During physical activity, the body responds physiologically. Most importantly, the body acts to ensure that the energy supply is adequate for the body’s energy needs. The body uses different energy production systems depending on the physical activity undertaken. Training for physical fitness improves the body’s capacity to produce and use energy. Other physiological effects or adaptations that result from training include changes to the body’s cardiorespiratory system.

For training programs to be effective, they need to address the health-related and skills-related components of physical fitness identified to be of most importance to individual athletes, based on their personal fitness capacity and the physical activity in question. Before designing a training program, it is essential that these components, as well as training methods and training principles, are understood.

The following chapters look at the energy systems used for various physical activities, the physiological adaptations that result from training and the fundamental elements of training program design. A step-by-step guide to designing a training program specifically for senior physical education is provided. Sports injuries—how they are classified, treated and managed—are also addressed.

**Focus questions**

- How do we get energy for movement?
- What energy systems contribute to physical activities?
- What are the effects of training?
- How are training programs designed?
- How are injuries treated and managed?

**COMING UP**

- The body’s response to physical activity page 124
- The fundamental of fitness page 156
- Designing and evaluating training programs page 222
- Sports injuries page 258
The body’s response to physical activity

BEFORE YOU START

Have you ever wondered how your body creates enough energy to perform its day-to-day tasks, let alone exercise? Is it simply a case of converting the food that you consume into energy, or is the process a little more complicated than that?

In this chapter, you will look at energy systems to investigate how the energy needed to fuel physical activity is created in the human body. The chapter discusses the body’s ability to create energy for different types of activities, taking a practical look at several physical activities and their differing needs. It also examines fatigue and recovery.

The second part of the chapter investigates the short-term and long-term physiological effects that training has on the human body.

CHAPTER OVERVIEW

Energy 125
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- Fatigue and recovery 142

Training effects 146
- Immediate physiological responses to training 146
- Long-term physiological effects of training 146
Energy

We are all familiar with the common use of the word energy: ‘I have no energy’ or ‘This washing machine is energy efficient’. What do such comments mean?

Energy can be defined as the capacity or ability to perform work. Without energy there would be no light or heat, and everything would be stationary. Energy is fundamental to everyday living and is needed for action and change.

Energy can be categorised into various forms, such as heat, light, electrical, nuclear, chemical and mechanical. Each of these can be converted from one form to another. For example, a light globe converts electrical energy into light energy; a gas heater converts chemical energy into heat energy.

When discussing energy and human movement, we are mainly concerned with the transfer of chemical energy into mechanical energy. In this process, the breaking of chemical bonds in molecules releases energy for the body to use. Humans obtain chemical energy from the food that we eat, and energy from food is measured in kilojoules.

For example, a football player who converts chemicals in the body (from food) into a mechanical action (such as jumping to take a mark) is transferring energy from one form to another. During this transfer, heat energy is also given off, which is why the football player feels warm after training.

The transfer of energy from chemical energy (food) into mechanical energy (action) in the human body is not direct. Instead, the energy gained from the breakdown of food is used to make a chemical compound called adenosine triphosphate. Only when energy is released by the breakdown of this compound can it be used by the body’s cells.

Adenosine triphosphate

Adenosine triphosphate (ATP) is an energy-rich chemical compound that is found in the body’s cells. It is almost always the source of energy for the reactions that take place in the body—especially for the muscle contractions that lead to movement.

As shown in Figure 4.2, ATP is made up of a smaller compound (adenosine) and three chained phosphate (P) groups (hence the name tri-phosphate). The final phosphate group is held on to the chain with a high-energy bond.
When ATP is broken down, releasing the final phosphate group in the chain, it releases energy. ATP is broken down into adenosine diphosphate (ADP)—that is, adenosine plus two phosphates—and a separate phosphate group (see Figure 4.3).

A great deal of energy is released when this bond is broken and this provides the energy that powers the human body. It provides energy for all processes, from breathing and digestion through to muscle movement.

Producing ATP from food

Food provides the source for ATP. Stored fuels, such as carbohydrates and fats, are not changed into ATP; rather, a portion of the energy that is released when these food chemicals break down triggers the joining of molecules to form ATP.

Food and energy are strongly linked. The three major nutrients found in food—carbohydrates, fats and proteins—all work in different ways to help with the production of ATP.

Carbohydrates

Carbohydrates are broken down by the body into glucose. The glucose is then stored in the muscles and liver as glycogen, which is a ready source of energy. Chemical reactions involving the breakdown of glucose (glycolysis) or glycogen (glycogenolysis) then produce ATP.

Simple carbohydrates (sugars) can provide energy, but the best sources come from complex carbohydrates, such as grains, cereals, breads, legumes and vegetables.

One gram of carbohydrate yields approximately 16 kilojoules of energy when broken down.

Fats

Triglyceride, which is found in fatty foods, is the digested form of fat needed for energy production. Fat is stored as triglyceride in both adipose tissue (fatty tissue) and the muscles. As exercise begins, triglycerides are broken down into fatty acids and glycerol—a process known as lipolysis.

Free fatty acids are the primary energy source when fat is used for energy, which is usually during prolonged lower-intensity work. The body uses the fatty acids to produce ATP and continues to break down the adipose triglycerides if exercise is prolonged at a low intensity. Free fatty acids produce the greatest amount of ATP, but they have disadvantages: it takes many more chemical reactions and much more oxygen to split them to resynthesise ATP.

One gram of fat yields approximately 37 kilojoules of energy when broken down.
Proteins
After digestion and absorption, proteins are broken down into amino acids. Under normal conditions, protein is not used to produce ATP. During extreme conditions (for example, starvation or prolonged exercise), protein will be used as a fuel source to produce ATP. Protein is used only when stores of fats and carbohydrates have been exhausted.

One gram of protein yields approximately 17 kilojoules of energy when broken down.

Energy systems
ATP does not exist in the muscles and tissues in an abundant supply waiting for activity to occur. In fact, the small amount of ATP that is present provides only enough energy for a few seconds of intense activity. The body does not produce ATP continuously, so it must be replenished and recycled in a process known as resynthesis. The process of resynthesis rebuilds ATP from ADP using one of three energy systems:

- the **alactacid system** (also called the phosphagen or ATP–PC system)
- the **lactic acid system** (also called the anaerobic glycolysis system)
- the **aerobic system** (also called the oxygen or oxidative system).

The major difference among the systems is that the alactacid and lactic acid systems resynthesise ATP anaerobically (without oxygen present), whereas the aerobic system resynthesises ATP aerobically (with oxygen present).

Which energy system is used by the body depends on:
- how long the activity will take
- the intensity of the activity.
ACQUIRE
1. Describe energy in your own words.
2. a. What compound is needed for muscle contractions to occur?
   b. Where is it found?
   c. Draw a simple diagram of this compound.
3. Name the three major nutrient groups found in food.
4. Explain what is meant by ATP resynthesis.
5. Define the terms ‘anaerobic’ and ‘aerobic’.

Alactacid system
The alactacid system, also known as the ATP–PC system, is used by the body to produce ATP quickly. High-intensity activities lasting for less than 10 seconds use this system as the primary source of energy. Such activities include throwing a shot-put, running a 100-metre sprint, making a jump shot and kicking a football.

This process is best described by the principle of coupled reactions, which means that the results of one reaction are used to drive another reaction. One reaction causes ATP to break down and become ADP, releasing phosphate and energy in the process. As ATP is being broken down in the muscle, another high-energy substance—phosphocreatine (PC)—is also being broken down. The breakdown of PC produces phosphate and energy. The energy from this reaction is used to join ADP and free phosphate molecules to produce ATP.

The amount of PC in muscles is limited. After about 5–10 seconds of strenuous work, it runs out and another of the three energy systems has to be activated. Although the stores of PC are quickly used up, they are also quickly restored within 2 minutes of resting. This allows for activity to be repeated in intense, short bursts, without immediate exhaustion.

The alactacid system represents the most readily available source of ATP for use by the muscles because:
- it does not depend on a long series of chemical reactions
- it does not depend on oxygen being transported to the muscles
- both ATP and PC are stored in muscle tissue.

Figure 4.6 The principle of coupled reactions explains how ATP is resynthesised from ADP.
Chapter 4—The body's response to physical activity

Lactic acid system

The other system that does not require oxygen to resynthesise ATP is the lactic acid system. This system involves the partial breakdown of glucose to release energy and lactic acid in a series of chemical reactions known as glycolysis. The glucose for this process comes either from glucose found in the blood or from the breakdown of glycogen in the liver or muscles—known as glycogenolysis.

This process is again the result of a coupled reaction—the results of one reaction are used to drive another reaction. The energy released in the breakdown of glucose is used to fuel the recombination of ADP and P to form ATP.

However, if the body continues to use the lactic acid system, as the glucose is broken down to form energy, lactic acid is produced. If lactic acid builds up in the muscles, it can result in a ‘burning’ sensation and inhibit the breakdown of glucose. This will usually cause athletes to decrease the intensity of the activity or stop altogether. To break down and remove lactic acid can take up to 2 hours, and an active recovery will aid this process. During recovery, the lactic acid is actually converted back to its original form: pyruvic acid.

Interestingly, new research into lactic acid has discovered that its accumulation could, in fact, be a protective mechanism that prevents too much damage to muscles.

Have you ever experienced lactic acid build-up? If so, how did your body respond and how long did it take to recover?

The lactic acid system provides a relatively quick supply of ATP, and is an important energy source for intense, short bursts of activity (usually 30–60 seconds, but can be up to 3 minutes). The lactic acid system is used by the body for activities such as 200-metre and 400-metre running sprints, 50-metre and 100-metre swimming sprints, and medium-length sprints in sports such as soccer. This system can provide energy for up to 30 minutes if exercise occurs at a sub-maximal level (no more than 60 per cent).
The lactic acid system provides more ATP than the alactacid system; however, it only yields about 5 per cent of the ATP that would be produced by the aerobic system.

**EXTENSION**

Investigate some of the facts and fallacies surrounding lactic acid. Use the Internet to assist your research.

Click to find out more about lactic acid.

### Aerobic system

The alactacid system and the lactic acid system produce ATP without the need for oxygen in the chemical reactions. In contrast, the aerobic system of energy production is known as such because it uses oxygen; aerobic means 'with air'.

In certain types of exercise, oxygen is made available to the muscles to use in the chemical reactions that resynthesise ATP. These reactions take place in specialised structures within the muscles, cells called **mitochondria**. Although these reactions cannot take place until sufficient oxygen is in the bloodstream, they are able to generate more abundant supplies of ATP than either anaerobic system—sometimes ten times more. For this reason, the aerobic system is the most efficient energy system.

The aerobic system allows the body to use carbohydrates, fats and proteins as the fuel to produce ATP.  
- Carbohydrates are broken down in a process called aerobic glycolysis. Carbohydrates are the preferred fuel as their breakdown requires the least amount of oxygen.  
- The breakdown of fats (oxidisation) requires significantly more oxygen to produce the same amount of ATP than the breakdown of carbohydrates. Fats are the preferred fuel only during low-intensity exercise, when the supply of oxygen is high relative to demand.  
- Protein will usually be used as an energy store only in extreme situations—when the previous two stores have been depleted.

The different ways that the aerobic system uses these fuels in the body explains why athletes 'carbohydrate load' long-distance events. They are trying to provide their bodies with enough fuel. As the activity continues, however, carbohydrate stores can become depleted, and fats become the major fuel source.

The by-products of the aerobic system are carbon dioxide, water and heat, all of which can easily be eliminated by the body.
ACQUIRE

1. Construct a flow chart of the processes involved in all three energy systems.
2. Describe one of the energy systems to your partner.
3. Describe how coupled reactions allow the release of energy for ATP resynthesis.
4. Discuss the similarities and differences between the anaerobic and aerobic processes of breaking down glucose (glycolysis).
5. Discuss the ATP yield from each of the energy systems.
6. Why are carbohydrates the preferred fuel for the aerobic system?

Table 4.1—A comparison of the three ATP-replenishing energy systems

<table>
<thead>
<tr>
<th>System</th>
<th>Source of fuel</th>
<th>Duration of system</th>
<th>Cause of fatigue</th>
<th>Efficiency of ATP production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alactacid system (ATP–PC)</td>
<td>Phosphocreatine (PC)</td>
<td>Up to 10 seconds</td>
<td>Depletion of PC stores</td>
<td>Rapid but limited</td>
</tr>
<tr>
<td>Lactic acid system</td>
<td>Glucose and glycogen</td>
<td>Up to 3 minutes</td>
<td>Build-up of lactic acid in the muscles</td>
<td>Rapid but limited</td>
</tr>
<tr>
<td>Aerobic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerobic system</td>
<td>Carbohydrates, glucose and glycogen, fats and protein</td>
<td>Indefinite at low intensities</td>
<td>Depletion of fuel sources</td>
<td>Slow but unlimited</td>
</tr>
</tbody>
</table>

Source: Adapted from ML Foss and SJ Keteyian, *Fox’s Physiological Basis for Exercise and Sport*, 6th edn, WCB/McGraw-Hill, Boston, 1998


Figure 4.10 The duration of activity determines the main energy system used.
Energy systems in practice

It is important to understand the energy demands of different types of physical activities. Once you determine the energy needs of an activity, you can adapt your training to suit its needs.

To explain how the three energy systems work in practice, the next section looks at four sports with very different energy demands.

Energy systems for rest: archers

When the body is at rest, the supply of oxygen easily meets its demand. As an archer’s objective is to remain still and calm throughout the event, the demands placed on the cardiorespiratory system are low. The emphasis on precision, rather than on strength and speed, means that the working muscles require little energy. Each breath taken by the archer supplies enough oxygen to the muscles to allow ATP to be resynthesised aerobically. At this low intensity, the major fuel supply is fat.

Energy systems for short, fast work: divers

Divers require an explosive burst of energy for just a few seconds, as they use all their muscles to propel their bodies through the take-off, flight (twists and turns) and entry of the dive. Because they are doing such high-intensity activity for just a short period, divers would use the alactacid system. The alactacid system uses the PC in muscles to resynthesise ADP and P.

Energy systems for continuous work: joggers

When a jogger starts running, the cardiorespiratory system has not yet had the few minutes it needs to increase the supply of oxygen to the working...
muscles. The immediate supply of oxygen is, therefore, insufficient for energy production to occur aerobically.

Joggers often feel sluggish for the first few minutes of running. This sluggishness is followed by a sudden feeling of ease, which usually signifies the takeover of the aerobic system. The aerobic system will remain the dominant system at work unless the joggers have to increase their effort. For example, when joggers begin to run up a hill, the muscles need more energy to work harder. Energy will be produced from ATP using the anaerobic energy systems until oxygen levels can be increased sufficiently to once again produce energy aerobically.

Athletes should be able to pace themselves to ensure that energy supplies are not depleted too early. In a race, athletes who go out too hard or begin the final sprint too soon will accumulate high levels of lactic acid, become tired and decrease their performance.

Table 4.2 shows the relative contributions of aerobic and anaerobic energy systems to the various running distances held in major athletic competitions.

Energy systems working together: soccer mid-fielders

During most physical activities, the body uses a combination of all three energy systems, depending on the duration and intensity of the activity.

For example, soccer mid-fielders use the aerobic system to provide the energy required to keep moving back and forth on the field—usually at moderate levels of intensity.

Occasionally, they may need to sprint down the wing to assist in attack or defence. These short sprints usually last 3–10 seconds and are fueled by the alactacid system. Because the body’s stores of PC are quickly replenished within 2 minutes, soccer players are able to sprint many times with rests in between.

It is only during a series of continued sprints, without any rest, that a mid-fielder’s lactic acid levels would accumulate to the point of fatigue.

Click for further case studies on how energy systems contribute to individual sports.
**APPLY AND EVALUATE**

Consider the energy systems contributing to the physical activity you are currently participating in.

1. Describe the contributing energy systems.
2. Justify how and in what order energy is provided for the duration of the activity.

### Table 4.2—Relative contributions of the energy systems to running events

<table>
<thead>
<tr>
<th>Duration of event</th>
<th>Anaerobic</th>
<th>Aerobic</th>
<th>Event (run)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 seconds</td>
<td>90%</td>
<td>10%</td>
<td>100 m</td>
</tr>
<tr>
<td>30 seconds</td>
<td>80%</td>
<td>20%</td>
<td>200 m</td>
</tr>
<tr>
<td>60 seconds</td>
<td>70%</td>
<td>30%</td>
<td>400 m</td>
</tr>
<tr>
<td>2 minutes</td>
<td>50%</td>
<td>50%</td>
<td>800 m</td>
</tr>
<tr>
<td>4 minutes</td>
<td>35%</td>
<td>65%</td>
<td>1500 m</td>
</tr>
<tr>
<td>10 minutes</td>
<td>15%</td>
<td>85%</td>
<td>5000 m</td>
</tr>
<tr>
<td>30 minutes</td>
<td>5%</td>
<td>95%</td>
<td>10 000 m</td>
</tr>
<tr>
<td>60 minutes</td>
<td>2%</td>
<td>98%</td>
<td></td>
</tr>
<tr>
<td>120 minutes</td>
<td>1%</td>
<td>99%</td>
<td>Marathon</td>
</tr>
</tbody>
</table>


### Table 4.3—Various sports and their predominant energy systems

<table>
<thead>
<tr>
<th>Sport or activity</th>
<th>Relative contribution of each energy system (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ATP–PC and anaerobic glycolysis</td>
</tr>
<tr>
<td>1 Aerobic dance</td>
<td>5</td>
</tr>
<tr>
<td>2 Baseball</td>
<td>80</td>
</tr>
<tr>
<td>3 Basketball</td>
<td>60</td>
</tr>
<tr>
<td>4 Hockey</td>
<td>50</td>
</tr>
<tr>
<td>5 Football</td>
<td>90</td>
</tr>
<tr>
<td>6 Golf</td>
<td>95</td>
</tr>
<tr>
<td>7 Gymnastics</td>
<td>80</td>
</tr>
<tr>
<td>8 Rowing</td>
<td>20</td>
</tr>
<tr>
<td>9 Skiing</td>
<td>80</td>
</tr>
<tr>
<td>a Slalom, jumping</td>
<td>50</td>
</tr>
<tr>
<td>b Downhill</td>
<td>5</td>
</tr>
<tr>
<td>c Cross-country</td>
<td>50</td>
</tr>
<tr>
<td>10 Soccer</td>
<td>60</td>
</tr>
<tr>
<td>a Goalie, wing, strikers</td>
<td>60</td>
</tr>
<tr>
<td>b Halfbacks or sweeper</td>
<td>60</td>
</tr>
<tr>
<td>11 Swimming and diving</td>
<td>98</td>
</tr>
<tr>
<td>a Diving</td>
<td>80</td>
</tr>
<tr>
<td>b 100-m swim</td>
<td>20</td>
</tr>
<tr>
<td>c 400-m swim</td>
<td>10</td>
</tr>
<tr>
<td>d 1500-m swim</td>
<td>70</td>
</tr>
<tr>
<td>12 Tennis</td>
<td>70</td>
</tr>
<tr>
<td>13 Walking</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Source: Adapted from ML Foss and SJ Keteyian, *Fox’s Physiological Basis for Exercise and Sport*, 6th edn, WCB/McGraw-Hill, Boston, 1998
ACQUIRE

1. For each of the three energy systems, identify the:
   a. process
   b. by-products of energy production
   c. rate of recovery.

2. Explain which energy system is the most efficient at producing ATP.

APPLY

1. Predict and justify, using Table 4.3 and Figure 4.10, the predominant energy systems for the following activities: 200-metre swimming, snowboarding, rugby league and lawn bowls.

2. Describe the use of the energy systems in a 1500-metre running event.

Oxygen and the aerobic system

We now understand that the aerobic system requires oxygen to create energy; however, many factors dictate just how much oxygen is available to an individual during exercise.

How the body obtains and uses oxygen

Breathing, or pulmonary ventilation, moves oxygen from the atmosphere to the lungs. Once oxygen has been inhaled, it travels through the respiratory system—down the trachea, through the main left and right bronchi that lead into the lungs and into the bronchioles, where it finally accumulates in tiny sac-like structures called the alveoli.

Each alveolus can be likened to a very thin balloon, which is surrounded by tiny blood vessels (capillaries). Inhaled oxygen passes through the alveoli walls and into the surrounding capillaries using a process known as diffusion. In the capillaries, oxygen attaches itself to the haemoglobin in red blood cells to become oxyhaemoglobin. This oxygen-rich blood is then transported from the lungs to the heart along the pulmonary veins. From the heart, it is pumped out to the working muscles.

When we breathe out, or exhale, carbon dioxide is removed from the body along the same path but in reverse. Carbon dioxide, a waste product of the aerobic energy system, is transported in the blood back to the heart from the working muscles. The heart then pumps this blood to the lungs, from which the carbon dioxide is eventually exhaled.

Highly trained endurance athletes have good respiratory and cardiovascular systems. Their ability to transport oxygen to the muscles depends on a combination of the following cardiorespiratory factors:

**Respiratory factors**
- the volume of gas inhaled or exhaled in one breath
- the diameter of the airways (people with chronic lung disease, such as asthma, have restricted airways)
- total lung capacity, which is the total amount of air in the lungs after maximal inhalation
- respiratory rate, or the number of breaths per minute

**Cardiovascular factors**
- the volume of blood pumped from the heart with each beat
- the number of heartbeats per minute (heart rate)
- the cardiac output, or volume of blood pumped to the working muscles per minute (which is a combination of stroke volume and heart rate)
Strong, healthy hearts and lungs are essential. In addition, well-trained athletes will have a high **oxidative capacity**. The phrase oxidative capacity refers to the muscles’ ability to obtain and use oxygen. A factor in athletes' ability to produce energy using oxygen and the aerobic system is the health and functioning of their mitochondria, which is where ATP is produced in the muscles. Muscle cells have more mitochondria than other types of cells in the body, which means that athletes with a high proportion of muscles will be better able to produce energy from ATP aerobically. This is one reason why training to build up muscle helps athletes.

**Figure 4.14** A high proportion of muscle cells, which are rich in mitochondria, allows athletes to produce more ATP aerobically.

**Figure 4.15** Gases transfer between the lungs and the bloodstream through capillaries surrounding the alveoli.
The circulatory system

1 Oxygen-poor (deoxygenated) blood from the body collects in the right atrium, which contracts, filling up the right ventricle.
2 The right ventricle contracts and pushes blood to the lungs.
3 In the lungs, blood loses carbon dioxide and picks up oxygen.
4 Oxygen-rich (oxygenated) blood returns to the left atrium, which contracts, filling up the left ventricle.
5 A powerful contraction of the left ventricle expels oxygen-rich blood into the aorta, from which artery branches distribute blood throughout the body.
6 In the muscles and body organs, blood releases oxygen and nutrients, and absorbs food and water from the intestines. The liver processes nutrients and, together with the kidneys, purifies the blood.
7 Oxygen-poor blood returns to the heart through the veins. Another cycle begins.

Figure 4.16 Blood travels through the body delivering oxygen and removing carbon dioxide.

ACQUIRE

1 Using Figure 4.16, explain to the person sitting next to you how oxygen is delivered to the muscles.
2 Outline why exhaled air contains more carbon dioxide than inhaled air does.

Steady state

At the beginning of any form of exercise or when the intensity of exercise increases, the working muscles are placed under an immediate increase in stress and require a rapid increase in ATP. As anaerobic forms of energy will only keep an athlete going for a few seconds or minutes, the muscles require a rapid increase in oxygen. To meet these needs, the cardiorespiratory system begins to work harder.

Figure 4.17 The heart delivers oxygenated blood to the working muscles.
If an athlete works at a constant intensity, such as during long continuous exercise, the oxygen supply will eventually meet the muscles' demand for oxygen. A 'steady state' is when the oxygen supply meets the body's demands.

**VO₂ max**

An individual's highest possible oxygen consumption during exercise is known as the volume of maximum oxygen (VO₂ max). It is measured by determining the maximum amount (in millilitres) of oxygen that can be used in one minute per kilogram of body weight. This measurement is used as it helps to determine an athlete's ability to use oxygen to produce energy.

Universities and research centres such as the Australian Institute of Sport have specialised laboratory equipment for exact VO₂ max measurement. These usually require athletes to exercise, often on a treadmill, to increase their heart rate and respiration, while their oxygen use is measured. When such equipment is unavailable, VO₂ max prediction tests are used as a guide to determine fitness.

Other factors determining an individual's VO₂ max include:

- **Genes**
  Athletes' genes, which establish the physical attributes they inherit from their parents, play a significant role in determining their VO₂ max level. Although genetic inheritance is important, effective training can still help athletes to improve their VO₂ max.

- **Age**
  Athletes' age affects their VO₂ max. For most people, VO₂ max decreases from the age of about 20 years.

- **Gender**
  Men and women have significant physical differences in body size, muscle size and blood volume. These differences explain why a man's VO₂ max is on average 20 per cent higher than a woman's.
Table 4.4—VO₂ max comparisons by sport and by gender

<table>
<thead>
<tr>
<th>Sport</th>
<th>VO₂ max Men</th>
<th>VO₂ max Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basketball</td>
<td>40–60</td>
<td>43–60</td>
</tr>
<tr>
<td>Cycling</td>
<td>62–74</td>
<td>47–57</td>
</tr>
<tr>
<td>Gymnastics</td>
<td>52–58</td>
<td>35–50</td>
</tr>
<tr>
<td>Rowing</td>
<td>60–72</td>
<td>58–65</td>
</tr>
<tr>
<td>Soccer</td>
<td>54–64</td>
<td>50–60</td>
</tr>
<tr>
<td>Swimming</td>
<td>50–70</td>
<td>40–60</td>
</tr>
<tr>
<td>Track and field – running</td>
<td>60–85</td>
<td>50–75</td>
</tr>
</tbody>
</table>

Source: Brian Mackenzie, UK Athletics Level 4 Performance Coach; www.pponline.co.uk

ACQUIRE

1. Define VO₂ max.
2. Outline the role it plays in sports performance.

APPLY AND EVALUATE

Study Table 4.4.

1. Explain why for each activity, the VO₂ max for females is considerably less than that of males.
2. Suggest reasons why the VO₂ max of a rower is greater than that of a basketball player.

Anaerobic and aerobic training thresholds

Training thresholds offer an explanation for the complex physiological changes that occur in the body in producing or maximising the training effect. Training thresholds are usually explained using the maximum heart rate in relation to the volume of oxygen uptake (VO₂).

During exercise, the following three factors increase in proportion to the intensity of exercise.

- **heart rate**—the rate at which the heart beats is usually measured in beats per minute (BPM)
- **ventilation**—the amount of air breathed in one minute
- **blood lactate**—the by-product of the lactic acid system.

It was thought that when athletes exercise at a steady state, or with slightly increasing intensity, most of the ATP produced came from aerobic sources. However, scientists found that as exercise increases, the amount of lactic acid in the blood evenly increases. This appears to be related to maximum oxygen consumption (VO₂ max), which is the greatest volume of oxygen used by the cells of the body in a given time.
This increase in lactic acid occurs in untrained athletes at around 50–60 per cent of VO$_2$ max, and in trained athletes at about 60–85 per cent of VO$_2$ max. The sudden rise in lactic acid represents an increasing reliance on the anaerobic energy system. Figure 4.20 shows the point at which this occurs for trained and untrained athletes.

The anaerobic threshold can be defined as that workload intensity (or level of oxygen consumption) at which anaerobic metabolism is increased; that is, when lactic acid starts to accumulate in the blood and muscles. The threshold is the maximum speed or effort that an athlete can maintain and have no increase in lactic acid. Activity over this limit can cause a deterioration in performance.

Anaerobic thresholds are often studied and discussed in exercise physiology. There is argument over the accuracy of the name. Many suggest that lactate threshold (LT) or onset of blood lactate accumulation (OBLA) is a more precise term because anaerobic energy is produced even at rest, meaning that lactic acid is formed and removed continuously. The basic argument against the term ‘anaerobic threshold’ is that there is uncertainty as to whether the rise in blood lactic acid is due to lack of oxygen in the muscles or is a result of other causes. These other causes have been measured and are valid for describing the inflection point.

They include:

- accelerated glycolysis (that is, the conversion of glucose and glycogen to pyruvic acid in the lactic acid system)
- increased use of fast-twitch muscle fibres (more fast-twitch activity leads to more lactic acid production)
- reduced rate of lactic acid removal (that is, lactic acid is produced and removed from the body, but when production exceeds the rate of disappearance, lactic acid accumulates in the blood).

It is possible that any one of the above, or a combination of factors (including lack of oxygen), might explain the LT or OBLA.

It is useful for athletes and coaches to know the inflection point at which LT/OBLA occurs. This information can help to place athletes in specific endurance events. It is a better indicator of aerobic endurance performance than VO$_2$ max is, and it can determine training intensities for optimal improvements in aerobic endurance. The major limitations of using LT to improve performance are:

- It is difficult to measure.
• It requires blood tests and takes a long time.
• There is no real proven benefit in training at this level.
• Athletes differ in their rates of reaching LT.

The **aerobic training threshold** is the intensity at which an athlete needs to work to produce an aerobic training effect or a physiological improvement in performance; that is, an improvement in the body’s ability to use oxygen during exercise. This occurs at about 70 per cent of the person’s maximum heart rate, or at approximately 50–60 per cent of that person’s VO₂ max. As exercise intensity increases, so do heart rate, ventilation and blood lactate. In fact, aerobic threshold can be defined as the training rate at which the baseline lactic acid level starts to rise. At this level of exercise, the person can still conduct a conversation comfortably. To obtain an aerobic training effect, an individual should exercise in the aerobic training zone; that is, between the aerobic and lactate thresholds as shown in Figure 4.21.

---

### Calculating your ideal heart rate for training

Calculating your heart rate is essential as it can tell you if you are getting the most out of your exercise. By determining the percentage of your maximum heart rate that you are working at, you can pinpoint whether you are in the correct training zone.

**Equipment**
- stopwatch

**Procedure**
1. Find your carotid pulse. Your carotid artery is located on your neck, just under your jaw line.
2. Count your pulse for 15 seconds. It easiest if you have a stopwatch to record the time while you count. Otherwise, it is a good idea to work with a friend.
3. Multiply your result by four. You have now calculated your beats per minute (BPM).
4. **Calculate your estimated maximum heart rate (MHR).** The general rule is that your MHR is 220 minus your age. Therefore, a 17-year-old would have an estimated MHR of 220 – 17 = 203 BPM.
5. **Calculate your current BPM as a percentage of your MHR using the formula**

\[
\text{BPM} \times \frac{100}{\text{MHR}} = \% \text{MHR}
\]

For example, for a 17-year-old working at 140 BPM, the percentage would be:

\[
\frac{140}{203} \times 100 = 68.9\%
\]

At 68% of MHR, this athlete would be working within the aerobic training zone.

---

Figure 4.22  Your carotid artery is located on your neck, just under your jaw.
Focus area B—Process and effects of training and exercise

Figure 4.23 Athletes’ performance can be affected by fatigue.

APPLY AND EVALUATE

1. Explain how an athlete with a lower VO₂ max than another athlete may produce a better aerobic endurance performance in the same event.

2. With reference to Figure 4.21 and your understanding of calculating ideal training heart rates, explain why a coach of a 17-year-old touch player would ask him to ensure that his heart rate remain between 170 and 180 beats per minute during a training session.

Fatigue and recovery

Fatigue

Fatigue is one of many factors affecting performance. The causes of fatigue vary and are usually activity-specific. For example, a 400-metre runner will experience fatigue differently from a marathon runner; however, both will feel unable to continue either at their current pace or with increased exertion.

Generally three areas of the body can account for the physical fatigue: the central and peripheral nervous systems, muscle fibres and energy systems. Fatigue can also be caused by psychological and environmental factors.

Central and peripheral nervous systems

How is it that sometimes, when they are totally exhausted and it seems that the last of athletes’ energy has gone, they are able to make one last push of strength? For example, marathon runners sometimes manage a sprint when entering the stadium before a cheering crowd.

Fatigue is a biological protective mechanism operated by nerves in the central and peripheral systems. Under certain conditions of fatigue, the nervous system tells the athlete’s brain that the body is exhausted, while the muscles still have small reserves of energy—in case of emergency or danger. Fatigue prevents people pushing themselves too far and damaging their bodies; it signals that the body needs time to rest and recover. While the marathon runner may still be able to produce some bouts of intense effort after the feeling kicks in, if they continued too far past the body’s ‘exhaustion warning system’, they could cause themselves harm.

Muscle fibres

Fatigue can occur when the muscle lacks oxygen due to insufficient blood flow or when it is unable to contract. For example, an injury could result in early fatigue.
In short, intense activities, the accumulation of lactic acid in the muscles and blood is often blamed for the onset of muscle fatigue. However, the lactic acid does not directly cause the fatigue. Rather, the fatigue is caused by a change in pH (a measure of overall acidity), which is brought about by the breakdown of lactic acid. The change in pH (in this case, a decrease) affects cell functions and causes sensations of pain.

**Energy systems**

Each of the energy systems has its own process of fatigue.

- In the alactacid system, fatigue occurs as the body’s store of ATP and PC is depleted.
- In the lactic acid system, the burning sensation caused by a build-up of lactic acid can cause fatigue.
- In the aerobic system, fatigue can occur when the body uses up its supply of fuel derived from carbohydrates, fats and proteins.

**Recovery**

Recovery processes are designed to restore the body to its pre-exercise state. The time taken to fully recover will depend on the type, intensity and duration of the activity, recovery techniques and the athlete’s accumulated oxygen deficit. There are two types of recovery: rest and active.

**Rest recovery**

Rest recovery is a period of no movement. Rest recovery is sometimes employed during sessions where an athlete has to complete many high-intensity repetitions of short duration.

**Active recovery**

In general, after an all-out exhaustive effort, an active recovery is recommended to restore ATP–PC stores and to remove lactic acid. Active recovery is more beneficial than rest recovery in most cases because of its ability to quickly reduce muscle lactate levels. So, what is an active recovery?

Active recovery includes performing light tasks, such as slow running, walking, stretching and minor games. Consuming complex carbohydrates after activity also helps to replenish muscle and liver glycogen stores.

Even athletes who do not exercise to exhaustion should still use active recovery techniques and replenish food and fluids.
### Table 4.5—Recovery times for various physiological functions

<table>
<thead>
<tr>
<th>Function</th>
<th>With active recovery</th>
<th>With rest only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Restoration of ATP–PC</td>
<td>2 minutes</td>
<td>5 minutes</td>
</tr>
<tr>
<td>Increase in oxygen consumption</td>
<td>3 minutes</td>
<td>6 minutes</td>
</tr>
<tr>
<td>Replenishment of muscle glycogen</td>
<td>10 hours (continuous exercise)</td>
<td>46 hours</td>
</tr>
<tr>
<td>Replenishment of liver glycogen</td>
<td>5 hours</td>
<td>24 hours</td>
</tr>
<tr>
<td>Reduction of lactic acid in muscles and blood</td>
<td>30–60 minutes</td>
<td>1–2 hours</td>
</tr>
<tr>
<td>Restoration of oxygen stores</td>
<td>10–15 seconds</td>
<td>1 minute</td>
</tr>
</tbody>
</table>

*Source: Adapted from ML Foss and SJ Keteyian, Fox’s Physiological Basis for Exercise and Sport, 6th edn, WCB/McGraw-Hill, Boston, 1998*

### Table 4.6—Fuel depletion and recovery

<table>
<thead>
<tr>
<th>Predominant energy system</th>
<th>Likely causes of fatigue</th>
<th>Types of recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP–PC</td>
<td>Fuel depletion ATP and PC</td>
<td>Rest recovery</td>
</tr>
</tbody>
</table>
| Lactic acid               | Accumulation of metabolic by-products | Non-diary 
  • H+ (hydrogen ions)
  • Pi (inorganic phosphates)
  NB: Lactic acid is no longer thought to contribute to fatigue. In fact, it is being regarded more as a positive performance enhancer rather than a negative. |
| Aerobic                   | Fuel depletion
  • Glycogen stores, then fats
  • Elevated body temperature leading to:
    - dehydration
    - blood flow away from muscles | Dietary
  • High GI foods
  • Rehydration via sports drinks:
    - Hypertonic to replace glycogen
    - Hypotonic to replace lost fluids
  Non-diary 
  • Active recovery
  • Massage
  • Water-based therapies, e.g. contrasting via hot/cold baths |

*Source: R Malpeli and A Telford, A+ Phys Ed Notes: VCE Physical Education Units 3 & 4, Nelson Australia, South Melbourne, 2008*

### Oxygen deficit

Have you noticed that at the end of a run you seem to be breathing in more air than you were during the actual run? Does your breathing return to its normal resting levels straight away? Most people have experienced this shortness of breath. With knowledge of energy systems, these physiological changes can be explained.
At the start of physical activity, the alactacid and lactic acid (anaerobic) energy systems supply the body with energy; however, this comes at a cost. The lactic acid energy system accumulates lactic acid that has to be broken down. Both systems break down ATP to produce energy. Breaking down lactic acid and resynthesising depleted PC—both consequences of the anaerobic system—require oxygen. So, even though anaerobic energy systems do not need oxygen to produce energy, the body does need extra oxygen during recovery.

We know from experience that our bodily functions do not return to normal immediately after exercise. Heart rate, body temperature and breathing all remain elevated after exercise. This is especially true after very intense exercise, when the body requires quite a while to return to resting levels.

The elevated physiological effects of exercise that continue after exercise has stopped—such as rapid heart rate and heavy breathing—allow the body temperature to return to normal, assist in removing lactic acid, and help replenish ATP–PC and glycogen stores. Importantly, the rapid heart rate and heavy breathing deliver more oxygen to the body.

The difference between the amount of oxygen the body uses when truly at rest and the amount of oxygen used when exercise has just stopped is called the oxygen deficit. Oxygen deficit is also referred to as ‘oxygen debt’, ‘recovery oxygen’ and ‘excess post-exercise oxygen consumption’ (EPOC).

Have you ever been short of breath after exercise? What did it feel like? At what level of intensity were you working?

Figure 4.25  Oxygen deficit, or EPOC, is the difference between the amount of oxygen the body uses when at rest and just after exercise.

Source: B Davis et al., Physical Education and the Study of Sport, Mosby, Edinburgh, 2005

ACQUIRE

1 Explain the difference between rest recovery and active recovery.
2 Describe oxygen deficit in your own words.
3 If anaerobic energy production does not require oxygen, what is the function of heavy breathing immediately after anaerobic exercise?
Training effects

Any time a person places their body under any stress beyond that of a normal resting level, such as during physical activity, the body must physically adapt to meet the increased demands. When an athlete does systematic fitness training, they intentionally increase the demands over time to promote long-term physiological changes. These changes are known as training effects. Training effects are the adaptations made by the body during physical activity, and they can be divided into two categories: immediate physiological responses and long-term physiological effects.

Immediate physiological responses to training

When people exercise, many physiological changes occur within their bodies. These range from a need for more oxygen in working muscles to an increase in body temperature.

During training, immediate physiological responses can be observed and measured in each of the following:

- **heart rate**—as exercise intensity increases, so too does the rate at which the heart beats. Heart rate is measured in beats per minute
- **ventilation rate**—at the beginning of exercise, there is an immediate increase in ventilation—both inspiration (breathing in) and expiration (breathing out)—followed by a continuing gradual rise in the depth and rate of breathing
- **stroke volume**—the amount of blood ejected with each contraction of the heart increases
- **cardiac output**—the volume of blood that is pumped out of the heart per minute increases during exercise, forcing more blood out of the heart. Cardiac output is a combined measure of heart rate and stroke volume
- **muscular responses**—the muscles contract, and different types of muscle fibres are recruited depending on the type and intensity of exercise. ATP–PC stores are depleted. The working muscles become warm due to increased blood flow
- **lactate levels**—lactic acid consists of a solution of lactate ions and hydrogen ions in water. With intensifying aerobic exercise, the level of hydrogen and lactate ions in the blood increases. This later evens out as lactate is removed as fast as it is made.

Cardiac output and ventilation increase to ensure that working tissues are supplied with the oxygen and nutrients they need and wastes are removed. To assist in these processes, the body directs blood away from non-working areas to working areas.

Long-term physiological effects of training

When people undertake any type of training, their main aim is to change or adapt some aspect of their body so that their performance improves. Whether they are undertaking strength training, aerobic training or anaerobic training, or attempting to increase their flexibility, the process of training leads to changes in the body. These changes can influence future performance.

Many of the changes occur to the cardiorespiratory system, and these lead to an improved ability to deliver oxygen to working muscles, more efficient energy production and a greater ability to remove waste products. Other changes relate to the size and use of the muscle fibres that produce the movement required for physical activity.

This section will look at the body’s adaptations following specific types of training and how these adaptations can lead to improved performance.
Before we begin to examine these changes, a few terms need to be explained: rest, sub-maximal exercise and maximal exercise.

- **Rest** is a state where no extra demands are placed on the body. Energy is required only to maintain normal bodily functions, such as breathing, heartbeat and digestion. This minimum rate of energy consumption is known as the **basal metabolic rate**.

- **Sub-maximal exercise** is exercise performed at a level that leaves the heart rate in a plateau (a consistent rate for an extended period of time) below its maximum number of beats per minute. Generally, this level of exercise can be maintained for more than 20 minutes at a time. Jogging, lap swimming and road cycling are all examples of sub-maximal exercise. Tests such as the Queens College step test are also undertaken at a sub-maximal level so that improvements in fitness can be reliably measured.

- **Maximal exercise** is activity that leads to a heart rate that approaches its maximum level. The maximum heart rate is usually calculated as being 220 beats per minute minus the person’s age; a typical eighteen-year-old would, therefore, have a maximum heart rate of 202 beats per minute. Sprinting (running less than 400 metres) and 100-metre swimming are examples of maximal exercise.

### Resting heart rate

When the body is at rest, the heart will beat enough times per minute to deliver oxygen via the bloodstream to all the cells of the body. The body’s minimum requirement for oxygen is reflected in the resting heart rate and is determined by the basal metabolic rate.

When athletes undertake an aerobic training program, their hearts will undergo significant changes. Training can lead to a reduction in the number of beats per minute required to meet the needs of the body at rest. In other words, the resting heart rate will fall as the body adapts to the training program. The heart rate will also be lower when undertaking sub-maximal exercise.
The main reason for the fall in the resting heart rate is the increase in stroke volume. This increase allows more blood to be pumped out for every beat the heart makes. Therefore, to deliver the same amount of oxygen to the body, fewer beats will be made. For example, a person who has a resting heart rate of 72 beats per minute before a training program and a stroke volume of 70 millilitres per beat will have a cardiac output of 5.04 litres per minute. This amount of blood represents the person's basal metabolic rate. Following an aerobic training program, the individual's stroke volume may rise to 80 millilitres per beat. This would lead to a resting heart rate of 63 beats per minute, which is a fall of nine beats per minute (even though the person's cardiac output remains at 5.04 litres per minute).

Resting heart rate and heart rate during sub-maximal work both fall as a result of aerobic training. However, heart rate during maximal exercise will be the same for both trained and untrained people. The difference is that the trained person is capable of doing a lot more work at a maximal level than an untrained person is.

Stroke volume and cardiac output

The total amount of blood to leave the heart has a direct effect on an individual's performance. The stroke volume of the heart and its cardiac output will determine the amount of blood being circulated and how much oxygen will reach working muscles.

Stroke volume

**Stroke volume** is the amount of blood that leaves the left ventricle each time the heart beats. The ability of the heart to push oxygen-rich blood into the arteries and towards working muscles is the biggest factor affecting aerobic-based performance. The more blood that the heart can push out, the more work individuals will be able to do; they will be able to exercise longer and faster.

Stroke volume is determined by a number of factors associated with the heart, including the:

- size of the ventricles
- thickness of the ventricle walls
- flow of blood through the veins back to the heart
- volume of blood in the body.

Aerobic training has a positive effect on stroke volume and, therefore, on an individual's potential to perform aerobically. Training causes the physical size of the heart and ventricles to increase. Additionally, the walls of the ventricles will become thicker and stronger. These two factors allow more blood to enter the heart as it is now bigger, and the stronger walls allow much more of the blood to be ejected each time a beat occurs.

When combined with an increase in blood volume, lower blood pressure and an improved ability to move blood through the veins back to the heart, a rise of 25 per cent in stroke volume can be achieved through aerobic training. That is, if stroke volume was 70 millilitres per beat before aerobic training program, it could be increased to 87.5 millilitres after. This increased stroke volume leads to higher cardiac output, more blood (and therefore more oxygen) going to working muscles, and improved performance in endurance events.

The effects of training on stroke volume are then evident regardless of whether exercise is being undertaken. Stroke volume increases at rest too, which causes the resting heart rate to fall while cardiac output remains steady. During sub-maximal exercise, stroke volume will have increased, resulting in a lower heart rate (again, cardiac output will remain steady). During maximal exercise, the increased stroke volume will lead to a large increase in cardiac output and improved performance.
Cardiac output
Cardiac output is the amount of blood leaving the heart each minute. Cardiac output reflects the ability of the heart to deliver oxygen-rich blood to working muscles. This oxygen enables the aerobic energy system to produce ATP to provide the energy needed for movement.

Cardiac output (Q) is a product of the heart rate (HR) and stroke volume (SV). In fact, this direct link can be expressed as an equation:

\[ Q = HR \times SV \]

As already discussed, undertaking an aerobic training program does not change cardiac output during rest and sub-maximal work. This is because the energy demands are unchanged and the same amount of blood (oxygen) is required. The biggest change occurs during maximal exercise. As the maximum heart rate will be the same for a trained or untrained individual (that is, 220 beats per minute, minus age), the greater stroke volume will lead to an increase in the cardiac output.

Table 4.7 shows us how a trained individual is able to deliver more blood to the working muscles: 17.8 litres per minute after training compared with 14.2 litres per minute before. This change is what has improved the individual’s potential following a training program.

Table 4.7—An example of the difference in cardiac output for trained and untrained 17-year-olds

<table>
<thead>
<tr>
<th>Exercise level</th>
<th>Heart rate (beats per minute)</th>
<th>Stroke volume (mL/beat)</th>
<th>Volume of blood (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Untrained</td>
<td>Trained</td>
<td>Untrained</td>
</tr>
<tr>
<td>Rest</td>
<td>72</td>
<td>57.6</td>
<td>70</td>
</tr>
<tr>
<td>Sub-maximal</td>
<td>152</td>
<td>121.5</td>
<td>70</td>
</tr>
<tr>
<td>Maximal</td>
<td>203</td>
<td>203</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 4.28
Aerobic training changes stroke volume and cardiac output during maximal exercise.

ACQUIRE
Referring to Table 4.7.
1. Explain why the trained person’s heart rate is lower than that of the untrained person.
2. Why is the trained person’s volume of blood at maximal work greater than that of the untrained person?
Oxygen uptake and lung capacity

The ability of the body to move oxygen into the bloodstream and remove carbon dioxide from it is not determined only by the heart and its functioning. The size of the lungs and the ability of the blood to absorb and carry the oxygen to the working muscles are also important aspects of performance.

Oxygen uptake

Oxygen uptake is the amount of oxygen absorbed into the bloodstream during exercise. If more oxygen reaches working muscles, they will be able to work for longer at a higher level. Improving this capacity is one of the goals of aerobic training.

Oxygen uptake is measured in litres per minute. Over many years, exercise physiologists (those who study the effects of exercise on the body) have determined how much oxygen is required to perform various activities. By using standard tests, you can work out your maximum oxygen uptake. As explained on page 138, an individual’s highest possible oxygen consumption during exercise is known as the volume of maximum oxygen (VO₂ max). The higher your VO₂ max, the better your aerobic system is functioning.

Before training an individual may have a VO₂ max of 2.5 litres per minute. After training this figure may rise to 3.2 litres per minute. Once again, the rise in the ability to deliver oxygen to the working muscles causes the improvement in performance after training.

Oxygen uptake improves following a training program for a number of reasons. These include the factors already discussed (such as improved stroke volume and cardiac output) as well as greater lung capacity and higher haemoglobin levels within the blood. All these capacities, when combined, allow the increased flow of oxygen-rich blood to working muscles.

Lung capacity

Lung capacity is the amount of air that can move in and out of the lungs during a breath. Many measures can be made of lung function, including tidal volume and vital capacity. The basic principle that needs to be understood is that when more air can be inhaled and exhaled during exercise, more oxygen can be absorbed into the bloodstream. More oxygen leads to improved performance during aerobic work.

A number of adaptations associated with lung function occur as a result of aerobic training. Three of these are described below.

1. The number of breaths that can be taken during maximal exercise can be increased. As the muscles around the lungs become larger and stronger, they can work faster. Maximal breathing rates can increase from 40 to 50 breaths per second as fitness develops.
2 The size of the lungs increases slightly, which allows for a greater volume of oxygen to be inhaled and for more carbon dioxide to be exhaled with each breath. As the muscles are stronger, more of the air inside the lungs can be exhaled with each breath, leading to a greater turnover of air.

3 The number of capillaries in the lungs will increase with training, allowing more oxygen to be absorbed with each breath taken in. In fact, with training, the volume of blood held within the capillaries of the lungs can rise by up to 80 per cent.

The combined result of these effects of training is that the total amount of air breathed during exercise can increase. The increase in lung size and the ability to breathe faster and more fully, allows pulmonary ventilation (the total volume of air moving through the lungs) to increase by up to 15 litres per minute. More oxygen is available to provide energy.

**Table 4.8—Predicting VO₂ max from recovery heart rate**

<table>
<thead>
<tr>
<th>Percentile ranking</th>
<th>Recovery HR, female</th>
<th>Predicted VO₂ max (mL/kg min)</th>
<th>Recovery HR, male</th>
<th>Predicted VO₂ max (mL/kg min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>128</td>
<td>42.2</td>
<td>120</td>
<td>60.9</td>
</tr>
<tr>
<td>95</td>
<td>140</td>
<td>40.0</td>
<td>124</td>
<td>59.3</td>
</tr>
<tr>
<td>90</td>
<td>148</td>
<td>38.5</td>
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<td>85</td>
<td>152</td>
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<td>37.0</td>
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<td>158</td>
<td>36.6</td>
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<td>35.7</td>
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<td>47.5</td>
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<td>55</td>
<td>164</td>
<td>35.5</td>
<td>154</td>
<td>46.7</td>
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<tr>
<td>50</td>
<td>166</td>
<td>35.1</td>
<td>156</td>
<td>45.8</td>
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<td>45</td>
<td>168</td>
<td>34.8</td>
<td>160</td>
<td>44.1</td>
</tr>
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<td>40</td>
<td>170</td>
<td>34.4</td>
<td>162</td>
<td>43.3</td>
</tr>
<tr>
<td>35</td>
<td>171</td>
<td>34.2</td>
<td>164</td>
<td>42.5</td>
</tr>
<tr>
<td>30</td>
<td>172</td>
<td>34.0</td>
<td>166</td>
<td>41.6</td>
</tr>
<tr>
<td>25</td>
<td>176</td>
<td>33.3</td>
<td>168</td>
<td>40.8</td>
</tr>
<tr>
<td>20</td>
<td>180</td>
<td>32.6</td>
<td>172</td>
<td>39.1</td>
</tr>
<tr>
<td>15</td>
<td>182</td>
<td>32.2</td>
<td>176</td>
<td>37.4</td>
</tr>
<tr>
<td>10</td>
<td>184</td>
<td>31.8</td>
<td>178</td>
<td>36.6</td>
</tr>
<tr>
<td>5</td>
<td>196</td>
<td>29.6</td>
<td>184</td>
<td>34.1</td>
</tr>
</tbody>
</table>


Click for information on how to calculate your heart rate, or refer to page 141.
Haemoglobin level

Haemoglobin is a protein found within red blood cells. Its main function is to absorb oxygen at the lungs and carry this oxygen to the working muscles via the bloodstream. The make-up of haemoglobin allows it to absorb oxygen quickly and efficiently transport it through the body. It also plays a less important role in the removal of carbon dioxide from working muscles.

During training, cells within the body become short of oxygen. One of the ways the body adapts to this is to produce more red blood cells and haemoglobin to meet the oxygen needs of the cells. While it is not a large increase, it does improve individuals' abilities to absorb and deliver oxygen to working muscles and, therefore, their performance in aerobic activities.

Many athletes try to boost their haemoglobin level through **altitude training**. Places that are higher above sea level have less oxygen in the air. As a result, people at high altitude breathe in less oxygen with each breath. This causes their bodies to produce more haemoglobin so that any oxygen breathed can be absorbed. The same effect has been achieved by some athletes by spending time in special chambers or tents that limit the supply of oxygen.

*Figure 4.30* Haemoglobin is found in red blood cells.

*Figure 4.31* Training at high altitudes encourages the body to produce more haemoglobin.
Chapter 4—The body’s response to physical activity

Figure 4.32  Lifting heavy weights builds muscle mass (muscle hypertrophy); frequently lifting light weights tones muscles.

Muscle hypertrophy

Hypertrophy simply means an increase in size, and muscle hypertrophy is the increase in the diameter of a muscle: ‘bulking up’. This occurs as a result of strength or resistance training and, unlike the adaptations discussed above, not as a result of aerobic training.

Muscle fibres enlarge after training for a number of reasons, including the production of more myofibrils (the contractile part of the muscle). The fibres also enlarge due to the increased stores of glycogen and the energy-supplying compounds of ATP and phosphocreatine (PC).

Muscle hypertrophy will occur if an athlete lifts medium to heavy weights during training, such as training for strength, power or lean body mass. Lifting heavier weights will cause the muscles to undergo a significant amount of stress. This enlarges them so that the next time they work they are better prepared for the task; that is, they have adapted. As with other adaptations that occur as a result of training, hypertrophy takes time to develop, and the reverse (muscle atrophy) will happen when training ceases.

Muscle endurance training (frequently lifting light weights) will assist in reducing the level of fat around the muscle. This will lead to muscle definition but not muscle hypertrophy.

After a resistance training program, muscles are capable of contracting with a greater force as more myofibrils are contributing to the contraction. This will improve performance in strength-related and power-related sports, such as throwing and sprinting.

Figure 4.33  Muscle hypertrophy is a result of body building.
Focus area B—Process and effects of training and exercise

Fast-twitch and slow-twitch muscle fibres

Muscle fibres can be classified into three groups:

- red slow-twitch fibres, which contain a large number of capillaries and produce a large amount of ATP slowly
- red fast-twitch fibres, which contain some capillaries and can rapidly produce ATP but fatigue faster than slow-twitch fibres
- white fast-twitch fibres, which contain few capillaries and rapidly generate ATP anaerobically.

The amount of each type of fibre in a muscle will depend on the muscle's usual function and use. A long-distance runner may have up to 75 per cent of muscles made up of slow-twitch muscle fibres, while sprinters may have up to 80 per cent fast-twitch muscle fibre. Undertaking training that is specific to the requirements of your sport will help to develop and adapt each type of the muscle fibre.

Endurance activities, such as running, swimming and cycling, help to develop slow-twitch muscle fibres. These activities encourage capillaries to form inside the muscle cells, allowing a greater transfer of oxygen into the muscles. Endurance activities can also result in some fast-twitch muscle fibres adapting to use oxygen to provide energy. This then leads to improvements in aerobic endurance and performance.

Sports that require power and muscle strength—from weightlifting to jumping and sprinting—require the development of fast-twitch muscle fibres. These fibres can be developed through the same sorts of training that create muscular power: lifting medium to heavy weights quickly. For example, 100-metre sprinters will train the fast-twitch muscle fibres in their legs by doing power squats that finish with a jump off the ground. This type of training will not only increase the capacity of the existing fast-twitch cells but will also cause some of the red muscle fibres to adopt the characteristics of white fast-twitch fibres. By increasing white fast-twitch fibres, muscle contractions can be made more quickly and anaerobic sources of energy can be used for longer.

Figure 4.34  Long jump requires the development of fast-twitch muscle fibres.
• The source of energy for muscle contraction is adenosine triphosphate (ATP).

• Three energy systems are used to resynthesise ATP:
  • the alactacid system (also called the ATP–PC system)
  • the lactic acid system
  • the aerobic system.

• Each energy system:
  • provides energy at different rates
  • recovers at different rates
  • creates a range of by-products
  • can contribute to energy production for different periods of time
  • is suited to different types of activity.

• A healthy cardiorespiratory system—heart and lungs—is essential for physical activity.

• An individual’s ability to take in and use oxygen, which drives the aerobic energy system, can improve with training.

• The time needed to recover and replenish energy stores depends on the type and duration of exercise.

• When people undertake any type of training, their main aim is to change or adapt some aspect of their body so that their performance improves.

• Training has immediate physiological effects on heart rate, ventilation rate, stroke rate, cardiac output, muscular responses and lactate levels.

• Training has long-term physiological effects on:
  • resting heart rate
  • stroke volume and cardiac output
  • oxygen uptake and lung capacity
  • haemoglobin levels
  • muscle hypertrophy
  • fast-twitch and slow-twitch muscle fibres.

NOW THAT YOU HAVE FINISHED ...

1 Explain how ATP provides energy for muscle contractions.

2 Describe the relationship between the breakdown of nutrients and the intensity and duration of exercise.

3 Identify the by-products of energy production for the lactic acid and aerobic energy systems.

4 Distinguish the energy system contributions for athletes in the following sports, events and positions:
   a hockey mid-fielder
   b pole vault
   c equestrian
   d 200-metre freestyle.

5 Outline the factors affecting an individual’s oxygen consumption and delivery.

6 Explain the concept of VO₂ max.

7 a Outline the adaptations that can occur as a result of aerobic training.
   b Explain how these adaptations lead to an improvement in performance.

8 Predict three physiological adaptations that could occur from long-term strength training.

9 Explain the difference between sub-maximal exercise and maximal exercise.

10 ‘Elite athletes are born, not made.’ Using your knowledge of muscle fibres, justify your opinion about this statement.