, lentils, milk...
and yoghurt (see figure 2.6(b)). Table 5.1 is a guide to the glycaemic index of many common carbohydrate foods.

![Graph showing blood-glucose level over time for high and low glycaemic index foods]

**TABLE 5.1 Glycaemic index of some common carbohydrate-rich foods**

<table>
<thead>
<tr>
<th>Food</th>
<th>Glycaemic index (glucose = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High glycaemic index</strong></td>
<td></td>
</tr>
<tr>
<td>Rice crackers</td>
<td>87</td>
</tr>
<tr>
<td>Cornflakes</td>
<td>81</td>
</tr>
<tr>
<td>Porridge, instant oats</td>
<td>79</td>
</tr>
<tr>
<td>Potato, boiled</td>
<td>78</td>
</tr>
<tr>
<td>Watermelon</td>
<td>76</td>
</tr>
<tr>
<td>White bread</td>
<td>75</td>
</tr>
<tr>
<td>White rice, boiled</td>
<td>73</td>
</tr>
<tr>
<td><strong>Moderate glycaemic index</strong></td>
<td></td>
</tr>
<tr>
<td>Popcorn</td>
<td>65</td>
</tr>
<tr>
<td>Sweet potato, boiled</td>
<td>63</td>
</tr>
<tr>
<td>Honey</td>
<td>61</td>
</tr>
<tr>
<td>Soft drink</td>
<td>59</td>
</tr>
<tr>
<td>Pineapple</td>
<td>59</td>
</tr>
<tr>
<td>Muesli</td>
<td>57</td>
</tr>
<tr>
<td>Porridge, rolled oats</td>
<td>55</td>
</tr>
<tr>
<td><strong>Low glycaemic index</strong></td>
<td></td>
</tr>
<tr>
<td>Sweetcorn</td>
<td>52</td>
</tr>
<tr>
<td>Pasta, white</td>
<td>49</td>
</tr>
<tr>
<td>Orange</td>
<td>43</td>
</tr>
<tr>
<td>Chocolate</td>
<td>40</td>
</tr>
<tr>
<td>Milk, full fat</td>
<td>39</td>
</tr>
<tr>
<td>Apple</td>
<td>36</td>
</tr>
<tr>
<td>Lentils</td>
<td>32</td>
</tr>
</tbody>
</table>


Knowledge of the glycaemic index allows athletes, coaches and sports dietitians to determine what carbohydrate foods to eat and when to eat them. Manipulated correctly, this can enable the athlete to optimise their carbohydrate availability and thereby optimally enhance their performance and recovery. Put more simply, there would appear to be times when foods with a low glycaemic index provide an advantage, and times when foods with a high glycaemic index are better. For best performance, athletes need to understand which foods have high and low glycaemic index ratings and when it is best to eat them.

**FIGURE 5.6** <caption to come>
5.2 Energy fuels: converting food to energy

**Carbohydrates in the body**

When carbohydrates are digested, they are broken down into glucose for transportation via the circulatory system (blood) and then stored as glycogen in the muscles and liver. Any excess carbohydrates can be stored as fat in the form of triglycerides within adipose tissue around the body.

**Carbohydrates as an energy source**

Carbohydrates are the most versatile fuel source available to supply energy for ATP resynthesis. Carbohydrates in the form of glycogen can provide the energy for ATP resynthesis under both anaerobic (no oxygen required) and aerobic (oxygen required) conditions. For example, glycogen can supply energy for ATP resynthesis during both high-intensity, short-duration activities, such as sprinting 200 metres or repeated work periods during a game of football (anaerobic activities), as well as being able to provide energy during submaximal, longer-duration activities, such as a 1500-metre swim or 5-kilometre jog (aerobic activities). At rest and during low-intensity exercise, carbohydrates contribute approximately one-third of the body’s energy requirements, with fats providing the other two-thirds.

**Carbohydrates in the diet**

Carbohydrates should make up approximately 55–65 per cent of total daily energy intake, although athletes in heavy training and competition may require a higher percentage intake (60–80 per cent) to ensure adequate levels in the body each day.

**Fats**

Fats (or lipids) are found in many different foods and can be divided into:

1. saturated fats
2. unsaturated fats.

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**Glucose** is the simplest form of carbohydrate and the basic ingredient for anaerobic and aerobic glycolysis.

**Glycogen** is the storage form of glucose found in the muscles and in larger quantities in the liver.

**Fats** (lipids) are an essential component of a balanced diet and should comprise about 20–25 per cent of the daily food intake. Fats are broken down through digestion to free fatty acids.

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**FIGURE 5.7** Examples of carbohydrate foods (a) with a high glycaemic index and (b) with a low glycaemic index.

- **High GI Food (70 and above)**: rice, corn flakes, watermelon, white bread.
- **Medium GI Food (56 and 69)**: popcorn, sweet potato, muesli, porridge.
- **Low GI Food (55 and under)**: pasta, corn, lentils, oranges.
Saturated fats are found in animal foods such as dairy products (e.g. milk, cheese) and meat products (see figure 5.8). This type of fat contains a substance called cholesterol that has been implicated in cardiovascular disease. When blood-cholesterol levels rise, blood vessels may become lined with cholesterol deposits leading to cardiovascular problems.

Unsaturated fats (see figure 5.9) come in two forms: polyunsaturated and mono-unsaturated. Polyunsaturated fats are found in most vegetable oils (e.g. sunflower oil) and oily fish (e.g. tuna), whereas mono-unsaturated fats are found in foods such as olive oil, avocados and nuts. Both types of unsaturated fat help lower the total cholesterol level and contain essential fatty acids that the body cannot produce itself.

**Fats in the body**

Fats are broken down through digestion and made available to the bloodstream as free fatty acids and glycerol. They are stored intramuscularly as triglycerides, with excess amounts stored subcutaneously within adipose tissue around the body, where they act as a substantial energy reservoir.
Fats as an energy source

Fats are the most concentrated form of energy for ATP resynthesis. Gram for gram, fats provide more energy than carbohydrates, with fats providing about 9 kilocalories per gram whereas carbohydrates provide about 4 kilocalories per gram. Despite this, fats are primarily used during rest and low-intensity exercise. At rest, fats provide approximately two-thirds of the energy needs of the body, with carbohydrates contributing the remaining one-third. During exercise, the percentage of fats being used as an energy source decreases as the exercise intensity increases. This is because, metabolically speaking, fats are more difficult to break down and, therefore, their rate of energy release is too slow (considerably slower than that from carbohydrates) during high-intensity activity where ATP resynthesis must keep pace with the rapid rate of ATP use. However, fats as an energy source become increasingly important when stores of carbohydrate start to deplete during endurance exercise (usually after 90–120 minutes of continuous activity).

Fats in the diet

It is generally recommended that fats should make up about 20–25 per cent of the average daily energy intake, although for endurance athletes in training 25–30 per cent may be more appropriate.

Protein

Animal foods such as meat, poultry, fish, eggs and dairy products are rich in protein and contain all the essential amino acids. Plant foods such as cereals, grains, lentils, beans and peas are also good sources of protein, although they do not contain all of the essential amino acids.

Protein in the body

Protein is broken down through digestion into amino acids of which there are two types:

1. essential amino acids — cannot be made by the body, so must be consumed as part of the diet.

FIGURE 5.9 Examples of foods containing unsaturated fats
2. non-essential amino acids — can be manufactured from other amino acids in the body. 

Excess protein (amino acids) is converted to fats and stored within adipose tissue. 

Proteins help the formation, growth and repair of body tissue, especially muscle tissue and cells. They also help in the production of red blood cells, hormones and enzymes.

**Protein as an energy source**

Under normal circumstances protein contributes only minimal energy for ATP resynthesis (estimates put this figure at no more than 5–10 per cent). However, in extreme circumstances (such as starvation or ultra-endurance events), when the body has severely depleted its supplies of carbohydrate and fat, proteins can become a viable source of energy for the replenishment of ATP. Due to complex reactions required to break down the food fuels of fats and protein, energy is produced at a slower rate than carbohydrate.

**Protein in the diet**

Nutritionists recommend that proteins contribute about 15 per cent of the average daily food intake. Athletes in training may require slightly more protein in their diet, especially athletes involved in strength and power sports.

**Protein and carbohydrates**

Protein and carbohydrates make excellent partners for post-exercise nutrition. When consumed together, they stimulate a greater release of insulin. Put more simply, the addition of protein amplifies the insulin response and promotes glucose delivery to depleted muscle cells.

- Insulin also plays a key role in the dynamics of protein synthesis.
- Insulin stimulates protein synthesis and helps to reduce protein breakdown.

The consumption of protein is therefore essential on two fronts:

- to help boost insulin release
- to provide the basic building blocks for muscle repair.

Examples of healthy snacks that include both protein and carbohydrates:

- yoghurt
- milk drinks
- fruit smoothies
- lean meat or cheese sandwiches.
## Summary of food fuels

The elite athlete will adjust percentage food fuel intake in consultation with a coach/dietician to ensure their needs are met. For example, the elite athlete may require a greater level of protein intake if building and repairing muscle is needed. Most elite athletes will have a greater intake of fuel than will the general population, due to their excessive energy requirements.

Table 5.3 provides a summary of the food fuels that are used to provide energy for ATP resynthesis.

### Table 5.3 Summary of food fuels

<table>
<thead>
<tr>
<th>Food sources</th>
<th>Transport form</th>
<th>Storage form in muscle</th>
<th>Excess</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td>Glucose</td>
<td>Glycogen</td>
<td>Liver — glycogen; Converted into fats — adipose tissue</td>
</tr>
<tr>
<td>High glycaemic index:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>most fruits and vegetables (except potatoes and watermelon), grainy breads, pasta, peas, lentils, milk and yoghurt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low glycaemic index:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sugar, honey, potatoes, watermelon, many breakfast cereals, most white rices and white bread</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fats (lipids)</td>
<td>Free fatty acids and glycerol</td>
<td>Triglycerides</td>
<td>Adipose tissue</td>
</tr>
<tr>
<td>Saturated fats:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>meat products and dairy products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unsaturated fats:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vegetable oils, oily fish (e.g. tuna), olive oil, nuts and avocado</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td>Amino acids</td>
<td>Amino acids</td>
<td>Adipose tissue</td>
</tr>
<tr>
<td>Animal foods:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>meat, poultry, fish, eggs and dairy products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant foods:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cereals, grains, lentils, beans and peas</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TEST your understanding

1. Explain the role of glycogen in providing energy for physical activity.
2. What percentages of carbohydrate, fat and protein are recommended as part of the daily dietary intake?
3. How would the dietary intake of food fuels differ for a weight-lifter compared with a long-distance runner?
4. Complete the following table to show the relationship between food fuels, the breakdown of these food fuels and the energy system or systems that use each food fuel.

<table>
<thead>
<tr>
<th>Food fuel</th>
<th>Broken-down form</th>
<th>Associated energy system or systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5. Carbohydrates and fats are the main food fuels used to supply energy for ATP resynthesis. Under what conditions would proteins be used to supply energy for physical activity?

### APPLY your understanding

6. How would knowledge of the glycaemic index of foods assist an athlete in terms of athletic performance?
7. Explain why, physiologically, it is inadvisable to consume a sugary food (with a high glycaemic index) just prior to beginning exercise.

### Learning activity: individual diet and energy

Record your total dietary intake for a continuous 3-day period. Record this intake in an appropriate table form. Assess the percentages of carbohydrate, fat and protein in your diet each day and for the 3-day period overall. Using your own dietary knowledge as a guide, how could you improve your diet to meet your energy needs? Write a brief report on your findings.

### EXAM practice

9. Explain the role of creatine phosphate.
10. What is the most concentrated form of energy for ATP resynthesis?
The energy that is required to enable ATP resynthesis to occur can be obtained via three distinct yet closely integrated metabolic pathways or energy systems that operate together to satisfy the energy requirements of the muscle. Two of these energy systems are anaerobic pathways and the third is an aerobic pathway, as shown in figure 5.11.

**FIGURE 5.11** The body relies on three energy systems — two anaerobic systems and one aerobic system.

The ATP–CP system refers to the processes involved in the breakdown of stored phosphagens — ATP and creatine phosphate — without oxygen being involved. This system is also commonly referred to as the ATP–PC system, the phosphate energy system, the phosphocreatine (PC) system or the phosphagen system.

The anaerobic glycolysis system involves the metabolism of carbohydrates (glycogen) to lactic acid through a series of chemical steps that do not require oxygen, whereas the aerobic system (or oxidative system) refers to the complete metabolism of primarily carbohydrates (glycogen) and/or fats (triglycerides) in the presence of oxygen.

### ATP resynthesis: demand, rate and yield

All three energy systems contribute to the resynthesis of ATP during physical activity. How each system works alongside the other energy systems is referred to as the interplay of energy systems. To determine which of the three energy systems is the predominant supplier of energy for ATP resynthesis at any point in time during an activity, we need to understand the concept of ATP demand.

During any activity, ATP resynthesis (supply) must be able to meet the ATP demand of the activity. Two factors determine the ATP demand of an activity:
1. exercise duration — how long the activity lasts for
2. exercise intensity — how hard the exercise is performed.

Exercise intensity determines the rate of ATP use and, consequently, resynthesis during the activity. Exercise duration determines the total amount or yield of ATP expended that is required to be resynthesised over the course of the activity. Generally
5.3 Energy systems and pathways

speaking, as exercise duration increases, the intensity at which it can be performed decreases. To help illustrate the concept of ATP demand, rate and yield, let us consider two different activities:

**100-metre sprint**
- Completed in around 10 seconds, the 100-metre sprint is a high intensity activity, during which the rate of ATP expenditure is very rapid as the leg muscles are required to contract powerfully and very quickly. Consequently, the rate of ATP resynthesis must also be very rapid in order to keep pace with the demand. However, because of this event’s short duration (less than 10 seconds), the yield (total amount) of ATP required is low.

**Marathon**
- Takes around two hours and 15 minutes to complete. Is undertaken at submaximal intensity and the rate at which ATP is required is much lower since the muscles are not required to contract as forcefully or as quickly as in the 100-metre sprint. Due to the marathon’s much longer duration, though, the yield (total amount of) ATP required is much, much greater (see figure 5.12).

**Meeting ATP demands**

The two anaerobic energy systems (ATP–CP and anaerobic glycolysis) can supply energy for ATP resynthesis at a rapid rate. However, they can do this for only a short period of time, due to the much smaller yield of energy for ATP resynthesis. Therefore, the anaerobic pathways are the major energy systems used during high-intensity, short-duration exercise, since muscles need a rapid supply of ATP during such activities. The aerobic system, on the other hand, supplies energy for ATP resynthesis at a much slower rate than the anaerobic pathways, but is capable of supplying a much greater yield of energy for ATP resynthesis than the anaerobic pathways. Therefore, the aerobic system is the predominant supplier of energy for ATP resynthesis when we are at rest, and also during longer-duration exercise that is performed at submaximal intensity.
While the rate of energy production via the aerobic system is much slower than that of the two anaerobic systems, it produces far more energy for ATP resynthesis than either of these anaerobic systems for a given amount of "fuel".

**Yield of ATP**

In terms of ATP yield:
- The ATP–CP system can produce only 0.7 moles of ATP from 1 mole of CP
- The anaerobic glycolysis system can produce only 2 moles of ATP from 1 mole of glucose
- The aerobic system can produce 38 moles of ATP from 1 mole of glucose
- The aerobic metabolism of fats produces by far the most ATP from a given amount of "fuel". One mole of fat can produce in excess of 100 moles of ATP.

**Rate of ATP**

When we consider rate of ATP supply, the reverse applies.
- The ATP–CP system can supply ATP at maximal intensity rate of 3.6 moles per minute.
- The anaerobic glycolysis system can supply ATP at a high intensity rate of 1.6 moles per minute.
- The aerobic system can supply ATP at a slow rate of around 1 mole per minute.

These differences in the capacity of the three energy systems are summarised in table 5.4.

### TABLE 5.4 Capacities of the three energy systems

<table>
<thead>
<tr>
<th>Fuel source</th>
<th>ATP–CP system</th>
<th>Anaerobic glycolysis system</th>
<th>Aerobic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrate (glycolysis)</td>
<td>Glucose</td>
<td>Glycogen</td>
<td>Glucose</td>
</tr>
<tr>
<td>Fats (lipolysis)</td>
<td>FFA</td>
<td>Triglycerides</td>
<td></td>
</tr>
<tr>
<td>Rate</td>
<td>Most rapid</td>
<td>Rapid</td>
<td>Slow</td>
</tr>
<tr>
<td>3.6 moles/min</td>
<td>1.6 moles/min</td>
<td>1.0 mole/min</td>
<td></td>
</tr>
<tr>
<td>Yield (moles of ATP per mole of fuel source)</td>
<td>Very small</td>
<td>Small</td>
<td>38 (glucose)</td>
</tr>
<tr>
<td>&lt; 1</td>
<td>2</td>
<td>39 (glycogen)</td>
<td>387 (triglycerides)</td>
</tr>
<tr>
<td>Dominant time period</td>
<td>0–10 seconds</td>
<td>10–75/90 seconds</td>
<td>75/90 seconds–90 minutes</td>
</tr>
<tr>
<td>Event</td>
<td>Power</td>
<td>Speed</td>
<td>Endurance</td>
</tr>
</tbody>
</table>

**Notes about table 5.4:**
- There is a trade-off between rate and yield for each of the energy systems.
- As the rate of ATP resynthesis increases, the yield decreases.
- The values shown in the table are general values and can vary from individual to individual.
- The capacity to produce energy via each of the three energy systems can vary with training.
- There is a transition period where one energy system is increasing its relative contribution while another is decreasing its relative contribution (interplay of energy systems).
- Fatigue-limiting factors will determine the transition from one energy system to another.
As you move down the pyramid:

- Decrease need for oxygen
- Increase yield of ATP
- Decrease rate of ATP synthesis

As you move up the pyramid:

- Decrease need for oxygen
- Decrease yield of ATP
- Increase rate of ATP synthesis

**FIGURE 5.13** The characteristics of the food fuels

**TEST your understanding**

1. List the three energy systems that are responsible for the production of energy for ATP resynthesis.
2. For each energy system, indicate the chemical and/or food fuels that can be used by that energy system.
3. What two factors determine the ATP demand of an exercise bout or activity?
4. Explain the difference between rate and yield in terms of ATP demand.
5. Rank the three energy systems in order from fastest (1) to slowest (3) in terms of the rate at which they are capable of providing energy for ATP resynthesis.
6. Rank the three energy systems in order from lowest (1) to highest (3) in terms of the yield of ATP they are capable of producing from an equivalent amount of their fuel source.

**APPLY your understanding**

7. **Learning activity: energy systems used in physical activities**
   - As a class, perform the following series of physical activities and/or events, allowing adequate time for recovery in between each activity. Have a partner time how long it takes you to complete each activity and then swap and do the same for them.
   - A basketball lay-up
   - A 200-metre sprint
   - An agility circuit around the gymnasium
   - 20 situps
   - A 1-kilometre jog around the oval
   - Record how you felt during and immediately after each activity. What energy system was predominant during your performance of each activity? Why was it important to record the time taken to complete each activity? Why was it important to allow for adequate recovery time (rest) between each activity? Present your findings and answers to these questions as a written report.

**EXAM practice**

8. State the rate and yield of ATP for anaerobic glycolysis.
The ATP–CP system is the least complicated of the three energy systems, and it produces energy for ATP resynthesis most rapidly. The ATP–CP system relies on the muscular stores of ATP and creatine phosphate. When creatine phosphate is broken down, the energy and phosphate group released is then used to resynthesise ATP. Therefore, as rapidly as ATP is broken down for muscular contraction, it is continually resynthesised from ADP and Pi by the energy released by the breakdown of creatine phosphate. However, creatine phosphate stores within the muscle are also limited and they deplete rapidly, particularly during high-intensity activity. This process is shown in figure 5.14.

![Creatine phosphate](image)

**FIGURE 5.14** The release of energy via the ATP–CP system for ATP resynthesis is quick and efficient, but short-lived.

When undertaking maximal-intensity exercise, ATP stores in the muscle will last for approximately 1–2 seconds. Thereafter, the resynthesis of ATP from the breakdown of creatine phosphate will continue until such time that creatine phosphate stores become depleted. On average, this occurs after approximately 6–8 seconds of high-intensity exercise. Combined, the ATP–CP system can therefore sustain all-out (maximal) exercise for approximately 8–10 seconds. If the activity is to continue beyond this immediate period, the body must rely predominantly on another energy system to provide energy for ATP resynthesis.

In conclusion, the ATP–CP system can provide only a very limited amount (yield) of energy for ATP resynthesis, although it is able to supply this energy at a very rapid rate. As a consequence, this system is the predominant energy system used during high-intensity activities such as sprints, throws and jumps that take approximately 0–10 seconds to perform.

**Fatigue**

The causal mechanisms of fatigue depend on the type, duration and intensity of the exercise being performed, as well as other considerations such as the fibre-type composition of the involved muscle or muscles, and the fitness and training status, nutritional state and mental state of the athlete. The fatigue experienced in these predominantly anaerobic events is very different from that experienced during and after a prolonged aerobic event, such as a marathon that takes over two hours to complete.
5.4 The ATP–CP system

**Fuel depletion**

When we refer to fuel depletion as a fatigue-causing mechanism, we are in fact referring to the depletion of energy fuels or substrates that serve to power muscular contractions. They include adenosine triphosphate (ATP) and creatine phosphate (CP).

**Creatine phosphate depletion**

During maximal intensity, short-duration, anaerobic-type activities, muscular stores of ATP are used within the first few seconds of activity. Once these stores have been depleted, the muscles then use their creatine phosphate stores as fuel to provide energy to replenish ATP from ADP and Pi.

- Creatine phosphate stores also deplete rapidly, and after about 10 seconds of all-out effort, the muscles’ stores of creatine phosphate are almost fully depleted.
- As creatine phosphate stores deplete, the ability to rapidly replenish ATP is considerably reduced.

The consequence of this reduction in the rate of ATP resynthesis is that activity cannot be sustained at the same intensity.

- The failure of the metabolic processes to resynthesise ATP at the required rate results in energy deficiency or muscular fatigue. It is never more obvious than towards the end of a burst of sprinting that fatigue is not only loss of the force that muscles can produce but also impairment of their shortening speed.
- Creatine phosphate stores play a role in fatigue during single and repeated sprints but also may play a role in long duration exercise with bouts of short duration, maximal intensity work.
Recovery

Post-exercise recovery aims to overcome the effects of fatigue and restore the body to its pre-exercise condition. Adequate and effective recovery is essential to provide the body with the opportunity to replenish, repair and rebuild itself in readiness for the next training session or exercise bout. Without sufficient recovery, subsequent performances will be compromised.

Passive recovery

After an athlete has completed maximal intensity and short duration activities, the ATP and the creatine phosphate stores must be rebuilt within the muscle if the ATP-CP system is to be utilised as a fuel source for the next activity.

- At the end of the activity, breathing rate is above normal and during this passive recovery time of resting or low-intensity activity, ATP and CP within the muscle are being rebuilt during the time of excess post-oxygen consumption (EPOC).
- The extra oxygen is used to restore ATP and some of the restored ATP is broken down. The energy from this is used to combine creatine and phosphate back into CP stores within the muscle.
- During passive recovery:
  - 50% of the ATP and CP is restored within 20 seconds
  - 70% of the ATP and CP is restored within 30 seconds
  - 75% of the ATP and CP is restored within 40 seconds
  - 87% of the ATP and CP is restored within 60 seconds
  - Most of the ATP and CP intramuscular stores are replenished within approximately 3 minutes.

The ATP-CP system and exercise

To further illustrate how the ATP-CP system functions, let us consider two activities in sport: one that takes just a few seconds to perform — a drive off the tee in golf — and another that takes about 10 seconds to perform — the 100-metre sprint in athletics.

The golf drive

The drive off the tee in golf only takes a second or so to execute. The energy required to perform this movement is derived almost exclusively from the breakdown of the muscular stores of ATP, which on average will last for 2–3 seconds of all-out effort (see figure 5.18). Fatigue limiting factor is reduced levels of ATP and a passive recovery will replenish ATP stores at the fastest rate.

The 100-metre sprint

- At the beginning of a 100-metre sprint (see figure 5.19), all three energy systems are activated.
- From the explosive push-off from the starting blocks until a few seconds into the sprint, the muscles’ ATP stores provide the energy for the repeated muscular contractions.
- During these few seconds, ATP stores in the muscles diminish, and the amount of ADP produced from the spent ATP increases.
- From this point in the event, the muscular stores of creatine phosphate now provide the energy and free phosphate for the resynthesis of new ATP from ADP, allowing the athlete to continue the sprint at maximal intensity.
- Rate of ATP is 3.6 moles/min
- Yield is <1 mole of ATP

**FIGURE 5.18** The drive off the tee in golf is an example of a powerful movement that relies heavily on the ATP–CP system.
- Towards the end of the race (from about 6 to 10 seconds onwards), the muscles’ stores of creatine phosphate are greatly depleted. The percentage energy contribution from the anaerobic glycolysis system during the final few seconds of the race becomes much more significant.
- Fatigue limiting factor is depletion of creatine phosphate.
- Passive recovery through rest or low intensity cool-down will replenish ATP and CP stores at the fastest rate, with 87% of the ATP and CP restored within 60 seconds.

**FIGURE 5.19** The cycle of ATP being broken down and resynthesised for powerful muscle movement centres around energy being released via the breakdown of creatine phosphate.
TEST your understanding
1 Describe the intensity and duration of a sporting activity where the ATP–CP system is the predominant energy system.
2 Outline the advantages and disadvantages associated with the ATP–CP system.

APPLY your understanding
3 Which fitness components would be most closely associated with the ATP–CP system? Explain the reasoning for your responses.
4 Learning activity: phosphate recovery test
As part of a class activity, undertake the phosphate recovery test. Details of how to perform this test can be found in your eBookPLUS.
(a) Use your understanding of energy systems to explain the interplay of the three energy systems that would occur during the performance of the phosphate recovery test.
(b) Use your understanding of energy systems to explain why, during the phosphate recovery test, each participant’s performance tends to decline over the course of the repetitions performed.
(c) Research a range of other laboratory and/or field tests that can be used to provide an indication of the capacity of the ATP–CP system. Explain how performance in each of these tests relates to the capacity of this system.

EXAM practice
5 The world record time for the 100-metre sprint is 9.58 seconds.
(a) State the energy system.
(b) Justify your response to part a.
5.5 The anaerobic glycolysis system

**KEY CONCEPT** The characteristics of the anaerobic glycolysis system for physical activity, including rate and yield of ATP, fatigue factors and recovery rates.

In the anaerobic glycolysis system, muscular stores of glycogen are converted into glucose and then, with the aid of enzymes, this glucose is broken down into a substance called pyruvic acid (or pyruvate). If oxygen is not available in sufficient quantities at this stage in the metabolic pathway then pyruvic acid is further converted to lactic acid. During this series of reactions energy is released, which is used to resynthesise ATP from ADP and Pi. The lactic acid that is produced dissociates into lactate and hydrogen ions (H+) within the muscle. The process of anaerobic glycolysis is shown in figure 5.20.

Pyruvic acid, also referred to as pyruvate, is an intermediate product in the metabolism of carbohydrates, formed by the anaerobic metabolism of glucose.

**The anaerobic glycolysis system and exercise**

The anaerobic glycolysis system is also activated at the onset of exercise and operates as the predominant supplier of energy for ATP resynthesis in the period from around 10 seconds of maximal effort (the time period when the ATP–CP system is no longer able to provide energy due to the depletion of phosphagen stores) to around 60 seconds of high-intensity effort. However, the aerobic energy system could become the predominant supplier of ATP as early as 30 seconds. The anaerobic glycolysis system may also become the predominant energy supplier during repeated short, high-intensity efforts (such as repeated sprint efforts), where the recovery period between efforts is too short to allow full replenishment of creatine phosphate stores. Furthermore, when a performer has gone beyond their maximum oxygen uptake level during an exercise bout, the anaerobic glycolysis system increases contribution to meet the demands of the task, as at this intensity, the aerobic system is unable to produce ATP at a fast enough rate to fully meet the body’s demands for the time period it takes until the performer is forced to either stop due to exhaustion or decrease the exercise intensity due to fatigue.
The 400-metre athletic event

To further illustrate how this system functions, let us consider the 400-metre running event in athletics. The men’s world record for the 400 metres is currently held by Wayde van Niekerk of South Africa who set a time of 43.03 seconds in 2016, while the record for the women’s 400 metres is currently 47.60 seconds set by Marita Koch of Germany in 1985. Cathy Freeman famously won the gold medal in the 400 metres at the 2000 Sydney Olympics in a time of 49.11 seconds (see figure 5.21).

During the 400-metre athletic event, the production of ATP relies on all three energy systems but predominantly on anaerobic glycolysis (see figure 5.22).

When the athlete pushes off the starting blocks, the ATP–CP energy system allows for an explosive start to the race.

However, after about 6–10 seconds, the ATP–CP system quickly loses its primary role in the production of energy for ATP resynthesis as CP stores are rapidly depleted.

For intensity to be maintained, anaerobic glycolysis assumes predominance throughout the middle to later stages of the race. During this time period (10 to 45+ seconds) glycogen stores within the muscle are used predominantly anaerobically in order to provide the energy needed to replenish ATP, thereby allowing the muscles to continue propelling the athlete around the track.

The aerobic system also plays a significant role in providing energy for ATP resynthesis during the final phase of the event (the final 100 metres or so). Recent studies indicate that in a 400-metre event taking approximately 45 seconds to complete, the aerobic contribution to ATP resynthesis during the event could be as high as 40 per cent, with the other 60 per cent derived from the two anaerobic systems.
The anaerobic glycolysis system

FIGURE 5.22 The 400-metre event provides a good example of an activity that relies heavily on the anaerobic glycolysis system.
A final word about anaerobic glycolysis

The contribution of the anaerobic glycolysis system to the supply of energy for ATP resynthesis increases rapidly after the initial 5–15 seconds of maximal-intensity exercise. This coincides with a drop in maximal power output as the immediately available phosphagens, ATP and creatine phosphate, deplete after approximately 6–10 seconds. For approximately between 10 and 30 seconds of sustained maximal intensity activity, the majority of energy comes from anaerobic glycolysis. After approximately 45 seconds of sustained maximal activity there is a second decline in power output as activity beyond this point corresponds with a growing reliance on the aerobic energy system.

Fatigue

Accumulation of metabolic by-products

Metabolic by-products or metabolites are substances produced as a result of chemical reactions within the body associated with the production of energy for ATP resynthesis. They are the ‘leftovers’, and include lactic acid (lactate and hydrogen ions), as well as inorganic phosphate (Pi) and adenosine diphosphate (ADP).

Lactic acid

Lactic acid accumulates in the muscles only after relatively short duration, high-intensity exercise.

Potential causes of lactic acid induced fatigue include:
- impaired isometric muscle contraction force
- impaired isometric muscle velocity force
- inhibition of glycolysis due to a decrease in intramuscular pH.

The lactic acid levels of endurance athletes, such as marathon runners and triathletes, at the completion of their events are not much higher than resting levels, despite their obvious fatigue.

Hydrogen ions (H⁺)

Research indicates that the accumulation of hydrogen ions in the muscle cells (stemming from their dissociation from the lactic acid as a result of anaerobic glycolysis during high-intensity activity) results in an increase in the acidity within the muscle (otherwise known as muscle acidosis). This increased acidity results in a decrease in the muscle pH from the normal value of around 7.1 at rest to 6.4 at exhaustion, a value that appears to be incompatible with normal muscle cell function. Changes in pH of this magnitude adversely affect energy production and muscle contraction, resulting in muscular fatigue (see figure 5.23).

A reduction in intracellular pH to less than 6.9 had been shown to inhibit the rate of glycolysis and ATP production by inhibiting the action of essential glycolytic enzymes, particularly phosphofructokinase or PFK. Furthermore, hydrogen ion accumulation has been shown to disrupt the muscle contractile process through interference with the role that calcium (Ca²⁺) plays in the mechanisms involved with the coupling of the actin–myosin cross bridges.

It is worth knowing that if the intramuscular pH level was to fall too low (e.g. down to a pH of 5.6), the muscle cells would effectively be killed. Fortunately, the body contains buffers, such as bicarbonate, which function to minimise the disrupting influence of the accumulating hydrogen ions. Because of this buffering capacity, the hydrogen ion concentration is kept lower than it otherwise would be, limiting the decline in pH to 6.6–6.4 at exhaustion. Lactate also plays a key role in reducing the accumulation of hydrogen ions and minimising the decrease in muscle pH and is an important source of fuel for skeletal muscles and the brain.

Muscle acidosis is a condition in which the pH of the muscle decreases as a result of the accumulation of metabolic by-products such as hydrogen ions within the muscle cells. The lower the pH level, the greater the acidity and the greater the likelihood of fatigue affecting performance.

pH is a measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. The pH scale commonly in use ranges from 0 to 14. The pH in muscle cells at rest is about 7.1 or 7.2.
5.5 The anaerobic glycolysis system

Inorganic phosphate (Pi)

One of the consequences of rapid creatine phosphate hydrolysis during high intensity exercise is the accumulation of inorganic phosphate (Pi), which has also been shown to inhibit muscle contraction. You will recall that when ATP is used to provide the energy for muscular contraction, it breaks down to ADP + Pi + energy. At the same time, creatine phosphate breaks down to creatine + Pi + energy. These processes result in an increase in Pi within the muscle. The exact mechanisms by which the rising levels of Pi contribute to muscular fatigue are still not fully known, but it would appear that it too (like increasing hydrogen ions) may have something to do with interference with the role of calcium (Ca^{2+}) in the contractile process and/or interference with the cross bridge coupling cycle.

Adenosine diphosphate (ADP)

Some research also points to rising levels of ADP that accompany high-intensity exercise as a possible mechanism of fatigue during such activities, although its exact role is still not well understood. However, it appears that rising levels of ADP interfere with muscle excitation–contraction coupling (see below) in a complex way, but predominantly through interference with the role that calcium (Ca^{2+}) plays in the contractile process.

Active recovery

Research has shown that an active recovery is an efficient first step in enabling the body to recover from exercise, particularly exercise lasting for more than a few seconds. After an athlete has completed a strenuous high-intensity anaerobic exercise bout at intensity close to or at VO_2 max, the fastest lactate/hydrogen ions clearance is achieved by active recovery at exercise intensity lower than the individual's lactate inflection point. Rather than sitting or lying down as soon as exercise is completed, the athlete should undertake light activity at a low intensity for a period of 5–10 minutes. The active recovery can also take the form of light, aerobically based cross-training activities performed after the exercise session.

The active recovery is used to:

- reduce heart rate to resting levels
- replenish oxygen levels in the blood, body fluids and myoglobin
- increase blood flow to the working muscles
- remove higher lactate concentration levels
- accelerate oxidation as this boosts the clearance rate of lactate
- resynthesise high-energy phosphates
- support the small energy cost to maintain elevated circulation and ventilation
- remove metabolites after exercise.

If previous exercise was strenuous, where lactate and body temperature have increased considerably, EPOC recovery would be slow (slow component). EPOC recovery may take several hours, depending on intensity and duration, before returning to pre-exercise oxygen consumption levels.

These activities should be different from those normally performed in the exercise bout. An example would be undertaking light pool work after a game of football. Studies have shown that active recovery can help to prevent venous pooling of blood after strenuous activity. Venous pooling occurs as the active muscles are no longer acting as pumps to propel the blood back to the heart. It can leave the athlete feeling dizzy as blood flow is compromised to the vital organs such as the brain.


**FIGURE 5.23**<Caption to come>

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**TEST your understanding**

1. What is the only fuel food that can be catabolised anaerobically?
2. What is the name for the series of reactions in which this process takes place?
3. What are the end products of this anaerobic process?
4. Describe the intensity and duration of a sporting activity where this anaerobic process is the predominant energy system.
5. Outline the advantages and disadvantages associated with the anaerobic glycolysis system.

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**APPLY your understanding**

6. Practical activity: measuring the capacity of the anaerobic glycolysis system

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As part of a class activity, undertake a 400-metre run test. Use your understanding of energy systems to explain the interplay of the three energy systems that would occur during the performance of this test.

**EXAM practice**

7. (a) Name the predominant energy system for the 200-metre sprint.
(b) State the predominant fuel for the 200-metre sprint.
(c) Explain how the rate of ATP production influences the average rate of speed for a 200-metre sprinter.
(d) At the end of the sprint, an active recovery session was used. Explain how this facilitates a faster recovery compared to passive recovery.
The aerobic system (or oxidative system) is the slowest energy system to contribute towards ATP resynthesis due to the complex nature of its chemical reactions, but it is capable of producing the greatest yield of ATP energy when comparing all three energy systems. It is also the most versatile of the three energy systems in that it can use a variety of different fuels including carbohydrates (glycogen), fats (triglycerides and free fatty acids) and, under extreme conditions, proteins.

Aerobic energy production from carbohydrates

The aerobic metabolism of carbohydrates involves three processes to produce energy for ATP resynthesis (see figure 5.24):

1. aerobic glycolysis (increasingly referred to as slow glycolysis as opposed to anaerobic or fast glycolysis)
2. the Krebs cycle (citric acid cycle)
3. the electron transport chain.

**Aerobic glycolysis**

Aerobic glycolysis (or slow glycolysis) is exactly the same series of reactions as anaerobic glycolysis (or fast glycolysis) in that glycogen is converted to glucose and then broken down by a series of chemical steps to pyruvic acid (pyruvate). However, in the presence of sufficient oxygen, pyruvic acid is converted to a substance called acetyl coenzyme A and channelled into the Krebs cycle rather than being converted to lactic acid.

**The Krebs cycle**

The **Krebs cycle** is a complex series of chemical reactions that continues the oxidation of glucose that was started during aerobic glycolysis. Acetyl coenzyme A enters the...
Krebs cycle and is broken down into carbon dioxide and hydrogen, allowing more energy for ATP resynthesis to be produced. The hydrogen ions produced in the Krebs cycle are then transported to the electron transport chain.

The electron transport chain
Hydrogen ions within the electron transport chain combine with oxygen to form water (H₂O). This process results in even more energy for ATP resynthesis being produced. The end products of this process are carbon dioxide (CO₂) and water (H₂O).

Aerobic energy production from fats
The aerobic system can metabolise fats as well as carbohydrates to produce energy for ATP resynthesis. Lipolysis is the term used to describe the breakdown of fat (triglycerides) into the more basic units of glycerol and free fatty acids. Glycerol and free fatty acids are then broken down to acetyl coenzyme A via a process called beta oxidation. Acetyl coenzyme A can now enter the Krebs cycle and from this point on fat metabolism follows the same path as carbohydrate metabolism.

Comparing carbohydrate and fat metabolism
The aerobic system can produce ATP through either fats (fatty acids) or carbohydrates (glycogen). The key difference is that the breakdown of fats produces significantly more ATP (greater yield) compared with that obtained from an equivalent amount of carbohydrates. However, the metabolism of fats requires far more oxygen than the metabolism of the equivalent amount of carbohydrates. Therefore, if your body is to use fats as the fuel source for ATP resynthesis it must be able to provide sufficient oxygen to meet the greater metabolic demand. If not, then the exercise intensity must decrease so that the oxygen requirement is reduced.

Aerobic energy production from proteins
Protein is thought to make only a small contribution (usually no more than 5–10 per cent) to energy production. However, amino acids, the building blocks of protein, can be either converted into glucose or into other intermediates used by the Krebs cycle such as acetyl coenzyme A. Protein may make a more significant contribution during very prolonged exercise (e.g. ultramarathons), perhaps as much as 15–20 per cent of total energy requirements.
5.6 The aerobic system

**The mitochondria**

Stages 2 and 3 of aerobic metabolism (the Krebs cycle and electron transport chain) occur within the **mitochondria**. The greater the number and size of mitochondria within the muscle cells, the greater the capacity for energy production.

**The aerobic system and exercise**

The aerobic system is used predominantly when at rest and during low- to moderate-intensity exercise. When you are at rest, your body has an abundant oxygen supply, so the energy required for the resynthesis of ATP is provided almost exclusively by the aerobic energy system. It relies on the breakdown of fats to provide about two-thirds of the energy required, while the other one-third comes from the breakdown of carbohydrates. However, when we are exercising, the body's preferred fuel is generally carbohydrates and the higher the exercise intensity the greater the reliance on carbohydrates. Carbohydrates are the preferred fuel source during exercise because:

- they can be metabolised aerobically or anaerobically
- carbohydrates produce energy at a faster rate than fat
- complete oxidation of carbohydrate requires less oxygen than complete oxidation of fat
- carbohydrate stores are more readily accessible than fat stores (this is true because triglycerides have to be reduced to glycerol and free fatty acids before they can be used to generate cellular energy).

The aerobic system, along with the other two energy systems, is also activated at the beginning of high-intensity exercise and it will become the predominant energy system after approximately 60 seconds of continuous activity. Of course, by this time the intensity of the activity will have decreased (it will now be what we refer to as submaximal exercise), and the body's supply and delivery of oxygen to the working muscles will have increased as a result of acute bodily responses to the demands of the activity. The aerobic system continues to be the predominant contributor to energy production for ATP resynthesis during continuous submaximal exercise that exceeds 1–2 minutes in duration (see figure 5.32).

**Fatigue**

The fatigue experienced in predominantly aerobic events is different from that experienced during and after a short, high-intensity anaerobic event, such as 100-metre or 400-metre sprints.

**Fuel depletion**

When we refer to fuel depletion as a fatigue-causing mechanism, we are in fact referring to the depletion of energy fuels or substrates that serve to power muscular
contractions. Glycogen is also the preferred fuel used by the aerobic system during exercise of sustained submaximal intensity (endurance exercise).

![FIGURE 5.27](image)

**FIGURE 5.27** Muscle ATP concentration at rest and various stages of prolonged cycling (a) and muscle glycogen concentration at the same points during the same exercise bout (b)

**Depletion of intramyofibrilar glycogen cluster**
Glycogen is stored within the muscle as clusters in three different sites:
- sub-sarcolemmal glycogen cluster (muscle fibre membrane)
- intermyofibrillar glycogen cluster (between myofibrils)
- intramyofibrillar glycogen cluster (within the myofibril — major glycogen cluster).

The majority of muscle glycogen stores (approximately 75%) are stored within the myofibril but exact distributions depend on training, muscle fibre type, fibre use and type of exercise. Most of the intramyofibrillar glycogen is stored near the t-tubules of the sarcoplasmic reticulum which has an important role for releasing calcium (Ca²⁺) for the excitation–contraction coupling process. Depletion of intramyofibrillar glycogen may cause a reduction in the production of ATP and impair the formation of actin-myosin cross bridges and the development of muscle force.

**Depleted glycogen and hypoglycaemia**
During various forms of exercise, the body will rely on four primary food fuel sources: muscle glycogen, muscle triglycerides, blood glucose and free fatty acids. The exercise mode, intensity and duration, training status, pre-exercise fuel status of the athlete and environmental conditions will determine which fuel is being utilised for ATP replenishment. During long endurance exercise, as muscle glycogen is depleted, blood glucose levels are maintained by the breakdown of glycogen in the liver. An increase in blood glucose use will lead to a situation where the liver can no longer supply glycogen and hypoglycaemia can develop. Hypoglycaemia may contribute to fatigue by limiting fuel supply to the working muscles and the brain.
Glycogen depletion during aerobic (endurance) exercise

During prolonged submaximal intensity aerobic (or endurance) exercise, the body preferentially uses muscle glycogen stores as the fuel source for providing energy for ATP resynthesis. Unfortunately, muscle glycogen stores are also limited and deplete relatively quickly.

- Muscle glycogen stores can be depleted within as little as 40 minutes during intense prolonged exercise such as distance running, although, more typically, glycogen stores can fuel continuous submaximal exercise for periods of 90–120 minutes.
- As glycogen stores deplete during prolonged endurance exercise, there is an increased reliance on fat (free fatty acid) metabolism. This increased reliance on fat oxidation necessitates a decrease in exercise intensity. Research strongly suggests that there is a correlation between depletion of glycogen stores and muscular fatigue.
- Depletion of muscle glycogen during prolonged, exhaustive exercise causes a decrease in calcium release inside the muscle, reducing muscle contractions.
- At exercise intensities between 65 per cent and 85 per cent of maximal oxygen uptake (VO2 max), muscular fatigue is highly correlated with depletion of muscle glycogen stores.
- Furthermore, glycogen depletion typically results in exercise intensity having to decrease to a level that can be supported predominately by fat metabolism; around 50 per cent of maximal oxygen uptake.

FIGURE 5.28 Contribution of primary food fuels during submaximal intensities and various durations

An increased reliance on fat oxidation further reduces an individual’s exercise capacity, as less ATP is generated from fats compared to glycogen per litre of oxygen consumed. Table 5.5 shows that about 7 per cent less energy is produced per given amount of oxygen with fat as a fuel compared to glycogen (carbohydrate) as a fuel. Once glycogen is depleted and fats become the predominant substrate, exercise pace must slow because less energy can be produced. Thus, glycogen depletion is associated with an inability to maintain the rate of prolonged aerobic exercise. In marathon running, the point in the race at which this occurs (typically around 28–35 kilometres) is referred to as ‘hitting the wall’. In cycling, it is called ‘bonking’. Studies on perceived exertion (how difficult an effort seems to be) also indicate that participants typically...
do not report exercise as being highly stressful or fatiguing until such time as muscle glycogen stores are near depletion (see figures 5.29 and 5.30). Thus, the sensation of fatigue during prolonged exercise seems to coincide with a decreased concentration of muscle glycogen.
While glycogen depletion is clearly associated with muscular fatigue during endurance-type activities, it is not an exclusive factor.

Summary
In summary, fuel depletion contributes to metabolic fatigue within the muscle due to a lack of intracellular energy to power muscle contractions. In essence, the muscle is unable to continue contracting at the same rate or force, basically because it lacks the energy to do so.

Impaired muscle excitability
Peripheral fatigue can also involve impairment of the mechanisms involved in muscle excitability; in other words, impairment in the processes involved in muscle excitation-contraction (E–C) coupling, which arises when a nervous impulse arrives at the muscle membrane. We have already seen that the accumulation of metabolic by-products such as hydrogen ions, inorganic phosphate and ADP are thought to interfere with the contractile process, including the excitation-contraction coupling process. Also implicated in interference with this process is potassium (K⁺).

Potassium
The excitability of the muscle membrane (membrane potential), or in other words its receptiveness to nervous stimulation, appears to be influenced by several substances that move into and out of the intracellular and intercellular spaces of the muscle during the contractile process. One of these substances is potassium (K⁺). During muscle contraction, potassium moves out of the muscle cells into the intercellular space. It builds up in the t-tubule system and the muscle fibre in general, and has the effect of depolarising the muscle membrane, making it more difficult to excite the muscle and therefore muscle contractions are inhibited or reduced. This occurs most markedly during high-intensity exercise. This appears to be some kind of safety mechanism protecting the muscle from damage that might result from repeated nervous stimulation.

Recovery
Active recovery is also beneficial in accelerating the process of ridding the muscle cells of any metabolic by-products that may have been produced and accumulated during the exercise period. During the active recovery period, the rate of oxygen consumption by the athlete remains above the required rate, given their level of activity. The term ‘excess post oxygen consumption’ (EPOC) has typically been used to describe this phase. Active recovery is suitable after aerobic type activities and allows:
- resynthesis of high-energy phosphates
- replenishment of oxygen in the blood
- replenishment of body fluids
- replenishment of myoglobin.

If previous exercise was primarily aerobic, EPOC recovery would be completed within several minutes (fast component).
FIGURE 5.31 Aerobic glycolysis is best exemplified in any low- to moderate-intensity longer duration event, in which it provides the bulk of the required energy to resynthesise ATP.

TEST your understanding
1 Describe the intensity and duration of a sporting activity where the aerobic system is the predominant energy system.
2 Outline a specific sporting activity or situation that clearly illustrates the use of the aerobic system as the predominant energy system.
3 Outline the advantages and disadvantages associated with the aerobic system.
4 What is the final common metabolic pathway for oxidative metabolism of fat, carbohydrate and protein?
5 Where in the cell do the reactions making up this pathway take place?

APPLY your understanding
6 Practical activity: multi-stage fitness test
As part of a class activity, undertake the 20-metre shuttle run test.

(a) Use your understanding of energy systems to explain the interplay of the three energy systems that would have occurred during your performance of the 20-metre multi-stage shuttle run test.
(b) Research a range of other laboratory and/or field tests that can be used to provide an indication of the capacity of the aerobic system. Explain how performance in each of these tests relates to the capacity of the aerobic system.

EXAM practice
7 (a) State the duration and fuel required for the aerobic pathway.
(b) Identify two by-products of the aerobic energy system.
(c) Explain why the average speed for the 1500 metre runner is slower than the 400 metre sprinter.
**5.7 Energy systems at work: interplay of energy systems**

**KEY CONCEPT** Energy systems work together to supply the energy required for ATP resynthesis.

This sub-topic will look at how the energy systems contribute during rest and exercise conditions. This will help you understand how the body adapts its metabolic activity during the transition from rest to exercise.

**ATP production at rest**

When at rest your body is not under physical stress and it has an abundant oxygen supply, so the energy required for the resynthesis of ATP is provided almost exclusively by the aerobic energy system. It relies on the breakdown of fats to provide about two-thirds of the energy required (again because of the abundance of oxygen), while the remaining one-third comes from the breakdown of carbohydrates (see figure 5.32).

**ATP production during exercise**

There is no exact or definitive point where one energy system drops off and another energy system becomes the predominant energy supplier. Rather, there is a gradual transition from one system being predominant to another system assuming predominance.

**Rest-to-exercise transitions**

Three rest-to-exercise transition scenarios can help to illustrate this interplay or transition of energy systems and when each of the three energy systems are called upon to provide the major portion of the ATP needed to sustain exercise at any given intensity. In looking at each scenario, it is important to recall that all the energy systems are contributing towards ATP production simultaneously throughout any exercise bout, but the proportional contribution of ATP from each system to the metabolic demand will shift according to exercise intensity.
As the relative exercise intensity increases, the rate of ATP production rises concurrently to meet the exercise energy demand.

**Source:** Brown, SP, Miller, WC & Eason JM, 2005, *Exercise physiology: basis of human movement in health and disease*, Lippincott Williams & Wilkins, page 76.

**Transition from rest to maximal-intensity exercise for 0 to 6 seconds**
- The ATP–CP system is the only system with the capacity to meet the high power output demand of very high-intensity exercise.
- Although the other energy systems will produce ATP at slower rates during maximal intensity exercise, their proportional contribution to the energy supply will be minimal.

**Transition from rest to high-intensity exercise for 30 to 45 seconds**
- Because of the longer duration of this exercise bout, intensity has to be reduced in order for the activity to continue for this period of time.
- After the first 6–10 seconds of exercise, the primary responsibility for providing energy for ATP resynthesis shifts from the ATP–CP system to the anaerobic glycolysis system, as creatine phosphate stores become depleted.
- Towards the end of the exercise bout, the aerobic system will be contributing quite significantly to ATP resynthesis.
- If the activity were to continue beyond 45–60 seconds, the intensity would have to be decreased to a moderate or lower level. At this lower exercise intensity, the aerobic system will assume the role of predominant energy supplier.

**Transition from rest to low/moderate intensity exercise**
- It is vital to understand that any time energy demand is increased above resting levels — whether it be starting out on a slow jog or pushing out of the blocks at the start of a 100-metre sprint — this increased energy demand immediately requires an increased oxygen supply to the working muscles as the body strives to continue to work predominantly aerobically.
- However, the respiratory and circulatory systems are unable to meet this increased demand immediately, so the body must use the anaerobic energy pathways to supplement the production of ATP until such time as the body is able to increase its oxygen delivery to meet the oxygen demand of the activity.
If the activity is being performed at low intensity, then this increase in oxygen supply will not take long to achieve and the aerobic system will quickly resume the role of predominant energy supplier.

However, with progressively higher exercise intensities, the relative energy contributions of the anaerobic systems become greater and greater.

**Intermittent exercise**

Many team sports require the players not only to run at maximal speeds for a short duration but also maintain their speed and endurance throughout the whole match. There may be periods within the match to recover CP and glycogen stores or reduce levels of lactate and hydrogen ions. For any intermittent activity, it is more accurate to consider the energy system contribution and interplay at various stages of performance by considering the key factors of intensity, duration, and availability of fuels throughout the whole event. For example, an AFL footballer playing in the full-forward position will rely on the ATP–CP system for maximal intensity short duration sprints to mark the ball. During low-intensity periods, the player could have sufficient time to replenish CP stores or reduce levels of lactate and hydrogen ions.

**The time–energy system continuum**

A means by which exercise physiologists have explained the relative contribution and interplay of the three energy systems during exercise is to consider the time–energy system continuum. This continuum assumes that an individual is exercising at a maximum sustainable intensity for a continuous period of time. Figure 5.34 indicates the relative contributions of each of the energy systems to the total energy requirements under these conditions. Figure 5.35 also indicates the relative percentage contribution of the three energy systems to maximal exercise of various durations.

![Figure 5.34 Approximate relative contributions of the three energy systems to energy production at maximum sustainable exercise intensity for varying durations.](image-url)
The identified percentage contributions of each energy system to exertions of different durations in the two graphs may vary from data obtained from different researchers. (Table 5.5) presents a compilation from a number of studies over the last 10 years of the relative anaerobic and aerobic contribution to maximal exercise efforts of different durations.

### Table 5.5 Anaerobic and aerobic energy system contributions to maximal exercise efforts of different durations

<table>
<thead>
<tr>
<th>Duration of exhaustive exercise (seconds)</th>
<th>Percentage anaerobic contribution</th>
<th>Percentage aerobic contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–15</td>
<td>88</td>
<td>12</td>
</tr>
<tr>
<td>0–30</td>
<td>73</td>
<td>27</td>
</tr>
<tr>
<td>0–45</td>
<td>63</td>
<td>37</td>
</tr>
<tr>
<td>0–60</td>
<td>55</td>
<td>45</td>
</tr>
<tr>
<td>0–90</td>
<td>44</td>
<td>56</td>
</tr>
<tr>
<td>0–120</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>0–180</td>
<td>27</td>
<td>73</td>
</tr>
<tr>
<td>0–240</td>
<td>21</td>
<td>79</td>
</tr>
</tbody>
</table>

Data obtained from both trained and untrained individuals during run, swim, bench or cycle ergometry exercise (Gaston, 2001).
## 5.7 Energy systems at work: interplay of energy systems

### TEST your understanding

1. At the onset of exercise, why are ATP and creatine phosphate the preferred energy sources over carbohydrates and fats?

2. During aerobic exercise the body may use both carbohydrates and fats to provide energy. Their relative contribution depends on the intensity of the exercise. Explain the relationship between intensity of aerobic exercise and relative use of carbohydrates and fats as fuel.

3. If the body starts to deplete carbohydrate (glycogen) stores during prolonged exercise bouts, it relies on fats as the food fuel for providing energy for ATP resynthesis. What is the major disadvantage of using fats as a fuel during exercise of this nature?

4. Netball is a physically demanding sport that requires many skills. The energy demand on players depends on the skills they are performing and the position they are playing. Identify the predominant energy system required to perform the following in netball:
   - (a) The Goal Keeper jumping up to grab a rebound
   - (b) The Centre covering much of the court throughout the match
   - (c) The Goal Defence breaking away from her opponent and receiving a pass from the Goal Keeper
   - (d) The Goal Attack sprinting 10 metres to receive the ball from the Goal Keeper, passing to the Centre player, sprinting into the goal third to receive a pass from the Goal Keeper and then shooting a quick bounce pass to the Goal Shooter in the goal circle
   - (e) The Umpire running up and down the sidelines throughout the match

5. Complete the table below outlining the characteristics of the three energy systems.

### APPLY your understanding

6. **Practical activity:** Select a specific activity from a sport of your choice. For this activity explain the interplay of energy systems that would occur during performance of the activity. Make sure you indicate the typical duration and intensity of the activity.

7. **Practical activity:** Cathy Freeman’s win in the 400 metres at the 2000 Sydney Olympics has been voted the greatest Australian Olympic performance of all time. Freeman won the race in a time of 49.11 seconds. In small groups, conduct your own 400-metre sprint test. Using stop watches and heart rate monitors, each group is to collect data on their sprinter in 100-metre splits. Clearly and accurately outline in your own words how the three energy systems would have contributed to the sprinter’s performance. Ensure that you use data when discussing the interplay of the energy systems.

### EXAM practice

8. Paul Biedermann broke the world record for the 400-metre swim with a time of 3:40:07 minutes in 2009. Explain how the energy systems interplayed to provide energy for Paul to complete this swim in record time.

---

### Interactivity

**Characteristics of the three energy systems**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ATP–CP</th>
<th>Anaerobic glycolysis</th>
<th>Aerobic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuels used (chemical and food)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensity and duration of peak energy production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Examples of activities in which the system is the predominant source of energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rate of energy supply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy yield per comparative amount of fuel source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>By-products</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue limiting factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advantages of the energy system</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disadvantages of the energy system</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.8 The significance of lactate

**KEY CONCEPT** Lactic acid splits into lactate and hydrogen ions. Lactate can provide fuel for energy production and reduce fatigue.

**Lactate**

Within muscle cells, lactic acid quickly dissociates (splits) into lactate and hydrogen ions ($H^+$). For many years lactic acid and lactate were seen to be very much the same thing and the prevailing knowledge was that the accumulation of lactic acid (lactate) that resulted from anaerobic glycolysis during high-intensity exercise was the cause of local muscular fatigue.

Lactate acts as an important intermediary in numerous metabolic processes; in particular, as a mobile fuel source for aerobic metabolism.

**The fate of lactate: the lactate shuttle**

Lactate can be shuttled, referred to as lactate shuttles, or moved intracellularly from the muscle cell cytoplasm to the mitochondria, extracellularly from one muscle fibre to a nearby adjacent muscle fibre, and between the muscle and the bloodstream where it can then be transported to other tissues and organs.

The intracellular lactate shuttle involves the movement of lactate between the muscle cell cytoplasm where it is produced and the mitochondria where it is oxidised to pyruvate, which then passes through the various stages of aerobic metabolism. In this way lactate is acting as an important intermediary fuel source for aerobic metabolism. Extracellular lactate shuttles act to move lactate between tissues and organs. Intramuscularly, most lactate moves out of active fast-twitch glycolytic fibres and into active oxidative type 1 slow-twitch oxidative fibres where it again acts as a fuel source for energy production during aerobic metabolism.

Some of the lactate also diffuses out of the muscle itself into the bloodstream. From there the lactate is transported to other tissues and organs, most notably the heart, respiratory muscles, brain and liver. The heart, respiratory muscles and brain are able to use lactate as an important fuel source, and in fact studies have shown that during high-intensity exercise these tissues use blood-borne lactate as their fuel source in preference to other fuels such as glucose. In the heart, for example, the uptake of lactate increases many-fold as the intensity of exercise increases, while the uptake of glucose remains unchanged. These tissues take up lactate at a fast rate to satisfy their energy needs.

Lactate in the bloodstream is also transported to the liver where it is converted to blood glucose and glycogen. This glucose can then be transported back to the muscles to act as a fuel source for further muscular contraction. This process is referred to as the Cori cycle (see Figure 5.36).

**FIGURE 5.36** The Cori cycle

Lactate shuttles are the processes by which lactate is shuttled from one location to another, for example, from the muscles to the liver, where it is converted to glucose that can then be used to provide further energy.

Type 1 slow-twitch oxidative fibres contain large and numerous mitochondria, high levels of myoglobin and a high capillary density. They are very resistant to fatigue and have a high capacity to generate ATP by oxidative metabolism.

The Cori cycle is the metabolic pathway in which lactate produced by anaerobic glycolysis in the muscles moves via the bloodstream to the liver, where it is converted to blood glucose and glycogen. The lactate takes some hydrogen ions with it as a way of reducing the hydrogen ion concentration in the muscle cells.
5.8 The significance of lactate

It is also important to note that when lactate diffuses into the bloodstream from the active muscles it takes with it some of the hydrogen ions \( (H^+) \) that are also produced as a result of anaerobic metabolism. In this way lactate helps to reduce the hydrogen ion accumulation within the muscle and so helps to delay the onset of muscle acidosis, which is implicated as a cause of muscular fatigue.

To summarise, the lactate shuttle involves the following series of events:
1. As we exercise, pyruvate is formed.
2. When insufficient oxygen is available to break down the pyruvate, lactate is produced.
3. Lactate enters the surrounding muscle cells, tissue and blood.
4. The muscle cells and tissues receiving the lactate either break down the lactate to provide energy for immediate use or use it in the creation of glycogen.
5. The glycogen then remains in the cells until energy is required.

**Lactate Inflection Point**

Changes in the lactate concentration of blood can be determined by graphing the results of blood testing during incremental exercise (exercise that progressively increases in intensity). Figure 5.37 identifies the lactate inflection point (LIP) which is the last point where lactate production and removal is balanced. It marks the point on the graph where there is an exponential or non-linear increase in the lactate concentration in the blood.

It is also identified as the final exercise intensity or oxygen uptake value at which the blood lactate remains relatively stable during a maximal aerobic test.

**Significance of the lactate inflection point**

The LIP establishes the exercise intensity beyond which a given exercise or power output cannot be maintained for any sustained period of time. Exercise intensities beyond the LIP are associated with a shortened time to fatigue or exhaustion. The higher the exercise intensity beyond the LIP, the more rapid the onset of fatigue. This decreased time to exhaustion appears to be primarily associated with an increase in the acidosis within the muscle due to the accumulation of metabolic by-products including, but not necessarily limited to, hydrogen ions.

The LIP can also be used to determine the highest intensity of aerobic exercise an athlete can sustain without the rapid accumulation of hydrogen ions. This is because the rise in blood lactate concentration is related to rising levels of hydrogen ions within the muscle (remember, lactic acid dissociates into hydrogen ions and lactate). It appears that the LIP can serve as a reasonably good indirect marker for muscle cell metabolic conditions that increase muscle acidosis, which in turn leads to muscular fatigue.
**TEST your understanding**

1. What is the fate of lactate that is produced in the muscle cells as a result of anaerobic metabolism? Why do we call the processes involved lactate shuttles?

2. Explain in your own words the meaning and significance of LIP.

**EXAM practice**

3. The 400-metre sprinter will work at an exercise intensity level above their lactate inflection point. What occurs physiologically beyond this LIP point?
KEY SKILLS ENERGY SYSTEMS AND INTERPLAY OF ENERGY SYSTEMS

- **yellow** identify the action word
- **pink** key terminology
- **blue** key concepts
- **light grey** marks/markings

STRATEGIES TO DECODE THE QUESTION

- **Identify the action word:** Describe — provide a detailed account of
- **Key terminology:** Energy system interplay — understanding how the energy systems operate together
- **Marking scheme:** 6 marks — always check marking scheme for the depth of response required, linking to key information highlighted in the question

HOW THE MARKS ARE AWARDED

1 mark: stating all energy systems contribute
1 mark: stating ATP–PC system utilised at the explosive start
1 mark: PC stores depleting
1 mark: to maintain intensity, anaerobic glycolysis is utilised
1 mark: aerobic system is dominant due to the duration being greater than 60 seconds
1 mark: aerobic ES resynthesises ATP with the greatest yield as oxygen is able to break down glycogen

UNDERSTANDING THE KEY SKILLS

To address these key skills, it is important to remember the following:

- The role of ATP to produce energy and how it is resynthesised
- The role of energy fuels or substrates that are used to provide the energy required for ATP resynthesis. You may be asked how food/chemical fuels resynthesise ATP; for example, how muscle glycogen can resynthesise ADP to ATP.
- ATP can be resynthesised via three energy pathways: ATP–CP, anaerobic glycolysis and aerobic energy system
- Understand, in specific detail, the characteristics of the three energy systems including fuel sources, rate of ATP, yield of ATP, dominant time period and type of event, fatigue and recovery
- Relationship between intensity of exercise and rate of ATP
- Relationship between duration of exercise and yield of ATP
- Fatiguing factors such as CP stores could deplete, and hydrogen ions and lactate levels could increase to a level that changes energy systems
- Each physical activity has a dominant energy system
- Interplay of the three energy systems
- Many factors contributing to fatigue
- Recovery strategies used to return to pre-exercise conditions

PRACTICE QUESTION

Brooke, a 20-year-old high-level female 1500 m runner, is preparing for the Australian Track and Field Championships. Her current personal best time is 4 minutes 30 seconds. Describe the energy system interplay in a 1500 m track event of a similar time to Brooke’s.

SAMPLE RESPONSE

At the start of the 1500 metre race, all energy systems contribute to the supply of ATP with one system being most dominant. As the athlete explodes away from the starting blocks, all energy systems contribute, however the ATP–PC is the predominant energy system due to the maximal intensity and the need to replenish ATP quickly (3.6 moles/min) for the first 6 to 10 seconds. As limited PC stores quickly deplete and there continues to be a need to supply ATP at a fast rate, anaerobic glycolysis becomes the predominate energy system for the next 30 to 45 seconds as exercise intensity is maintained. ATP is resynthesised at a fast rate (1.6 moles/min) with muscle glycogen broken down without oxygen available. As the duration of the race continues beyond 60 seconds, the aerobic energy system becomes the dominant energy system for the rest of the race. The aerobic ES begins to have a greater contribution to resynthesising ATP, at a slower rate (1.0 moles/min) but with a greater yield (38 moles of ATP) as the body is able to supply oxygen to the working muscles.
CHAPTER REVIEW  ENERGY SYSTEMS AND INTERPLAY OF ENERGY SYSTEMS

CHAPTER SUMMARY

ATP: The body’s energy currency
- The energy for physical activity is released by the catabolism (breaking down) of adenosine triphosphate (ATP). This energy source is stored in only very limited quantities within muscles and must be constantly replenished or resynthesised in order for muscular contractions to continue.
- ATP breaks down to ADP and Pi. ATP can be resynthesised from ADP and Pi but energy is required in order to do this.
- The energy required to resynthesise ATP from ADP and Pi is produced via three energy pathways: the ATP–CP (or phosphate) energy system, the anaerobic glycolysis system and the aerobic system.

Energy fuels
- The fuels or substrates that are used by the body’s three energy systems include creatine phosphate, carbohydrates, fats and protein. The energy systems break down these fuels to provide the energy to resynthesise ATP.
- Creatine phosphate is a chemical compound which, like ATP, is stored in limited quantities within muscle cells.
- Also like ATP, creatine phosphate is a high-energy substance capable of storing and releasing energy via the high-energy bond that binds the creatine and phosphate parts of it together. When this bond is broken, energy is released that enables ATP to be resynthesised from ADP and Pi.
- Carbohydrate is broken down into glucose. Glucose is stored as glycogen in the muscles and liver. Any excess is stored as fat in adipose tissue around the body.
- Fats provide more energy per gram than the other fuels, but the body prefers carbohydrate as an energy source during exercise because it is easier to break down and produces energy at a faster rate.
- Protein is used as an energy source only when carbohydrate and fats are depleted; for example, in extreme conditions such as in ultra-endurance events.

Energy systems and pathways
- The ATP–CP system uses creatine phosphate to create new ATP supplies without using oxygen. The phosphate energy system can create ATP very quickly, and is the predominant energy contributor to maximal intensity, short-duration activities of up to 6–10 seconds’ duration.
- The anaerobic glycolysis system involves the metabolism of glycogen stores within the muscle without oxygen needing to be present. The anaerobic glycolysis system takes longer to create ATP than the ATP–CP system, and it is the major contributor to high-level exertions of 10–60 seconds’ duration. This system creates lactate and hydrogen ions as by-products.
- The aerobic energy system can use glycogen and fats (and protein under extreme conditions) to provide energy for ATP resynthesis, but oxygen must be present for the chemical reactions involved in aerobic metabolism to take place.
- The aerobic system is the major contributor to energy production during rest and low- to moderate-intensity activity. It becomes the primary energy contributor to sustained maximal activity after approximately 60 seconds.
- Aerobic metabolism occurs primarily within specialised cell structures known as mitochondria, which can be considered the ‘power houses’ of the cell.
- Tables 5.6 and 5.7 summarise the main information that has been presented in this chapter.
TABLE 5.6 Summary: the conversion of food to energy

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Carbohydrates</th>
<th>Fats</th>
<th>Proteins</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conversion and storage</strong></td>
<td>• Transformed into blood as glucose</td>
<td>• Free fatty acids in blood</td>
<td>• Broken down through digestion into amino acids</td>
</tr>
<tr>
<td></td>
<td>• Stored in muscle cells as muscle glycogen</td>
<td>• Stored as triglycerides in muscle</td>
<td>• These amino acids stored in muscles as muscle amino acids</td>
</tr>
<tr>
<td></td>
<td>• Stored in liver as glycogen</td>
<td>• Stored as fat in adipose tissue</td>
<td>• Excess amino acids stored as fat in adipose tissue</td>
</tr>
<tr>
<td></td>
<td>• Excess carbohydrates stored as fat in adipose tissue</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Major role and function</strong></td>
<td>• The most readily available source of energy to fuel working muscles during exercise performance (moderate- to high-intensity exercise)</td>
<td>• The most concentrated form of energy, but a secondary source of energy during moderate- to high-intensity exercise</td>
<td>• Help the formation, growth and repair of body tissue</td>
</tr>
<tr>
<td></td>
<td>• Carbohydrates as fuel can last for up to 90–120 minutes of continuous exercise</td>
<td>• Primarily used as a source of energy during rest and low-intensity exercise</td>
<td>• Help in the production of red blood cells and enzymes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Provide an emergency fuel source for energy during prolonged exercise, when carbohydrate and fat stores are depleted</td>
<td>• Generally only occurs in extreme situations such as starvation and ultra-endurance events such as the Hawaii triathlon</td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>• At rest and during low-intensity exercise provide about one-third of the energy required</td>
<td>• At rest provide approximately two-thirds of the energy needs of the body</td>
<td>• Animal foods such as meat, poultry, fish, eggs and dairy products are rich in protein and contain all the essential amino acids</td>
</tr>
<tr>
<td></td>
<td>• During moderate- and high-intensity exercise are used as the primary energy source</td>
<td>• As exercise intensity increases, the percentage of fats being used as an energy source decreases</td>
<td>• Plant foods such as cereals, grains, lentils, beans and peas are also good sources of protein, although they do not contain all of the essential amino acids</td>
</tr>
<tr>
<td></td>
<td>• Carbohydrates as fuel can last for up to 90–120 minutes of continuous exercise</td>
<td>• Fats as an energy source become increasingly important when stores of carbohydrates become depleted during endurance exercise (usually after 90–120 minutes of continuous activity).</td>
<td></td>
</tr>
<tr>
<td><strong>Percentage of total daily intake</strong></td>
<td>• Average person: 55–60 per cent</td>
<td>• Average person: 20–25 per cent</td>
<td>• Average person: 15 per cent</td>
</tr>
<tr>
<td></td>
<td>• Athletes in training: 60 per cent or greater, or 7–10 grams of carbohydrate per kilogram body mass</td>
<td>• Endurance athletes in training: 20–30 per cent</td>
<td>• Athletes in training: strength athletes may require slightly more protein in their diets</td>
</tr>
<tr>
<td><strong>Common food sources</strong></td>
<td><strong>Foods with low glycaemic index:</strong></td>
<td><strong>Saturated fats:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Those carbohydrate-rich foods that take longer to digest and release glucose at a slower but more sustained rate</td>
<td>• Found in animal foods such as milk, cheese and meat products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Include bread, cereals, pasta, lentils and baked beans</td>
<td>• This type of fat contains cholesterol (implicated in cardiovascular disease)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Foods with high glycaemic index:</strong></td>
<td><strong>Unsaturated fats:</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Those carbohydrate-rich foods that are digested rapidly and release glucose at a fast rate</td>
<td>• Two groups of unsaturated fats: polyunsaturated and mono-unsaturated.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Include sugar, honey, bananas, potatoes, jelly beans, soft drinks and sports drinks</td>
<td>• Polysaturated fats are found in most vegetable oils (e.g. sunflower oil) and oily fish (e.g. tuna)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Mono-unsaturated fats are found in olive oil, avocados and nuts</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Both types of unsaturated fats help lower total cholesterol levels</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 5.7 Summary: characteristics of the three energy systems

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>ATP–CP system</th>
<th>Anaerobic glycolysis system</th>
<th>Aerobic system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alternative name or names</strong></td>
<td>Phosphagen system</td>
<td>Anaerobic phosphate system</td>
<td>Aerobic system</td>
</tr>
<tr>
<td><strong>Aerobic or anaerobic</strong></td>
<td>Anaerobic</td>
<td>Anaerobic</td>
<td>Anaerobic</td>
</tr>
<tr>
<td><strong>Fuel or fuels used</strong></td>
<td>Creatine phosphate (also known as phosphocreatine) — stored in small quantities within muscle cells</td>
<td>Carbohydrates — stored as glycogen within muscle cells and the liver</td>
<td>Carbohydrates — preferred fuel during exercise</td>
</tr>
<tr>
<td><strong>Maximal rate of energy production</strong></td>
<td>Fastest rate of energy release for resynthesis of ATP from ADP and Pi</td>
<td>Provides energy for ATP resynthesis rapidly, but not as quickly as the ATP–CP system</td>
<td>Slowest system to provide energy for ATP resynthesis due to complex nature of its chemical reactions, and the fact that sufficient oxygen has to be made available to the muscle cells</td>
</tr>
<tr>
<td><strong>Maximum ATP production (yield) per mole of fuel source</strong></td>
<td>Small amounts of ATP produced</td>
<td>Approximately twice as much ATP produced as the ATP–CP system</td>
<td>Vastly greater amounts of ATP produced compared with the two anaerobic systems</td>
</tr>
<tr>
<td><strong>Duration and intensity of peak energy production</strong></td>
<td>Activated at the beginning of maximal-intensity exercise</td>
<td>Also activated at the beginning of high-intensity activity</td>
<td>Also activated at the start of high-intensity exercise and will become the predominant supplier of energy for ATP resynthesis during continuous submaximal intensity exercise that exceeds 1–2 minutes in duration</td>
</tr>
<tr>
<td></td>
<td>Predominant energy supplier within the first 6 seconds of high-intensity exercise, but its capacity is depleted after 6–10 seconds of maximal intensity exercise</td>
<td>Predominant energy contributor for ATP resynthesis from the time when the phosphagen system is rapidly depleting up until about 30–60 seconds during high-intensity exercise</td>
<td>In a maximal effort lasting 75 seconds, equal energy is derived from the aerobic and anaerobic systems</td>
</tr>
<tr>
<td></td>
<td>May also become predominant producer of energy for ATP resynthesis during repeated short-duration maximal intensity efforts that have insufficient recovery time to allow for full replenishment of creatine phosphate stores</td>
<td>May also become predominant producer of energy for ATP resynthesis during repeated short-duration maximal intensity efforts that have insufficient recovery time to allow for full replenishment of creatine phosphate stores</td>
<td>As event duration increases and intensity decreases, the contribution of the aerobic system to energy production increases while that of the anaerobic systems diminishes</td>
</tr>
<tr>
<td></td>
<td>(continued)</td>
<td></td>
<td>(continued)</td>
</tr>
</tbody>
</table>
TABLE 5.7 (continued)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>ATP–CP system</th>
<th>Anaerobic glycolysis system</th>
<th>Aerobic system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific examples</td>
<td>• Athletic field events (e.g. high jump, shot put)</td>
<td>• 400-metre athletic event</td>
<td>• 10 000-metre athletic event</td>
</tr>
<tr>
<td></td>
<td>• Short sprints (50- to 100-metre)</td>
<td>• 50-metre swim</td>
<td>• Marathon</td>
</tr>
<tr>
<td></td>
<td>• Tennis serve</td>
<td>• High-intensity tennis rally of 15–30 seconds’ duration</td>
<td>• 2000-metre rowing event</td>
</tr>
<tr>
<td></td>
<td>• Gymnastics vault</td>
<td></td>
<td>• Mid-field players in many team sports (e.g. Australian Rules, soccer)</td>
</tr>
<tr>
<td></td>
<td>• Golf drive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fatigue limiting</td>
<td>• Depletion of creatine phosphate stores</td>
<td>• Changes in the intra-muscular environment due to the accumulation of hydrogen ions (H⁺)</td>
<td>• Depletion of glycogen stores</td>
</tr>
<tr>
<td>factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of recovery</td>
<td>• Passive</td>
<td>• Active</td>
<td>• Active</td>
</tr>
<tr>
<td>Metabolic by-products</td>
<td>• Inorganic phosphates (Pi)</td>
<td>• Lactic acid — lactate and hydrogen ions (H⁺)</td>
<td>• Carbon dioxide (CO₂)</td>
</tr>
<tr>
<td></td>
<td>• ADP</td>
<td>• ADP</td>
<td>• Water (H₂O)</td>
</tr>
<tr>
<td>Links to fitness</td>
<td>• Muscular strength</td>
<td>• Anaerobic capacity</td>
<td>• Heat</td>
</tr>
<tr>
<td>components</td>
<td>• Muscular power</td>
<td>• Local muscular endurance</td>
<td>• ADP</td>
</tr>
<tr>
<td></td>
<td>• Anaerobic power</td>
<td>• Speed and agility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Speed and agility</td>
<td>• Muscular power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Reaction time</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Relevant to all fitness components because it provides the basis for recovery in anaerobic-type tasks as well as the bulk of energy production for submaximal activities</td>
</tr>
</tbody>
</table>

Fatigue
- Fatigue is the inability to continue functioning at the level of one’s normal physical abilities, and usually manifests itself as local muscular fatigue.
- Muscular fatigue is a highly complex phenomenon that consists of numerous factors acting at multiple sites within the contracting muscles themselves.
- The causal mechanisms of local muscular fatigue depend on the type, duration and intensity of the exercise being performed, as well as other factors such as the fibre-type composition of the involved muscle or muscles, the fitness and training status of the athlete, the nutritional state of the athlete, and even the athlete’s mental state.
- Fatigue may result from fuel depletion, the accumulation of metabolic by-products and/or impaired muscle excitability. Whatever the causal mechanism, the muscular fatigue that results manifests itself as the eventual lack of ability of a single muscle or local group of muscles to do work at a given intensity.

Recovery
- Recovery can be defined as the overcoming or reversal of fatigue experienced as a result of training or some form of exercise.
- In general terms, the recovery process encompasses active recovery or passive recovery immediately post-exercise.
- Active recovery is at a lower intensity and is used to:
  - reduce heart rate to resting levels
  - replenish oxygen levels in the blood, body fluids and myoglobin
  - increase blood flow to the working muscles
  - remove higher lactate concentration levels
  - accelerate oxidation as this boosts the clearance rate of lactate
  - resynthesise high-energy phosphates
  - support the small energy cost to maintain elevated circulation and ventilation
  - remove metabolites after exercise.
- Passive recovery is used to replenish ATP and creatine phosphate stores at the fastest rate.
MULTIPLE-CHOICE QUESTIONS

1. State the energy rate and yield associated with the ATP–CP system.
   (A) Rate is 0.7 moles per minute and yield is 3.6 moles per mole of fuel substrate
   (B) Rate is 1.6 moles per minute and yield is 1.0 moles per mole of fuel substrate
   (C) Rate is 3.6 moles per minute and yield is 0.7 moles per mole of fuel substrate
   (D) Rate is 3.6 moles per minute and yield is 38.0 moles per mole of fuel substrate

2. List the metabolic by-products of the aerobic energy system.
   (A) Carbon dioxide, hydrogen ions and ADP
   (B) ADP, water and heat
   (C) Lactate and inorganic phosphates
   (D) Carbon dioxide, water and heat

3. Complete the following diagram outlining the metabolism of lactic acid.
   Lactic acid + oxygen → _______ + _______
   (A) Lactate and hydrogen ions
   (B) Inorganic phosphates and carbon dioxide
   (C) Carbon dioxide and water
   (D) Lactate and water

4. In which energy system or systems are hydrogen ions a metabolic by-product of the chemical process?
   (A) Anaerobic glycolysis
   (B) ATP–PC
   (C) Aerobic glycolysis
   (D) Aerobic lipolysis

5. State an advantage of using creatine phosphate as a fuel.
   (A) Readily available in the liver
   (B) Breaks down slowly with oxygen
   (C) Provides a large yield of ATP at a rapid rate
   (D) Breaks down rapidly without oxygen

6. State which factors significantly influence the causes of fatigue.
   (A) Nutritional and training status of the athlete, type, intensity and duration of exercise
   (B) Intensity and duration of exercise
   (C) Nutritional and training status of the athlete
   (D) Type of exercise

7. Lactic acid is a by-product of
   (A) aerobic lipolysis.
   (B) aerobic glycolysis.
   (C) anaerobic glycolysis.
   (D) lactate.

8. ‘Hitting the wall’ is a term used to describe a condition caused by
   (A) the depletion of fat stores.
   (B) the depletion of glycogen stores.
   (C) the depletion of creatine phosphate stores.
   (D) an increase in lactate.

9. The point just before hydrogen ions increase exponentially is known as
   (A) pyruvate inflection point.
   (B) lactic acid inflection point.
   (C) lactate inflection point.
   (D) lactate transition point (LT1).

10. The goalie and wing player in hockey would possibly complete the following recovery activities.
    (A) Passive recovery (wing player) and active recovery (goalie)
    (B) Passive recovery (wing player) and passive recovery (goalie)
    (C) Active recovery (wing player) and active recovery (goalie)
    (D) Passive recovery (goalie) and active recovery (wing player)
TRIAL EXAM QUESTIONS

Question 1  (adapted from ACHPER Trial Exam 2015, question 2)
Wayde van Niekerk from South Africa is the current Olympic champion in the 400 m track event. Van Niekerk won this event in Rio in a time of 43.03 seconds.
Mo Farah from Great Britain is the current Olympic champion in the 10 000 m track event. He won his gold medal in a time of 27 minutes 5 seconds.
List the predominant energy system used to complete their specific event.
2 marks
Wayde van Niekerk (400 m) ____________________________
Mo Farah (10 000 m) ____________________________

Question 2  (ACHPER Trial Exam 2015, question 8)
Passive and active recovery strategies can both be effective. Identify the best time to engage in each recovery strategy and provide a suitable example for each.

<table>
<thead>
<tr>
<th>Passive recovery strategy</th>
<th>Active recovery strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best utilised</td>
<td></td>
</tr>
<tr>
<td>Example</td>
<td></td>
</tr>
</tbody>
</table>

4 marks

Question 3  (ACHPER Trial Exam 2015, question 11d)
Discuss the predominant fuels required for resynthesis of ATP in race walking compared to the High Jump event.
4 marks

Question 4  (ACHPER Trial Exam 2014, question 8b part iii)
Jana Pittman is a Australian athlete. Prior to 2013 she represented Australia in the 400 m hurdles at the summer Olympics and World Championships. Her fastest time was 53.82 seconds and she won the world championships twice.
She represented Australia in the two person Bobsled at the 2014 Sochi Winter Olympics. Jana is the ‘breakperson’ which involves pushing a sleigh (with her partner in unison) on ice for approximately 50 metres in 6 seconds before loading into the bobsled to ride to the finish line.
(www.olympic.org/figbt-bobsleigh)
Jana would incorporate recovery techniques into her training. Active and Passive recovery are better suited to certain events. Identify the type of recovery best suited to each of Jana’s events and justify your selection.
4 marks

<table>
<thead>
<tr>
<th>400 m Hurdles</th>
<th>Bobsled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of recovery</td>
<td></td>
</tr>
<tr>
<td>Justification</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Question 5

(a) Describe the relationship between the three energy systems as shown in the graph.

(b) At what time does the anaerobic glycolysis system become predominant?

(c) Explain why there is a delay before the aerobic energy system becomes predominant and what occurs in the interim.

(d) Why does the ATP–PC energy system predominantly contribute to energy production for only a short period of time?

Question 6

The graph below shows a recreational runner’s blood lactate concentration during two different running treadmill tests until they reach exhaustion. The second test was completed 4 months after the runner completed a regular training program.

5 marks
a. Identify what points labeled A and B represent. 1 mark

b. The test is completed when the runner is unable to continue, due to fatigue. What is the most likely cause of this fatigue? 1 mark

**Question 7**  
(ACPER Trial Exam 2013, question 11b)

Brooke, a 20 year old high-level female 1500 m runner, is preparing for the Australian Track and Field Championships. Her current personal best time is 4 minutes 30 seconds.

In various periods throughout the race, Brooke exercises above her VO2 maximum. Outline how the body enables this increase in intensity to happen.

2 marks

**Question 8**  
(ACPER Trial Exam 2013, question 13)

The anaerobic energy systems (ATP–PC and anaerobic glycolysis) have a finite capacity which ultimately impacts on performance. Outline the major fatiguing factors for the ATP–PC and anaerobic glycolysis energy systems, and their impact on performance in the diagram below.

4 marks
Question 9  
(ACHPER Trial Exam 2008, question 16)

Bryan Clay (USA) won the Gold Medal in the decathlon at the Beijing Olympics in 2008. He competes in 10 different events over a 48-hour period. Three of these events and his results are shown below. Use this information to complete the table below.  
7 marks

<table>
<thead>
<tr>
<th>Event and result</th>
<th>Major fuel/s used for this event</th>
<th>Predominant energy system used in this event</th>
<th>One characteristic of this energy system that makes it suitable for the event</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-metre run 48.92 secs</td>
<td>i.</td>
<td>ii.</td>
<td>iii.</td>
</tr>
<tr>
<td>Shot put 16.27 m</td>
<td>Phosphocreatine</td>
<td>iv.</td>
<td>v.</td>
</tr>
<tr>
<td>1500-metre run 5 min 06.59 secs</td>
<td>vi.</td>
<td>Aerobic energy system</td>
<td>vii.</td>
</tr>
</tbody>
</table>