Sport and Exercise Physiology 1

Getting to know your unit

Assessment
This unit is assessed by an examination that is set and marked by Pearson.

When your body is doing little physical activity, your oxygen and energy demands are low and are easily met by shallow breathing and a low pulse rate. The blood circulating around your system delivers glucose and oxygen to your cells and takes away waste products, such as carbon dioxide.

But if you were to get up and run around a sports field, significant changes would take place. To fuel this activity, your body must adapt quickly and it does so in a variety of ways involving many processes. This unit is designed to examine these processes and their implications for sports performance.

How you will be assessed

This unit will be assessed externally using an examination set by Pearson. The examination will be 90 minutes long. The number of marks available is 80. The paper will contain a number of short- and long-answer questions that will assess your understanding of exercise physiology in both normal conditions and in different environmental conditions.

Throughout this unit you will find activities that will help you work towards your assessment. Completing these activities will not mean that you have achieved a particular grade, but you will have carried out useful research or preparation that will help you later when you do your external assessment.

This unit has four Assessment Outcomes (AO) which will be included in the external examination. Certain 'command words' are associated with each assessment outcome (see Table 1.1).

- **AO1** Demonstrate knowledge and understanding of body systems and how they respond and adapt to exercise in different environments
  - Command words: identify, describe, give, state/name, explain
  - Marks: range from 1–5 marks
- **AO2** Apply knowledge and understanding of body systems and how they respond and adapt to exercise in different environments in context
  - Command words: describe, explain
  - Marks: range from 1–5 marks
- **AO3** Analyse sports performance data to interpret the body's responses and adaptations to exercise and evaluate their impact on sport and exercise performance
  - Command words: analyse, assess, evaluate, discuss
  - Marks: 10 marks
- **AO4** Make connections between how the body systems work together in response to the demands of sport and exercise and to enhance performance
  - Command words: analyse, assess, evaluate, discuss
  - Marks: 10 marks

Table 1.1: Command words used in this unit

Command word	Definition – what it is asking you to do
Analyse	Identify several relevant facts of a topic, demonstrate how they are linked and then explain the importance of each, often in relation to the other facts.
Assess	Evaluate or estimate the nature ability, or quality of something.
Describe	Give a full account of all the information, including all the relevant details of any features, of a topic.
Discuss	Write about the topic in detail, taking into account different ideas and opinions.
Evaluate	Bring all the relevant information you have on a topic together and make a judgement on it (for example, its success or importance). Judgements should be clearly supported.
Explain	Make an idea, situation or problem clear to your reader, by describing it in detail, including any relevant data or facts.
Give	Provide examples, justifications and/or reasons to a context.
Identify	State the key fact(s) about a topic or subject. The word *Outline* is similar.
State/name	Give a definition or example.

Getting started

Chris Froome is a two-time winner of the Tour de France. During a race, his muscles need a supply of fuel and oxygen while his lungs eliminate waste products such as carbon dioxide. These processes occur when you do any form of exercise. The difference is that Froome can push them much further. Why can you not ride at the same intensity as Froome?

A Response of the body systems to a single sport or exercise session

Physiology is the study of your body's responses to exercise and and training. When exercising, you increase your body's energy use. This is reflected in increased oxygen consumption. Under certain conditions where the work rate is constant, the pattern of oxygen consumption shows an initial rise then levels off: once this plateau is reached, oxygen consumption remains steady over the period of the exercise.

For example, if you undertake 20 minutes of continuous same-speed jogging, a number of responses occur. Your heart and respiratory rates increase to accommodate the demands placed on the body, more ATP is produced and neuromuscular changes occur. (These changes are covered later in this unit.) After 3 or 4 minutes your body adapts to the increase in exercise intensity and your physiological demands level out. For the remaining time, you undergo 'steady-state exercise'.

Throughout this unit two key words crop up repeatedly.

- **Aerobic** means 'with oxygen' and involves the use of oxygen in energy production. In general, aerobic exercise is performed at a moderate level of intensity over a long period of time, such as long-distance running at a moderate pace. During aerobic exercise, your body uses oxygen in a number of different chemical reactions to generate energy almost as quickly as it is being used, depending on the exercise intensity. Glycogen is broken down to produce glucose, but in its absence fat metabolism is used instead.
- **Anaerobic** means 'without oxygen'. Anaerobic exercise relies on energy sources stored in the muscles and, unlike aerobic exercise, is not dependent on oxygen. Anaerobic exercise includes heavy weightlifting, sprints (running, cycling) and isometrics (in which one part of the body is used to resist the movement of another part) or any rapid burst of hard exercise.

Skeletal system responses

Long-term exercise slows the rate of skeletal ageing. People who maintain active lifestyles have greater bone mass compared to those who participate in less exercise. Weight-bearing exercises (e.g. running or walking) are particularly beneficial to the skeletal system, but this is also dependent on adequate **calcium** supply.

Bone is a dynamic tissue. It is constantly reshaped by **osteoblasts**. In return, **osteoclasts** break down the tissue to allow new growth. During midlife, osteoblast and osteoclast activity is in balance. However, as the body ages, osteoclast activity increases, breaking down bone tissue to release calcium and other minerals into the bloodstream. Research suggests weight-bearing exercise stimulates the activity of osteoblasts and suppresses osteoclast activity, maintaining a healthy bone density.

Link

This unit links with *Unit 2: Functional Anatomy* and *Unit 7: Biomechanics in Sport and Exercise Science*.

Key terms

Physiology – study of the way that the body responds to exercise and training.

Calcium – mineral required for development of bones and teeth, and for the maintenance of overall health.

Osteoblasts – specialised bone cells that build new bone tissue.

Osteoclasts – large nucleated cells that destroy bone cells, reabsorb calcium and play a major role in bone remodelling.

Key terms

Viscosity – how thick a fluid is, affecting its resistance to flow.

Cardiac muscle – muscle tissue found only in the heart.

Maximal exercise – level of training intensity when an athlete approaches their maximal heart rate and performs exercise to an increasingly anaerobic level.

Synovial fluid is a thick, straw-coloured liquid that acts as a lubricant and is found primarily in the cavities of synovial joints. Exercise increases the amount of synovial fluid, decreasing its **viscosity**, keeping joints healthy, while stopping cartilage from drying out. Research suggests exercise also increases the range of movement at the joints as more synovial fluid is released into them.

Muscular system responses

High-intensity cardiovascular exercise can improve the strength of **cardiac muscle**, while intense strength conditioning can decrease sensitivity to muscular soreness post-workout. These short-term effects enable a performer to be more resilient to injury while improving their muscular strength and endurance in the long term.

Muscle fibre recruitment (Type I, Type IIa, Type IIx)

Recruitment of muscle fibres during exercise follows a specific pattern (see Figure 1.1). First, slow-twitch (Type I) muscle fibres are brought into action, then fast-twitch muscle fibres (first Type IIa and finally Type IIx). The level of recruitment is generally determined by the demand placed on the muscle. However, even during **maximal exercise** activity, the nervous system does not use all the muscle fibres. Generally, only a fraction of muscle fibres are recruited at any one time to avoid muscle damage and injury.

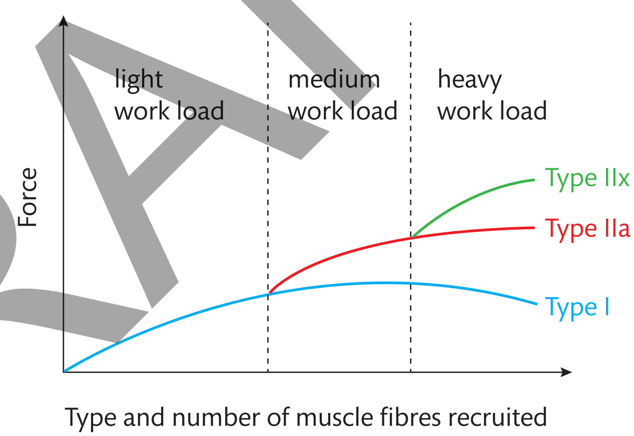


Figure 1.1: Recruitment of muscle fibres during exercise

Muscle fibres will react to long-term exercise depending on the type of exercise they are subjected to. When training for muscular endurance events the main adaptations will occur in Type I fibres, creating within the muscle a greater ratio of Type I to Type IIa and Type IIx fibres. The result will be greater endurance capacity but a decrease in strength capacity. When training for muscular strength, Type IIa and Type IIx fibres must be recruited; the best way to achieve this is by lifting heavy weights.

Blood flow to working muscles

Cardiac output (the amount of blood the heart pumps through the circulatory system in a minute) is, at rest, approximately 5–6 litres for an adult male but the blood flow is never evenly distributed throughout the body's organs and tissues. Instead, the body sends blood where it is needed. This redistribution of blood is achieved primarily by **vasoconstriction** (reduction in the diameter of blood vessels) and **vasodilation** (expansion in the diameter of blood vessels), which are regulated by hormones or chemicals. (For more about vasoconstriction and vasodilation, see page 8.)

At rest, approximately 20 per cent of the blood goes to muscles. Blood flow is distributed according to the need of the organs involved in the digestive process. During exercise, cardiac output can increase from 5–6 litres to 15–20 litres per minute and blood flow distribution changes dramatically, with up to 86 per cent of the blood going to the muscles.

Micro-tears

Every muscle in the body is made up of hundreds of thousands of tiny fibres. During exercise, muscle fibres will contract and relax against each other, resulting in microscopic tears to the fibres. By resting after the activity your body heals and uses proteins to fill the gaps in the tears, resulting in extra strength and, depending on the exercise type, an increase in muscle size.

Temperature

During exercise all muscles require energy, gained from burning fuels such as carbohydrates and fats. One of the products is heat. As the muscles warm up, blood circulating through the muscles is also warmed resulting in a rise in the body's temperature. The amount of heat your muscles produce is related to the amount of work they perform. Therefore, the more intense the exercise, the more heat they produce.

PAUSE POINT Do you think there is merit in training endurance athletes with heavy workloads requiring increased force production?

Hint Think about the types of muscle fibres endurance athletes use most often.

Extend Consider what types of gym-based exercises an endurance athlete might perform, in terms of workloads, reps and sets.

Respiratory system responses

The levels of oxygen in arterial blood change very little, even during exercise, but carbon dioxide levels vary according to the level of physical activity. The more intense the exercise, the greater the carbon dioxide concentration in the blood. To combat this, your breathing rate increases to help expel the carbon dioxide.

Control of breathing rate

Physical exercise increases the oxygen consumption of skeletal muscles. A trained athlete at rest might use 250 ml of oxygen per minute, but require 3600 ml per minute during maximal exercise. When oxygen consumption increases, the volume of carbon dioxide produced also increases. Decreased blood oxygen (the amount of oxygen in blood) and increased blood carbon dioxide concentration stimulates the respiratory centre to increase breathing rate (chemical control). A minor increase in breathing rate before exercise is known as an **anticipatory rise**. However, when exercise begins, there is an immediate and greater increase in breathing rate due to receptors in the muscles and joints (neural control).

After several minutes of aerobic exercise, breathing continues to rise at a slower rate, levelling off (while exercise intensity remains constant) until exercise ends. If the exercise is maximal then breathing rate continues to rise until exhaustion. In both cases, after exercise is finished, breathing returns to normal – rapidly to begin with and then more slowly.

The increase in breathing rate during exercise demands an increase in blood flow to the skeletal muscles. Should respiratory or muscular systems fail to keep up with demands, you will feel out of breath. This is due to the inability of the heart and circulatory system to move enough blood between the lungs and the skeletal muscles, not necessarily an inability of the respiratory system to provide sufficient oxygen.

Key terms

Anticipatory rise – a minor increase in breathing rate prior to exercise.

Link

Information about the functioning of the respiratory muscles can be found in *Unit 2: Functional Anatomy*.

Respiratory muscles

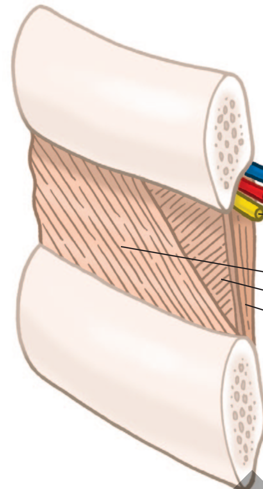


Figure 1.2: Eleven pairs of intercostal muscles occupy the spaces between 12 pairs of ribs

During exercise, forced breathing is used. This differs from normal breathing because, during expiration, the internal intercostal muscles contract (see Figure 1.2), moving the ribs and sternum upwards and outwards forcibly. The abdominal muscles also contract, increasing the pressure of the abdominal cavity, helping the diaphragm to rise more forcibly. During exercise the muscles involved in the breathing process can use up to 10 per cent of the body's total oxygen uptake. Cramp in these muscles is thought to be the cause of a 'stitch'.

Tidal volume

Tidal volume is the amount of air ventilated in or out of the lungs in one breath. More information can be found on page 52 in *Unit 2: Functional Anatomy*. It increases dramatically during exercise due to the body's demand for more oxygen and/or the need to offload increased levels of carbon dioxide. Increases in breathing rate maintain **alveolar ventilation** during steady-state exercise. Trained athletes achieve the required alveolar ventilation by increasing tidal volume and only minimally increasing breathing rate. With deeper breathing, alveolar ventilation can increase from 70 per cent at rest to over 85 per cent of total ventilation during exercise. This increase occurs because deeper breathing causes a greater tidal volume to enter the alveoli.

Key term

Alveolar ventilation – tidal volume minus dead space (air that remains in trachea, bronchi, etc.).

Minute volume (VE)

At a low to moderate exercise intensity, tidal volume and breathing rate increase proportionally. However, at a high exercise intensity, tidal volume reaches a peak so any further increase in minute volume requires an increase in breathing rate. Minute volume is measured in litres per minute and is calculated by multiplying tidal volume by breathing rate. For example, an adult with a tidal volume at rest of 0.4l, who breathes 12 times per minute will have a minute volume of 4.8l/min.

Theory into practice

Calculate the number of breaths taken by an adult over 1 year with the following approximate criteria:

- average period of sleep per day = 8 hours during which the breathing rate is 10 breaths per minute
- remainder of time deemed to be awake and the average breathing rate is 12 breaths per minute.

Oxygen dissociation curve

The oxygen dissociation curve (see Figure 1.3) shows the relationship between the percentage of oxygen saturation of blood (a measure of oxygen dissolved or carried in blood) and the **partial pressure** of oxygen. During steady-state exercise, increased temperature and lower blood pH concentration affect the oxygen–**haemoglobin** dissociation curve so that more oxygen can be unloaded to supply the active muscle. In prolonged high-intensity exercise, large amounts of **lactate** enter the blood from the active muscle. At exhaustion, **blood pH** can approach 6.8. Only after exercise ceases does blood pH stabilise and return to 7.4.

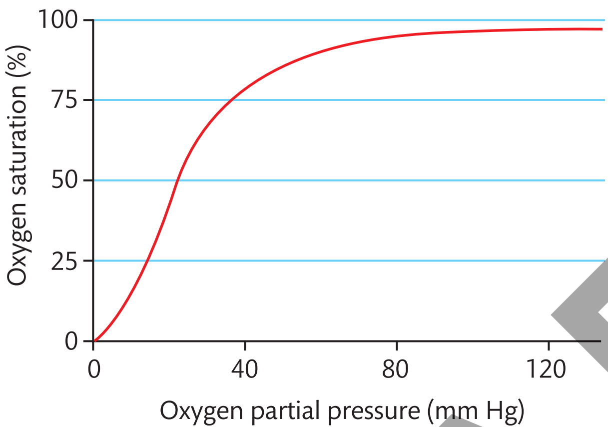


Figure 1.3: Oxygen dissociation curve

Key terms

Partial pressure – pressure applied by a single gas in a mixture of gases.

Haemoglobin – oxygen transporting component of red blood cells.

Lactate – product of lactic acid which occurs in blood.

Blood pH – measure of acidity or alkalinity of a solution.

Research

Asthma is a common condition among the general population. Find out how asthma affects the respiratory system and what problems it might present for sports participation.

Case study

Elite athletic performance

Mary Keitany is an elite distance runner who has won both London and New York marathons. She completed the London Marathon in 2012 in a time of 2 hours, 18 minutes and 37 seconds. Crossing the line, Mary was clearly tired. She took several rapid and deep breaths once she had stopped. But within a few minutes, her breathing rate had slowed enough for her to hold brief media interviews.

Check your knowledge

Why would it be virtually impossible for Mary to give an interview immediately after she had crossed the finish line? Concentrate on the physiology of the respiratory responses to exercise and why Mary needed those extra few minutes before holding a conversation.

PAUSE POINT Do you understand the various measures of respiratory volumes?

Hint Using paper, whiteboard or a tablet, list the measures of respiratory volumes and provide a brief description for each.

Extend Think about how these volumes might be improved. What types of training will have a positive effect on these volumes?

Link

More information about the cardiovascular system can be found in *Unit 2: Functional Anatomy*.

Key terms

Cardiac cycle – the sequence of events (systole – during which cardiac muscle contracts – and diastole – during which cardiac muscle relaxes) that take place during a single heartbeat.

Neurotransmitters – chemicals used to carry signals or information between neurons and cells.

Stroke volume – volume of blood pumped out of the heart's left ventricle per beat.

Cardiovascular system responses

When exercising, changes occur within the cardiovascular system. You must understand these changes as they affect an athlete's training and performance.

Cardiac cycle

When the body detects an increase in exercise intensity, the **cardiac cycle** must respond accordingly. It achieves this by speeding up to meet the demands of the exercise. As a result, heart rate will increase, the amount of blood filling your atria and ventricles will increase, your systolic blood pressure will rise and blood will be diverted to the skeletal muscles that require the necessary increase in nutrients and oxygen, and remove waste products such as carbon dioxide, in order to perform effectively.

- **Vasodilation** – during exercise, the vascular portion of active muscles increases through dilation of arterioles, a process known as vasodilation that involves an increase in the diameter of the blood vessels resulting in an increased blood flow to the muscle area supplied by the vessel (or arteriole).
- **Vasoconstriction** – vessels can also shut down blood flow to tissues. This process is known as vasoconstriction and involves a decrease in diameter of a blood vessel by contraction of involuntary muscle fibres in the vessel walls. For example, at rest kidney function requires about 20 per cent of cardiac output. During maximal exercise, blood flow to the kidneys decreases due to vasoconstriction to approximately 1 per cent of cardiac output as the kidneys effectively shut down during exercise.

Anticipatory increase in heart rate

An anticipatory increase in heart rate occurs before the start of exercise. Heart rate can be changed by **neurotransmitters** such as adrenaline and noradrenaline, released from the brain. Therefore, before exercise, the heart rate increases and the subsequent increase in blood flow has already begun to supply oxygen and nutrients to the muscle or muscles about to be worked.

Cardiac output

Cardiac output is the volume of blood pumped out of the heart in 1 minute. It is expressed as Q and is equal to heart rate multiplied by the **stroke volume**. Cardiac output may reach up to 30 litres per minute during extreme exercise.

Stroke volume

Stroke volume is the amount of blood pumped by the left ventricle in one contraction. About two-thirds of the blood in the ventricle is put out with each beat. During exercise, stroke volume increases progressively and gradually levels off at a higher level until the exercise has ended. Assuming normal stroke volume ranges between 70 and 80 ml per beat, a trained athlete's stroke volume can be 110 ml. During exercise, blood flow increases sharply, allowing for a greater oxygen supply to the skeletal muscles.

Heart rate

Heart rate changes according to the body's needs. It increases during exercise (see Figure 1.4) to deliver extra oxygen to tissues and remove carbon dioxide. At rest, a normal adult heart beats approximately 75 times per minute, peaking at around 200 beats per minute for strenuous activity, depending on age.

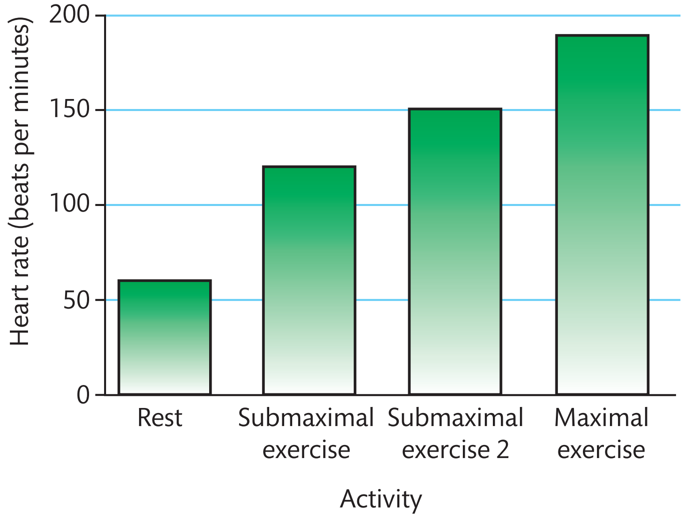


Figure 1.4: Heart rate during exercise. 'Submaximal exercise 2' is aerobic exercise of greater intensity than 'Submaximal exercise' given the increased heart rate

Heart rate is controlled by the **sinoatrial node** (SAN). The rate goes up or down when the SAN receives information via nerves that link the SAN with the cardiovascular centre in the brain. When you exercise, information is communicated and the heart adapts accordingly. It does so in two ways:

- the **sympathetic nerve** speeds up the heart – the synapses at the end of this nerve secrete a hormone called noradrenalin
- the vagus nerve (**parasympathetic nerve**) slows down the heart – the synapses at the end of the nerve secrete a hormone called acetylcholine (see Figure 1.5).

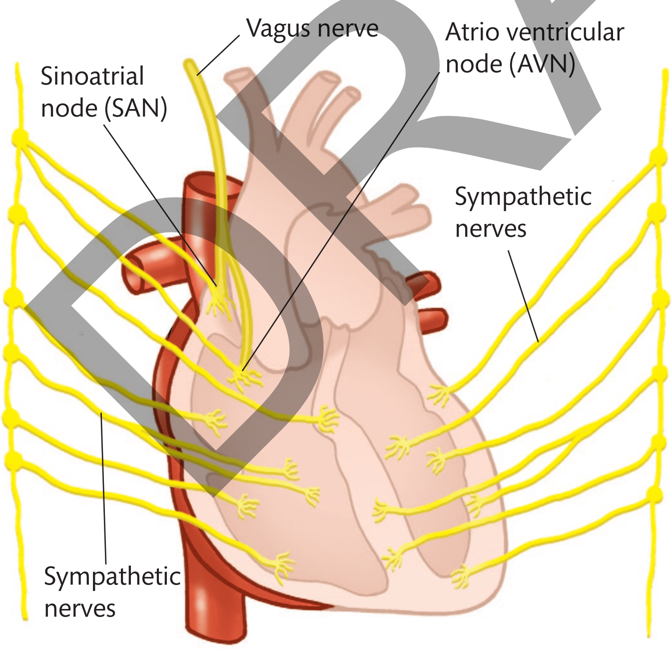


Figure 1.5: The heart is connected via the vagus nerve and sympathetic nerves to the brain

Stroke volume reaches a peak during submaximal exercise and does not increase during maximal exercise. The greatest increase in stroke volume occurs in the transition from rest to moderate exercise. During maximal exercise, stroke volume does not increase as the left ventricle is, at this point, already full to capacity. The body tolerates maximal activity for as long as it can by increasing heart rate and maintaining stroke volume.

Changes to cardiac output

Approximately 5 litres of blood are circulated each minute at rest for trained or untrained athletes, so approximately 1 litre of oxygen is available to the body. An increase in cardiac output has benefits for trained athletes as they can transport more blood to the working muscles and, therefore, more oxygen. Given the formula for cardiac output is stroke volume × heart rate, if the average stroke volume is 70 ml and the average resting heart rate is 70 beats per minute, the average cardiac output of a healthy adult is:

70 × 70 = 4900 ml of blood per minute

A key adaptation of long-term exercise is that resting heart rate decreases while stroke volume increases. A trained athlete can have a stroke volume of 110 ml and a resting heart rate of 50 beats per minute. The average cardiac output of a trained athlete is:

110 ml × 50 bpm = 5500 ml per minute

Therefore, greater cardiac output maintained by fewer beats is an indication of increased fitness.

Starling's law

Starling's law is a theory which states that stroke volume increases in response to an increase in blood volume filling the heart. This stretches the ventricular wall, causing the cardiac muscle to contract more forcefully. The stroke volume may also increase due to stronger contractions in the cardiac muscles during exercise. Therefore, the reduced heart rate of a trained athlete allows for greater filling during the longer diastole, so the stretch of the cardiac muscle is greater. This in turn increases the stroke volume.

Blood pressure

Blood pressure is determined by two factors:

- the resistance offered by blood vessel walls to blood flow – this can depend on several factors including blood vessel length and radius
- cardiac output or blood volume pumped out of the heart's left ventricle in 1 minute.

Therefore, blood pressure is defined as:

cardiac output × resistance

During steady-state exercise, dilation of the blood vessels in active muscles increases the vascular area for blood flow. The alternate rhythmical contraction and relaxation of the skeletal muscles forces blood through the vessels and returns it to the heart. During exercise, although both cardiac output and blood pressure increase, mechanisms act to restrict the blood pressure from rising too high.

The higher the exercise intensity, the greater the rise in heart rate and, consequently, an increase in **systolic pressure** generally occurs. Muscular strength training can significantly raise blood pressure levels. This occurs because the blood has to be forced through skeletal muscle tissue subject to increased intra-muscular pressure, so the cardiovascular system has to work harder to achieve circulation requirements.

Key term

Systolic pressure – pressure exerted in the arteries when the heart contracts.

Readings

Medical staff sometimes measure blood pressure manually using the brachial artery. A blood pressure cuff is wrapped around the arm above the elbow and inflated until a brachial pulse cannot be felt or heard. The pressure is gradually released and the first sounds of forced blood through the brachial artery are listened for with a stethoscope.

This gives the systolic pressure. As cuff pressure reduces the sounds of the forced blood disappear, giving the **diastolic pressure**. Alternatively, blood pressure can be easily measured at the touch of a button using digital instruments.

At rest, normal adult systolic pressure varies between 110 and 140 mm Hg, and diastolic pressure between 70 and 80 mm Hg (see Figure 1.6). Blood pressure varies with age, gender, race and amount of physical activity carried out: remember, what is normal for one person may not be normal for another.

Blood pressure around 120/80 mm Hg is optimal for adults. Systolic pressure readings of 120 to 139 mm Hg or diastolic pressure of 80 to 89 mm Hg is considered as **prehypertension** and needs to be watched carefully. A blood pressure reading of 140/90 mm Hg or higher is considered to be hypertensive. **Hypertension** is high blood pressure and increases the risk of cardiovascular diseases or kidney failure because it adds to the workload of the heart.

Key terms

Diastolic pressure – pressure exerted in the arteries when the heart relaxes and fills with blood.

Prehypertension – means someone does not have high blood pressure now but they are likely to develop it in future.

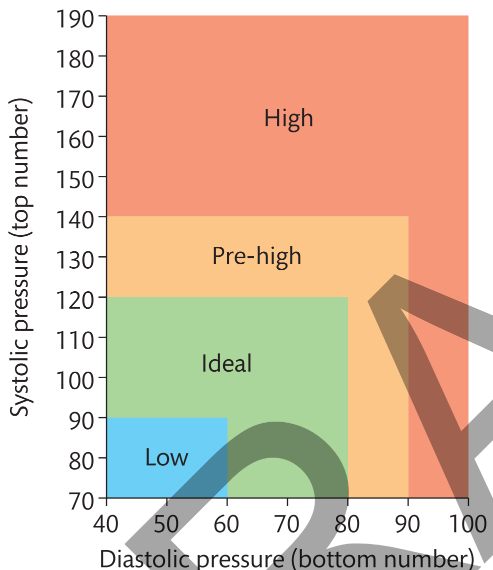


Figure 1.6: Blood pressure chart

During aerobic exercise, oxygen consumption and heart rate increase in relation to the intensity of the activity. Systolic blood pressure rises progressively, while diastolic blood pressure stays the same or decreases slightly. The pulse rate rises and blood flow to the muscles increases.

Theory into practice

Work in pairs or small groups. Use a digital blood pressure monitor to determine your own blood pressure and that of your friends. Compare your readings against the blood pressure norms identified in the main text.

Changes in blood pH

The pH of a substance refers to a measure of acidity or alkalinity. A pH value of 7 indicates neutral, a value above 7 indicates alkalinity, and below 7 indicates acidity. The pH of blood is generally between 7.2 and 7.5, indicating very weak alkalinity. However, during exercise blood pH can drop and become more acidic (i.e. below pH 7). The acidity is due to the inclusion of waste products such as carbon dioxide in the blood due to exercise intensity. During high-intensity exercise using anaerobic metabolism, lactic acid is released into the blood again as a waste product.

Key terms

Arterial blood – bright red in colour due to high concentrations of oxygen.

Venous blood – darker red than arterial blood due to high concentrations of carbon dioxide.

Diffusion rate

During exercise, diffusion rates increase to allow more oxygen movement from the capillaries to the working muscles, while carbon dioxide is exchanged into the blood for exhalation. The more you exercise, the more efficient this process becomes so that, with long-term aerobic training, your body becomes more efficient at allowing oxygen and carbon dioxide to diffuse.

Arteriovenous oxygen difference (a–VO2 diff)

Arteriovenous oxygen difference is the difference in the oxygen content between **arterial** and **venous blood**. Exercise leads to an increase in this difference because, as exercise intensifies, the working muscle tissue demands more oxygen from the arterial blood, so the oxygen content of venous blood decreases.

Theory into practice

Imagine you have undertaken a 20-minute steady jog at a steady 10 km/h. Draw a graph with time along the horizontal axis and heart rate along the vertical axis. Sketch a line on your graph that indicates approximately how your heart rate has changed throughout the course of the 20-minute exercise, assuming you did not run to exhaustion.

PAUSE POINT When you exercise, what is a key indicator that the pH of your blood has dropped?

Hint Consider which energy system lowers the pH of your blood and what type of exercise is likely to cause this effect.

Extend What type of training is likely to improve your resistance or ability to tolerate a lower blood pH?

Neuromuscular system responses

The term 'neuromuscular' refers to both the nervous system and the muscular system. There are two kinds of nerves:

- **sensory neurons** (or 'sensory nerves') which carry information from our extremities (the skin) to the central nervous system (the brain and spinal cord)
- **motor neurons** (or 'motor nerves') which carry information from our central nervous system to our muscles.

Nervous control of muscular contraction

Muscles contract when stimulated by nerves. Three basic types of contraction can occur during exercise, each with a variation of contraction pattern.

- **Isotonic contraction** – the muscle shortens as it develops tension.
- **Isometric contraction** – the muscle develops tension but does not change length.
- **Isokinetic contraction** – the muscle contracts to its maximum at a constant speed over the full range of movement.

Muscles contract and relax due to muscle filaments moving backwards and forwards across each other. What causes these backwards and forwards movements to occur is the actions of specialised nerve cells called motor units working at a neuromuscular junction.

- **Neuromuscular junction** – a neuromuscular junction is the site at which a motor neuron communicates with a muscle fibre using nerve impulses.

- **Motor unit** – a motor unit is made up of a motor neuron and all the associated muscle fibres it affects. Motor units work together to coordinate contractions of a single skeletal muscle, although the number of fibres in each unit varies based on the muscle size and role. During low-intensity exercise, Type I motor units are recruited. As the intensity is increased Type IIa motor units are recruited until the intensity is enough to recruit Type IIx motor units.

Muscle spindles and Golgi tendon organs (covered in the next sections) provide sensory information about the intensity of exercise, allowing smooth, coordinated movement patterns.

Muscle spindles

Muscle spindles (see Figure 1.7) are **proprioceptors** found in skeletal muscles, located within muscle fibres known as **intrafusal fibres**. They detect muscle stretch and initiate a reflex that resists the stretch and prevents muscle tears. When muscle is stretched, primary sensory receptors in the muscle spindle respond to the velocity and degree of stretch, then send this information to the brain via the spinal cord. Secondary sensory receptors detect and send information about the degree of stretch to the central nervous system. This information is transmitted to a motor neuron, which activates the muscle to contract, thus reducing the stretch. The more your body is used to steady-state exercise, the more efficient the muscle spindles become at transmitting this information.

Key term

Proprioceptors – sensory receptors found in muscle tissue, tendons and joints which tell the brain about the physical state and position of a muscle or joint.

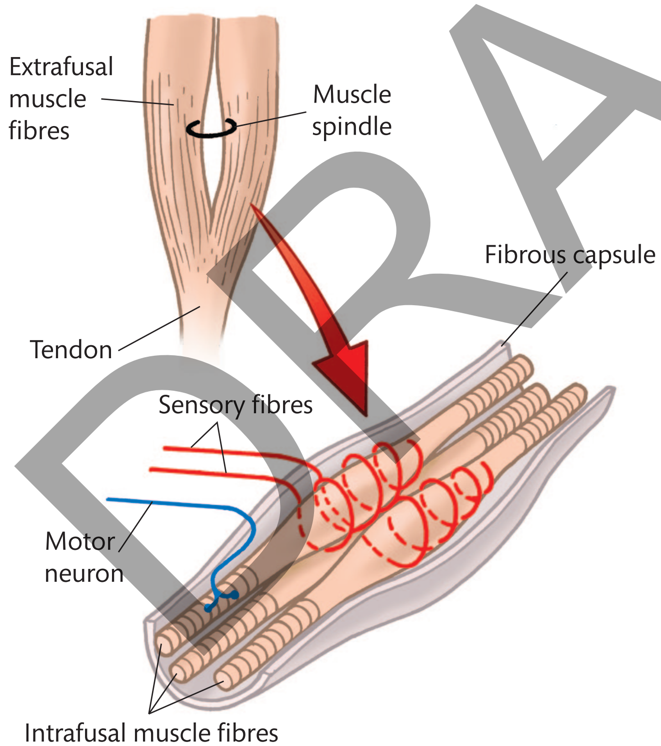


Figure 1.7: Muscle spindles provide information about any changes in length and tension of muscle fibres

Golgi tendon organs

Golgi tendon organs (GTOs) are proprioceptors located within the tendons and are sensitive to stretch. Golgi tendon organs send information to the central nervous system concerning the strength of a muscle contraction and, together with muscle spindles, facilitate smooth movement patterns.

Chemoreceptors, thermoreceptors and baroreceptors

Receptors are groups of specialised cells that detect changes in the environment (internally and externally), which send impulses to the brain that result in the body adapting to these changes.

- **Chemoreceptors** – sense chemical stimuli within the body. For example, chemoreceptors detect carbon dioxide in the blood. If, during exercise, increased levels of carbon dioxide are detected, the brain sends a signal to the respiratory system to increase the breathing rate to allow the carbon dioxide to be offloaded by exhalation.
- **Thermoreceptors** – sense changes in temperature and are key to the thermoregulation process. If a thermoreceptor senses a warm environment or increased body temperature due to exercise, the body's cooling processes are activated (see pages 32–33 of this unit). Likewise, if the environment is cold the body will respond with warming actions (e.g. shivering or blood diversion).
- **Baroreceptors** – located in blood vessels and sense blood pressure. The information from baroreceptors is sent to the brain so that correct blood pressure can be maintained at all times. The information provided by baroreceptors can influence cardiac output during exercise.

Endocrine system responses

The endocrine system is the body system consisting of organs and tissues that secrete hormones in response to exercise and other external factors. The main hormones of the body are:

- **adrenaline** – secreted by the adrenal glands, it increases heart rate, breathing rate and metabolic rate and improves the force of muscle actions, delaying the onset of fatigue
- **noradrenaline** – closely related to and with similar properties to adrenaline, noradrenaline is also secreted by the adrenal glands and acts as a neurotransmitter. Low levels of noradrenaline are associated with depression
- **cortisol** – associated with stress, cortisol increases blood sugar levels, suppresses the immune system and aids the metabolism of macronutrients
- **testosterone** – the primary male sex hormone involved in the development of muscle tissue and muscular strength, testosterone increases the number of neurotransmitters, encouraging muscle tissue growth. Testosterone also increases levels of human growth hormone (HGH) which makes the appropriate type of exercise promote the building of muscle tissue
- **human growth hormone (HGH)** – secreted by the pituitary gland which stimulates general body growth and the lengthening of bones in particular
- **oestrogen** – the primary female sex hormone that is known to inhibit bone resorption.

PAUSE POINT How do you think hormone effects might be exploited by athletes looking to cheat their way to success?

Hint Research high-profile cases of athletes looking to enhance their performance using steroids and HGH.

Extend Research the potential impact and negative effects of illegal ergogenic aids designed to enhance performance.

Energy systems responses

Energy sources

The body relies on three energy systems, which are outlined later in this section:

- the ATP-PC system
- the lactate system
- the aerobic system.

During exercise, the body does not switch from one energy system to another – energy is derived from all systems at all times. However, the emphasis changes depending on the intensity and duration of the activity.

Theory into practice

Energy systems do not operate in isolation; they interact to supply the energy required for muscular movement. Energy systems are like 'taps' that are never fully turned off – the energy flows continually (like water at differing pressures) according to the exercise being undertaken. Select two sports or activities and compare the likely energy system usages (as a percentage) for each.

Exercise requires the body to extract energy from food. Carbohydrate, fat and protein follow different metabolic pathways but ultimately produce **adenosine triphosphate (ATP)**, the only molecule that is able to provide energy to muscle fibres. Phosphocreatine (PC) is another high-energy compound stored in cells and can be rapidly used to help short explosive physical efforts. To sustain any physical activity, the body must constantly replenish its ATP and PC stores.

- Carbohydrates are broken down into blood glucose, the body's main energy source. Blood glucose can be used immediately as fuel, or can be sent to the liver and muscles and stored as glycogen. During exercise, muscle glycogen is converted back into glucose for use by working muscle fibres.
- Fat is the body's most concentrated source of energy, providing more than twice as much energy as carbohydrate or protein (9 calories per gram versus 4 calories each per gram). During exercise, fat (in the form of triglycerides in adipose or fat tissue) is broken down into fatty acids. These are transported through the blood to the muscles as fuel. This is a slower process than the mobilisation of carbohydrate for fuel.
- Protein is used to build, maintain and repair body tissues. Under ordinary circumstances, protein meets only approximately 5 per cent of the body's energy needs. Under more extreme circumstances, for example, when we eat too few calories or not enough carbohydrate, as well as undertaking the final stages of endurance exercise, once the glycogen reserves are depleted then skeletal muscle is broken down and used as fuel.

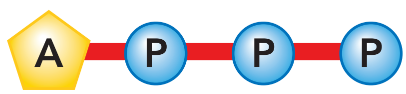
ATP production

Your body stores only a small quantity of ATP in its cells – enough to power only a few seconds of all-out exercise. Therefore, your body must replace or resynthesise ATP on a continual basis. ATP consists of a base (adenine) and three phosphate groups (see Figure 1.8). It is formed by a reaction between an adenosine diphosphate (ADP) molecule and a phosphate. When a molecule of ATP is used, the last phosphate group splits off and energy is released.

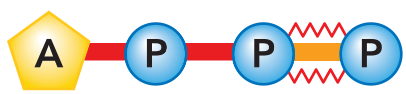
Training to improve ATP energy transfer capacity requires repetitive, intense, short-duration exercise. The activities chosen should engage muscles in the movement for which the athlete desires improved anaerobic power. This enhances metabolic capacity of engaged muscle tissue or fibres and improves neuromuscular adaptations to the sport-specific pattern of movement.

Discussion

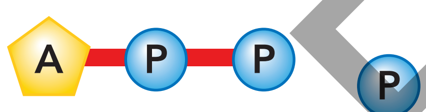
Look back at the definitions of 'aerobic' and 'anaerobic' provided on page 3. Consider the various movements and actions undertaken by a footballer during a match (for example, heading, shooting, tackling, jogging, marking, etc.). Which rely primarily on aerobic metabolism and which rely primarily on anaerobic metabolism? As a group discuss and justify your decisions.



(a) ATP is formed when adenosine diphosphate (ADP) binds with a phosphate (P)



(b) Energy is stored in the bond between the second and third phosphate groups



(c) When a cell needs energy, it breaks the bond between the phosphate groups to form ADP and a free phosphate molecule

Figure 1.8: ATP production (a) – (c)

ATP-PC system

ATP and creatine phosphate (phosphocreatine or PC) make up the ATP-PC system. PC is broken down, releasing both energy and a phosphate molecule (which is then used to rebuild ATP). The enzyme that controls the breakdown of PC is called **creatine kinase**.

The ATP-PC system can operate with or without oxygen, but because it does not rely on the presence of oxygen it is anaerobic. During the first five seconds of exercise, regardless of intensity, the ATP-PC system is relied on almost exclusively. The ATP-PC system can sustain all-out exercise for 3 to 15 seconds. If activity continues beyond this period, the body must rely on an additional energy system to resynthesise ATP.

Lactate system (anaerobic glycolysis)

Glycolysis is the term used to describe the breakdown of glucose. It consists of a series of enzymatic reactions. The end product of glycolysis is pyruvic acid which is used in a process called the **Krebs cycle** (see Figure 1.9) or converted into lactic acid.

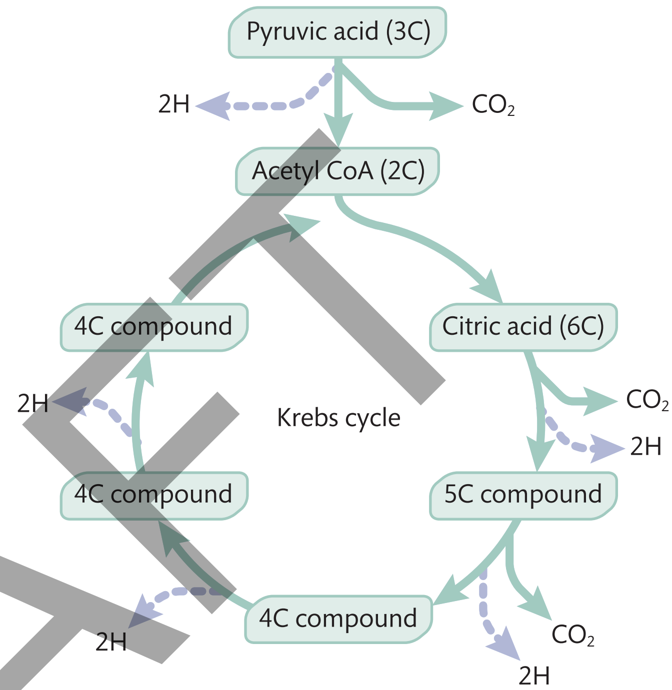


Figure 1.9: Krebs cycle

Anaerobic glycolysis occurs at times when energy is required in the absence of oxygen. It is vital for tissues with high energy requirements or an insufficient oxygen supply. It involves the breakdown of glycogen to form ATP (for energy) plus lactate. The build-up of lactate in the muscles ends the use of this energy system after 40 to 60 seconds of maximum effort, so this system is called on by athletes whose sports demand high-energy expenditure for up to 60 seconds, such as 400 metre runners and rugby players.

Glycolysis forms pyruvic acid and hydrogen ions (H+). A build-up of hydrogen ions makes the muscle cells acidic and interferes with their operation, so carrier molecules called nicotinamide adenine dinucleotide (NAD+) remove the H+. As they do this, the NAD+ is reduced to NADH, which deposits the H+ during the **electron transport chain** to be combined with oxygen to form water.

Key term

Electron transport chain – a series of biomechanical reactions during which free energy contained within hydrogen (derived from the Krebs cycle) is released. For more information, see pages 17–18.

If there is insufficient oxygen, NADH cannot release the H+ and they build up in the cell. To prevent a rise in acidity, pyruvic acid accepts H+, forming **lactic acid** that then dissociates into lactate and H+. Some of the lactate diffuses into the bloodstream. The normal pH of the muscle cell is 7.1, but if the build-up of H+ continues and pH is reduced to around 6.5, muscle contraction is impaired.

Aerobic energy system

The aerobic energy system uses carbohydrates, fats and proteins extracted from the diet to resynthesise ATP. This system produces more ATP than the ATP-PC or the lactate system, but does so at a slower rate and is therefore less suitable for intense exercise. The aerobic system consists of three stages, each of which produce ATP.

Stage 1: Aerobic glycolysis

Aerobic glycolysis converts stored glycogen to glucose. This glucose is broken down by enzymes in the presence of oxygen. Two ATP molecules are used to fuel aerobic glycolysis and four are created, resulting in a gain of two ATP molecules for use in muscle contraction. Pyruvate is created as the end product of the breakdown of glucose and, in the presence of oxygen, the pyruvate is converted into acetyl coenzyme A. Acetyl coenzyme A can be synthesised during the second and third stages of the aerobic system to create more ATP.

This system involves prolonged work at low intensity and increases in importance with the longer the sport's duration. Lack of fuel, overheating or **dehydration** will end the exercise.

Fuel for this system varies according to duration and intensity of exercise. In prolonged aerobic exercise, the preferred fuel is free fatty acids because glycogen stores are limited compared to our plentiful fat stores.

Stage 2: Krebs cycle

Acetyl coenzyme A enters what is called the Krebs cycle (see Figure 1.9) and is broken down, producing ATP and the by-products of carbon dioxide and water.

The Krebs cycle is a series of aerobic reactions that take place in the matrix in mitochondria. Carbon dioxide is produced and hydrogen removed from carbon molecules and joins NAD to form $NADH_2$. The Krebs cycle provides a continuous supply of electrons to feed the electron transport chain. This cycle begins when the 2-carbon acetyl CoA joins with a 4-carbon compound to form a 6-carbon compound called citric acid. Citric acid (6C) is gradually converted back to the 4-carbon compound ready to start the cycle once more.

Key terms

Dehydration – depletion of fluids that can impede thermoregulation and cause a rise in core body temperature.

Mitochondria – the cellular site of aerobic respiration. Pyruvate oxidation and the Krebs cycle take place in the matrix (fluid) of the mitochondria, while the electron transport chain takes place in the inner membrane itself.

During both the Krebs cycle and aerobic glycolysis, hydrogen ions are produced which, if left unchecked, would cause cells to become too acidic. The Krebs cycle tackles this problem by transferring the hydrogen ions (acid) to the electron transport chain (third stage) where the acidity issue is dealt with while enabling the aerobic system to continue resynthesising ATP.

To summarise, the key steps of the Krebs cycle are:

1. acetyl coenzyme A enters Krebs cycle
2. acetyl coenzyme A is broken down into carbon dioxide and hydrogen ions
3. 2 ATP are synthesised and made available to fuel muscle contraction
4. hydrogen ions are transferred to the electron transport chain (Stage 3).

Stage 3: Electron transport chain

The electron transport chain (see Figure 1.10) is a series of biomechanical reactions during which free energy contained within hydrogen (derived from the Krebs cycle) is released, so that it can be used to synthesise ATP during aerobic metabolism. The electron transport chain occurs in the many cristae in **mitochondria**. Each reaction involves a specific electron-carrier molecule which has a particular attraction for hydrogen. The final link in the electron transport chain is oxygen, which combines with the hydrogen and electrons to form water. The electron transport chain produces 34 ATP for every molecule of glucose used.

The key steps of the electron transport chain are:

1. hydrogen ions from the Krebs cycle are carried to the electron transport chain by carrier molecules
2. hydrogen ions undergo a series of chemical reactions
3. a hydrogen ion gradient is created – as hydrogen ions move across this gradient adenosine diphosphate (ADP) is phosphorylated (adds another phosphate group) to form ATP
4. water is created as a by-product.

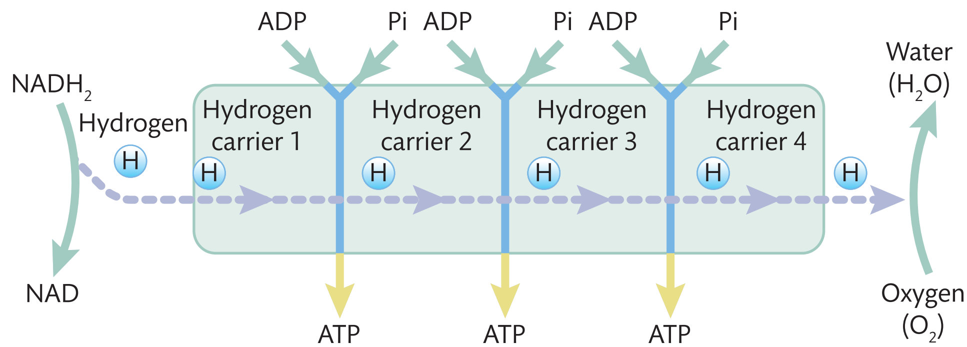


Figure 1.10: The electron transport chain

ATP yield for each system

Each energy system produces a different amount of ATP, shown in Table 1.2.

Table 1.2: ATP yield for each energy system

Energy systems	ATP yield per molecule of glucose
Aerobic glycolysis	2 ATP
Krebs cycle	2 ATP
Electron transport chain	34 ATP
Anaerobic glycolysis	2 ATP

Energy system continuum

Energy systems are viewed as a continuum. High-intensity exercise lasting 8–10 seconds requires the ATP-PC system to meet the energy demands. As the duration increases the intensity of the demand decreases and the lactate system is used. The point at which blood lactate builds up so it prevents effective muscle contraction occurs between 30 seconds and 3 minutes depending on the intensity of exercise and the fitness of the athlete. This point is known as the onset of blood lactate accumulation or OBLA (see the next section for more about this). Once the duration of exercise goes beyond 3 minutes, the majority of energy comes from the aerobic system.

However, while the energy continuum looks at the three energy systems as separately engaged entities, in reality this is not the case. Providing energy for resynthesis of ATP involves all the systems operating at once. For example, at rest the majority of the energy demands are met by the aerobic system, with the ATP-PC and lactate system playing small roles. During intense exercise the demands for energy increase dramatically and the ATP-PC and lactate systems play a more active role to supply the energy needed as anaerobic sources can supply energy at four times the rate of aerobic sources. It is therefore the duration and intensity of exercise that governs which of the energy systems resynthesise ATP at the required rate.

Table 1.3 gives some examples of the three energy systems, their duration and their uses.

Table 1.3: The three energy systems, their duration and their uses

Energy system	Fuel	Duration	Intensity	By-products	Sporting example
Phosphocreatine	Phosphocreatine (PC)	8–10 seconds	High	Free creatine	100 metres/short sprints
Lactic acid/anaerobic glycolysis	Carbohydrate	30–90 seconds	Medium	Lactic acid and associated H+	400 metres/repeated runs in football or rugby
Aerobic	Carbohydrate, fat, protein	Hours	Low	CO_2 and H_2O	10,000 metres/mountain hike

Onset of blood lactate accumulation (OBLA)

OBLA is the level above which blood lactate is produced faster than it can be used aerobically. OBLA occurs when the concentration of blood lactate reaches approximately 4 mmol/L. Continued exercise above the lactate threshold results in the accumulation of hydrogen ions in muscle tissue, causing fatigue and intramuscular pain.

Recovery time for each system

Approximate recovery times for each system are outlined in Table 1.4. However, it should be stressed that recovery rates are very much dependent on the duration and intensity of the exercise undertaken.

Table 1.4: Energy system recovery times

Energy system	Fuel	Recovery period
Phosphocreatine	Phosphocreatine (PC)	Approximately 180 to 240 seconds to replenish Phosphocreatine (PC) levels
Lactic acid/anaerobic glycolysis	Carbohydrate	2–10 minutes will allow removal of most lactic acid produced
Aerobic	Carbohydrate, fat, protein	60–180 seconds – an athlete showing signs of fatigue will require longer to recover and replenish muscle energy stores

Reflect

Think about your own training and how your fitness levels have improved over time. Do you now understand how your body has adapted to training and why you are able to train or compete?

PAUSE POINT Do you know which energy system you use primarily for your chosen sport?

Hint Is your sport more aerobic or anaerobic? It could be a combination of both.

Extend Try allocating a percentage to each of the three energy systems for your chosen sport.

Assessment practice 1.1

Finlay is a club-level rugby player who has just returned to the sport as a centre after a one-year break due to a fractured right femur. He needs to improve his fitness to resume full training in eight weeks' time. He has joined a gym and has been given the following training programme to increase his fitness levels:

- Monday: 20–30 minutes continuous running
- Tuesday: weight training (lower body)
- Wednesday: rest day
- Thursday: 20–30 minutes continuous rowing
- Friday: weight training (upper body)
- Saturday: 20–30 minutes walking in morning

1. Explain how this programme will increase the strength of Finlay's bones.
2. How is the programme designed to decrease Finlay's resting heart rate?
3. Explain how Finlay's nervous system can control the force exerted by his muscles during weight training sessions.
4. Finlay underwent a series of fitness tests at the beginning and the end of his fitness training programme. His test results at the end showed an increase in his VO_2 max and tidal volume. Explain the impact of the training on Finlay's cardiovascular and respiratory systems and explain how this might affect his future rugby performances.
5. After the programme, Finlay commented that he felt much stronger and had noticed an increase in muscle size and definition. Explain how the programme caused Finlay's energy systems to adapt. What further adaptation of his endocrine system could also explain his increased muscle definition and size?

B Fatigue and how the body recovers from exercise

Exercise places demands on the body. Fatigue is the exhaustion of muscle from prolonged exertion or over-stimulation. We cannot exercise indefinitely because of neuromuscular fatigue, which occurs as a result of the different causes and systems explored in this learning aim. For example, during short-term maximal exercise, insufficient oxygen and/or increased lactate levels can bring about fatigue – reliance on anaerobic metabolism impairs energy transfer via glycolysis and inhibits the contractile mechanisms of muscle fibres.

Case study

Fatigue

It is not uncommon to hear of Tour de France riders suffering while riding its many stages, but what does this suffering actually entail? The 180 km plus stages require constant physical exertion for several hours at a time, resulting in sore or aching muscles, cramp, lack of energy and difficulty breathing. The riders must consume around 6000 calories and many additional litres of fluid per day. Despite the hours in the saddle, many of the stages end with a sprint to the finish when the riders approach speeds up to 60 km/h.

Check your knowledge

6 What visual clues might indicate a cyclist is suffering from fatigue?

7 How might a cyclist try and combat the onset of fatigue during a race?

8 What processes might coaches employ to help a cyclist recover from fatigue after a race?

Causes of fatigue

Depletion of energy sources

One of the causes of fatigue is when your body suffers from depleted energy sources, denying it the energy it needs in order to function effectively.

- Fatigue can result from a fall in the amount of **phosphagen**. Phosphagen is synthesised in the liver and transported to skeletal muscles for storage. It is used to form ATP from ADP and is particularly important for intense efforts of physical exercise. A fall in this will lead to less ATP in the bloodstream.
- Another cause is a reduction in **muscle and liver glycogen and blood glucose** during submaximal exercise. Once glycogen stores are depleted, muscles cease contracting – even during steady-state exercise – as the body is unable to use fat as the only fuel source. Marathon runners must be careful not to deplete their glycogen stores early in a race by setting off too fast, so that they can run at a pace that metabolises fats so the rate of glycogen depletion is reduced.

Triathletes often suffer from fatigue as they finish an event

Accumulation of waste products

The main waste products of exercise are urea, carbon dioxide, water and lactic acid. Urea and water are filtered through the kidneys, while carbon dioxide is carried in the blood to the lungs, into the alveoli and then expelled from the body.

- **Blood lactate accumulation** – during exercise, raised levels of carbon dioxide increase blood acidity, increasing lactic acid which dissociates into lactate and hydrogen ions in blood.
- **Carbon dioxide** – in the blood, carbon dioxide combines with water producing carbonic acid.
- **Increased acidity** – carbonic acid is further broken down into bicarbonate and hydrogen ions. The hydrogen ions contribute to the blood's increased acidity.

Muscle lactate is disposed of first by oxidation to pyruvate and then by dissimilation to carbon dioxide and water. Some blood lactate is taken in by the liver which reconstructs it to glycogen. Remaining blood lactate diffuses back into the muscle to be oxidised then dismantled.

Neuromuscular fatigue

Neuromuscular fatigue is an inevitable after-effect of prolonged exercise. The physical factors employed by the central nervous system (CNS) (e.g. motor units) may, after prolonged exercise, become compromised and reduce their ability to carry out their functions effectively, resulting in a loss of performance.

- **Depletion of acetylcholine** – acetylcholine is a neurotransmitter released to stimulate skeletal muscles and the parasympathetic nervous system. Its effect is short-lived because it is destroyed by acetylcholinesterase, an enzyme released into the sarcolemma of muscle fibres to prevent continued muscle contraction in the absence of additional nervous stimulation.
- **Reduced calcium-ion release** – as part of the sliding filament theory (see page 65), calcium ions are released within the structure of muscle fibre allowing actin and myosin to couple and form actomyosin. If the store of calcium ions is reduced, the ability of the actin and myosin to couple is compromised, preventing continued muscle contraction.

Research

Explain why the mineral calcium is important to help prevent fatigue.

Recovery of energy systems

Once fatigue has set in, a number of processes have to be satisfied before the exhausted muscle can again perform to its optimum level.

Excess post-exercise oxygen consumption (EPOC)

The need for additional oxygen to replace ATP and remove lactic acid is known as 'oxygen debt' or excess post-exercise oxygen consumption (EPOC). The two major components of EPOC are:

- **fast components** (alactacid oxygen debt) – the amount of oxygen required to synthesise and restore muscle phosphagen stores (ATP and creatine phosphate)
- **slow components** (lactacid oxygen debt) – the amount of oxygen required to remove lactic acid from muscle cells and blood.

Bodily processes do not immediately return to normal after exercise. After light exercise recovery takes place quickly but with more intense steady-state exercise it takes time for the body to return to normal.

Fast components

- **Restoration of muscle phosphagen stores** – alactacid oxygen debt (without lactic acid) represents the oxygen used to synthesise and restore muscle phosphagen stores (ATP and phosphocreatine) that have been almost completely exhausted during high-intensity exercise. During the first 3 minutes of recovery, EPOC restores almost 99 per cent of ATP and phosphocreatine used during exercise (see Table 1.5).

Table 1.5: Restoration of muscle phosphagen

Recovery time (seconds)	Muscle phosphagen restored (%)
10	10
30	50
60	75
90	87
120	93
150	97
180	99
210	101
240	102

Key term

Catabolised – the breaking down of molecules into smaller units or components.

- The removal of lactic acid – lactic acid is **catabolised** into lactate and hydrogen ions, and removed, resulting in the feeling of pain or burning sensation in the muscles.

Slow components

The slow component of EPOC concerns the removal of lactic acid from the muscles and the blood. This can take several hours, depending on the intensity of the activity. Around half of lactic acid is removed after 15 minutes, and most is removed after an hour. Once exercise is over, the liver synthesises lactic acid into glycogen via a process called gluconeogenesis. This process is one of several mechanisms used by the body to maintain blood glucose levels while the remainder of the body can remove small amounts of lactic acid through respiration, perspiration and excretion.

- Myoglobin is an oxygen-storage protein found in muscle. Like haemoglobin, it combines with oxygen while the supply is plentiful, and stores it until the demand for oxygen increases. During exercise the oxygen from myoglobin is quickly used up, and after exercise additional oxygen is required to replace any oxygen that has been borrowed from myoglobin stores.
- The replenishment of muscle and liver glycogen stores depends on the type of exercise. Short-distance, high-intensity exercise may take two or three hours, whereas long endurance activities such as a marathon may take several days. Replenishment of glycogen is most rapid during the first few hours after training. Complete restoration of glycogen stores is accelerated with a high carbohydrate diet.

Nutritional strategies to help recovery

Adequate **protein intake** is essential to aid recovery, particularly for strength training when muscle tissue requires repair after training or exercise. Protein can also be metabolised for energy, so it is also useful for energy-demanding aerobic endurance sports. Protein requirements generally form 20 per cent of dietary intake, which is often enough to repair any micro-tears resulting from training or exercise.

Carbohydrate requirements are dependent on the fuel needs of an athlete's training or performance levels. As the body's carbohydrate storage is limited, athletes are encouraged to plan their carbohydrate intake around training and competition and, given the requirements as an exercise fuel, carbohydrates generally account for approximately 70 per cent of dietary intake.

Athletes should always begin exercise or training in a well **hydrated state** to prevent fatigue. Immediately after exercise, athletes should drink according to thirst and not drink too much fluid too quickly.

Research

In groups, research the commercially available dietary supplement products, such as protein shakes and carbohydrate drinks/gels, designed to help athletes recover after exercise. What do these products contain that helps athletes with the recovery process? Discuss your answers.

PAUSE POINT Why is it important for coaches and sport scientists to understand the impact and consequences of fatigue?

Hint Think about the potential negative effects of fatigue that may impair future training and performance.

Extend What steps can a coach or sport scientist make to counteract fatigue immediately after training or competition?

Recovery of musculoskeletal system

After exercise, the musculoskeletal system also takes a while to recover due to the number of potential fatigue factors.

- **Replacement of collagen in tendons and ligaments** – tendons and ligaments are made of collagen. When the body undergoes a period of exercise, these are placed under forces due to muscle contraction and body locomotion. When tendons and ligaments are damaged or stressed, the body produces collagen to heal them. However, tendons and ligaments have a poor blood supply, resulting in the potential for neither to heal completely. To help avoid sprains or strains of tendons or ligaments, which often require prolonged periods of recovery, it is important to perform appropriate stretching techniques before and after exercise.
- **Replacement of calcium in bones** – physical activity increases bone density throughout the body, not only in the bones being stressed during exercise. Bone hypertrophy is stimulated by the amount of loading placed on the skeletal system rather than the frequency of loading. Therefore, weightlifters will have a greater bone density than marathon runners. In both cases, exercise stimulates the release of calcium and vitamin D as part of the process of ossification, which increases bone strength and density.
- **Repair to micro-tears in muscles** – exercise places stress on muscles, leading to tiny tears in the muscle fibres. These tears will cause some pain and swelling in the muscle tissue. Protein is needed to build and repair these tears, making the muscle tissue stronger.
- **Delayed onset of muscle soreness (DOMS)** – DOMS is muscular discomfort which develops 24–48 hours after exercise. Research suggests it is caused by structural damage to muscle cells or inflammatory reactions in and around the muscle tissue. It is recommended that exercise is not resumed until the effects of the DOMS has worn off. Experienced athletes are less susceptible to the effect of DOMS unless their training programme undergoes changes.

Over-training

Link

This section links to *Unit 3: Applied Sport and Exercise Psychology* (pages XX–XX).

Over-training is exercise at a level beyond normal physical tolerance limits, meaning the body is unable to recover adequately during rest periods. Over-trained athletes often complain of tiredness, lack of motivation and difficulty sleeping. Over-training can be caused by exercise addiction (a state of dependence on the feelings associated with exercise) and an imbalanced training programme concentrating on one area of training.

Physiological effects of over-training

There are three main physiological effects of over-training.

- **Imbalance in the endocrine system** – exercise requires the constant input of the endocrine system to release hormones to control important body functions. Over-training disrupts the endocrine system, resulting in the production of too much or too little of the various hormones secreted which can have knock-on effects on the digestive and nervous systems.
- **Excess adrenaline and cortisol production** – a periodised training programme allows adrenaline and cortisol levels to return to a normal state. In contrast, over-training is associated with imbalances or elevated levels of adrenaline and cortisol, leading to a suppressed immune system and reduced capacity to exercise before fatigue sets in.
- **Insufficient rest periods to repair muscular and skeletal tissues** – adaptation to training will only result in performance gains if the body is provided with adequate rest and training. In over-training there is insufficient rest and little or no adaptation in terms of muscle or bone growth.

Link

Periodised training is covered in *Unit 8: Specialised Fitness Training.*

Impact on performance and body system

Over-training has an impact on performance and body systems in the following ways.

- **Decrease in performance level** – over-training leads to performance decline, fatigue and sluggishness, prolonged recovery after competitive events, and an inconsistent level of performance.
- **Decreased immune function** – excessive training impacts the number and function of immune system cells such as white blood cells and antibodies. Inadequate rest increases the danger of infection, especially in the respiratory tract.
- **Increased susceptibility to injury** – the physiological effects associated with over-training combine with insufficient rest and recovery to increase the risk of injury. Overuse injuries can occur, such as microtrauma to muscle tissue, bone tissue or connective tissue.

- **Disruption to sleep** – over-training can lead to a hormonal imbalance (raised cortisol and adrenaline levels) which can disrupt sleep patterns. Normal sleep patterns are essential for the body to recover and repair itself.

PAUSE POINT Do you think over-training is more of an issue for athletes who train alone (without a coach)?

Hint A coach should notice the tell-tale signs of over-training and implement the required changes or rest.

Extend What strategies would you suggest to help an athlete who trains alone to check or watch for the signs of over-training?

Assessment practice 1.2

Amy took part in a cycling event that covered 300 miles. The event was made up of three stages on consecutive days.

- Stage 1 – 100-mile daytime across mostly flat terrain with the occasional slight incline
- Stage 2 – 100-mile daytime ride over hilly terrain (climbs and descents) for the middle 50 miles, with the 25 miles either side relatively flat. The final mile of the stage was a steep incline (10 per cent gradient)
- Stage 3 – 100-mile daytime ride across mostly flat terrain; the last 20 miles were by the coast, with strong cross winds.

Approximately two hours before each stage Amy consumed a large healthy meal with plenty of complex carbohydrates. During each stage, which lasted 5–6 hours, Amy consumed carbohydrate gels at hourly intervals.

1 Explain why Amy needed to consume a large healthy meal with plenty of carbohydrates before each stage and why she had carbohydrate gels every hour during each stage.

2 Explain why Amy's legs felt sore during the hill climbs (especially during Stage 2) compared to the flat stretches.

3 Explain why Amy had to take deep breaths throughout her slow, steady hill climbs during Stage 2, but was able to breathe relatively easily on the flat terrain.

4 The morning after completing Stage 3, Amy's legs were tired and her leg muscles were sore. Justify why the muscles in her legs were sore despite her obvious levels of physical fitness.

C Adaptations of the body systems to exercise

The body adapts to exercise with permanent changes that take place as a result of long-term exercise. If you exercise regularly, your body adapts and you get fit. This means you are able to cope with exercise that previously you might have found difficult, allowing you to cope with your chosen sport.

Link

There is more information on these body systems in *Unit 2: Functional Anatomy*.

Skeletal system adaptations

The skeletal system makes several adaptations in response to long-term exercise, shown in Table 1.6.

Table 1.6: Skeletal system adaptations to long-term exercise

Adaptation area	Description
Osteoblast, osteoclast and osteocyte activity	• **Osteoblasts** migrate to the surface of the bone, making it more dense allowing the manufacture of new cells at the outer layer known as the periosteum. Weight-bearing exercise increases the width, density and strength of bones. In long bones, osteoblasts carry out **ossification**, which transforms fibrous tissue or cartilage into bone. • **Osteoclasts** are cells that destroy bone and reabsorb calcium and play a key role in **bone remodelling**, helping to regulate bone growth. Weight-bearing exercise suppresses osteoclast activity, maintaining a healthy bone density. • Exercise and an adequate diet containing sufficient calcium and vitamin D are essential for ossification.
Mineral content	Long-term exercise slows skeletal ageing. People who maintain active lifestyles have greater bone mass. Exercise of moderate intensity provides a safe and potent stimulus to maintain and increase bone mass.
Collagen and increased tendon strength	Collagen is a fibrous protein found in all connective tissue. It is the most common protein in the human body, giving bone its flexibility and helping bone resist tension (i.e. weight-bearing exercise). Weight-bearing exercise causes micro-tears to connective tissue and the body adapts by regenerating new tissues made of protein that is mostly collagen.

Muscular system adaptations

There are several different muscular system adaptations that the body makes to exercise (see Table 1.7).

Table 1.7: Muscular system adaptations to long-term exercise

Adaptation	Description
Hypertrophy	An increase in muscle size from training with greater resistance. Increases cross-sectional size of existing muscle tissue due to increases in the number of myofibrils and connective tissue (tendons and ligaments), which then become more pliable.
Increase tendon strength	As skeletal muscles become larger, stronger or more efficient, connective tendons adapt to meet increased demands to avoid injury from increased forces of contraction.
Muscle tone	An unconscious low-level contraction of muscle tissue while at rest, achieved via an effective training programme keeping muscle tissue primed. This state of constant muscle activation helps maintain balance and posture, and allows for quick reflex actions.
Muscle endurance	Endurance training improves muscular endurance by increasing the number of capillaries per area of muscle tissue, increasing oxygen supply to the muscle.
Hyperplasia	The action of splitting muscle cells contributing to muscle growth (different from hypertrophy which increases the number of individual cells). Research into hyperplasia continues, and it remains controversial and limited evidence suggests it is a recognised adaptation.
Increased mitochondria	With training, muscles increase oxidative capacity through an increase in the number of mitochondria in the muscle cells, an increased ATP supply and an increase in the quantity of the enzymes involved in respiration.
Increased myoglobin stores	With training, muscles increase their ability to store glycogen and myoglobin.
Increased storage of glycogen and triglycerides	With training (especially steady-state exercise), muscles increase the ability to store and use both triglycerides and glycogen as energy stores.
Adaptation of muscle fibres	Exercise leads to an increase in number and size of mitochondria within Type I and some Type IIa fibre cells. This improves muscle fibres' oxidation ability and their capacity to use oxygen. Strength training for Type IIx and some Type IIa muscle fibres can increase the number of contractile proteins (actin and myosin) and increase the recruitment of these fibres.
Capillarisation	Exercise enables muscle tissue to increase capillary density, supplying muscles with increased amounts of oxygen, and to remove more carbon dioxide, allowing greater exercise intensity and endurance.

PAUSE POINT What do you think happens to the skeletal or muscular adaptations of an athlete once they retire from competition?

Hint Would you expect atrophy if training is not maintained (a decrease in bone density, muscle size and tendon elasticity)?

Extend Investigate how retired athletes try to maintain some degree of fitness after retirement.

Key term

Minute ventilation – also known as minute volume = tidal volume × frequency of breaths per minute.

Respiratory system adaptations

Table 1.8 outlines the three main adaptations that the respiratory system makes to long-term exercise.

Table 1.8: Respiratory system adaptations to long-term exercise

Adaptation	Description
Respiratory muscle efficiency	An increase in strength allows the external intercostal muscles greater contraction, while internal intercostal muscles relax during inspiration, forcing more air into the lungs. The greater the degree of contraction of the internal intercostals and relaxation of the external intercostals, the greater the volume of air inspired.
Lung volume adaptations	• Tidal volume can increase dramatically, to approximately 1litre for an average adult and 2 litres for an elite athlete. • Vital capacity can increase allowing for deeper and more oxygen-rich breaths. Residual volume is also likely to increase in proportion to this increase. • Trained athletes' **minute ventilation** can increase by 50 per cent to 150 litres per minute.
Respiratory rate	As exercise continues, the body adapts by increasing respiratory rate (breaths per minute and depths of breath) to aid delivery of more oxygen to the working muscles. However, over time the tidal volume of athletes undertaking long-term exercise increases, so their respiratory rate can decrease for normal breathing but has the capacity to process increased amounts of oxygen at higher breathing rates.

Cardiovascular system adaptations

Table 1.9 outlines the four main areas and parts of the cardiovascular system that make adaptations to long-term exercise.

Table 1.9: Cardiovascular system adaptations to long-term exercise

Area	Description of adaptation
Cardiac cycle	• Heart size increases, particularly the chambers, allowing a greater stroke volume and a lower resting heart rate. This leads to a greater cardiac output, allowing the athlete to more easily continue working at a certain intensity. • The increased size of the left ventricle (cardiac hypertrophy) also lowers systolic blood pressure as less arterial pressure is needed to pump an increased volume of blood through the aorta. This also increases cardiac output. • Increased blood flow leads to an increase in blood volume. • Increased stoke volume and cardiac hypertrophy leads to a fall in resting heart rate. • Overall, the cardiovascular system becomes more efficient and able to deliver a greater volume of oxygen and nutrients to working muscles.
Sinoatrial node	Training causes an increase in the parasympathetic activity of the heart, decreasing the sinoatrial node's firing rate and slowing or lowering resting heart rate.
Blood composition	• Exercise raises the amount of proteins in blood plasma causing water retention and elevating blood volume. • Exercise also increases the number of red blood cells within the body. Elite athletes have a proportionally greater number of red blood cells. This enhances the ability to transport oxygen to working muscles during exercise. In trained males, blood volume equates to approximately 75 ml per kg of bodyweight, and in females it is approximately 65 ml per kg of bodyweight.
Diffusion rate	Long-term exercise can lead to the development of a capillary network to a part of the body. Aerobic training improves capillarisation of cardiac and skeletal muscles by increasing the number of capillaries and their density (the number of capillaries in a given area of muscle tissue), allowing for greater diffusion of oxygen from the blood to the tissues and greater removal of carbon dioxide.

Neuromuscular system adaptations

Table 1.10 outlines the three adaptations that the nervous system makes to long-term exercise.

Table 1.10: Nervous system adaptations to long-term exercise

Adaptation area	Description
Motor units	The ability of a motor unit to summate (fire a lot of impulses in target muscles all at once) is improved with strength and power training as they require maximum activation of target muscles to create the desired force.
Neural pathway transmission efficiency	Changes include **cellular adaptations**, modifications of neurotransmitters, alterations in reflex, and chemical and biochemical responses. For example, sprint training actually produces relatively small metabolic changes but has substantial effects on performance.
Nervous inhibition	Training is known to decrease nervous inhibition which itself is a response of the central nervous system to feedback sent from the muscle tissue. Nervous inhibition prevents the muscle from overworking and potentially ripping itself apart as the muscle undergoes levels of force it is not used to.

Key term

Cellular adaptations – changes within the cell structure (for example, an increase in mitochondrial size).

PAUSE POINT Can you think of a situation where a decrease in nervous inhibition leads to negative implications for an athlete?

Hint Consider what may happen during intense exercise or competition that may cause injury or trauma to an athlete.

Extend Research any high-profile sudden injury cases that resulted in unexpected muscle tears or other tissue damage.

Endocrine system adaptations

The endocrine system produces chemical messages in the form of hormones, which are carried by the bloodstream to tissues or organs throughout the body. These messages include signals for either an increase or decrease in tissue or organ activity. During exercise, adrenaline, noradrenaline and cortisol function together to synthesise fuel for the production of ATP. There are three adaptations that the endocrine system makes to long-term exercise, as shown in Table 1.11.

Table 1.11: Endocrine system adaptations to long-term exercise

Adaptation area	Description
Adrenaline and noradrenaline secretion	These enhance cardiac output by increasing heart rate, vasodilation in targeted blood vessels and increasing blood pressure. In strength and endurance training these direct blood flow to the tissues that are being exercised. Long-term exercise makes this system more efficient and increases the body's capacity to secrete both into the bloodstream.
Cortisol	Cortisol enhances muscle tissues by increasing blood glucose levels to provide quick bursts of energy. However, cortisol is 'catabolic' and interferes with anabolic functions. If the body remains in a catabolic 'breakdown' state this can lead to a decrease of muscle tissue, immunity is lowered and imbalances in blood sugar levels develop. However, strength training can lead to an increase in cortisol at rest which enables an increased supply of blood glucose for the next exercise session.
Testosterone and HGH	Testosterone and human growth hormone (HGH) are the two hormones primarily involved in strength training adaptations. Testosterone aids the release of HGH and interacts with the nervous system. Research indicates strength training increases the frequency and volume of both testosterone and HGH secretion, which, in turn, increases muscle hypertrophy. Strength training can increase the HGH at rest which enables an increase in strength capabilities for the next training session.

Discussion

Do you think it is acceptable for athletes to take legal ergogenic aids (any product that gives them a physical benefit) that might raise their testosterone levels for training and competition? What physical benefits do you think may occur as a result of taking such aids?

Energy systems adaptations

Table 1.12 outlines the five adaptations that the energy system makes to long-term exercise.

Table 1.12: Energy systems adaptations to long-term exercise

Adaptation area	Description
Increased anaerobic and aerobic enzymes	Cellular adaptation, such as an increase in number and size of mitochondria, is usually accompanied by an increase in the level of aerobic system enzymes, which enhances the ability of slow-twitch muscles to generate adenosine triphosphate (ATP), allowing an athlete to sustain prolonged periods of aerobic exercise. The anaerobic system also undergoes changes, including an increase in the intramuscular levels of ATP and an increase in the enzymes (especially in fast-twitch muscles) that control the anaerobic phase of glucose breakdown.
Increased stores of phosphocreatine (PC)	An adaptation of strength training in particular is an increase in muscle cells' ability to store phosphocreatine (PC), enabling short burst of high-intensity exercise.
Decreased stores of triglycerides	Research shows that individuals who exercise regularly have lower blood levels of triglycerides than sedentary individuals.
Increased use of fats	The use of fats as an energy source occurs during low-intensity exercise. Fat combustion powers almost all exercise at approximately 25 per cent of aerobic power. Fat oxidation increases if exercise extends to over an hour as glycogen levels deplete. Beyond an hour, fats account for approximately 75 per cent of total energy required.
Higher tolerance of lactic acid	As you get fitter, oxygen is used to break down lactate to carbon dioxide and water, preventing lactate from pouring into the blood. Low lactate threshold can be due to: • not getting enough oxygen inside your muscle cells • inefficient lactate buffering (i.e. carnosine and phosphate) • insufficient mitochondria in your muscle cells • muscles, heart and other tissues being inefficient at extracting lactate from the blood. Long-term exercise saturates muscles in lactic acid, training your body to deal with it more effectively. The accumulation of lactate in working skeletal muscles is associated with fatigue after 50–60 seconds of maximal effort. Therefore, training continuously at about 85–90 per cent of your maximum heart rate for 20–25 minutes improves the body's tolerance to lactic acid. For example, a sedentary individual's OBLA will activate around 50–60 per cent of VO_2 max, whereas a trained athlete's OBLA will activate around 70–80 per cent of VO_2 max. Given a trained athlete will have a higher VO_2 max anyway, the increase in OBLA for trained athletes can be quite significant. Long-term exercise can lead to an ability to exhale an increased level of carbon dioxide during intense exercise delaying OBLA. This process causes the respiratory exchange ratio (RER) to exceed a normal value of 1.00 (i.e. equal inhalation/exhalation ratio of oxygen/carbon dioxide).

Measurement of body systems and their contribution to sport and exercise performance

Measurement of body systems can provide an indication of current fitness levels and, if previous baseline tests have been undertaken, any increase in fitness levels (for example VO_2 max) can be determined along with an estimate of the impact of a training programme (see Table 1.13).

Link

You can read more about measuring body systems in *Unit 4: Field- and Laboratory-based Fitness Testing*.

Table 1.13: Body systems that can be tested to measure fitness

Body system	Description
VO_2 max	This is one of the best indicators of cardiovascular fitness. Increased VO_2 max indicates a high rate of absorption and use of oxygen, giving the potential to train at higher intensities before muscle tissue demand for oxygen exceeds supply. High VO_2 max indicates a very efficient cardiovascular system, allowing for increased endurance performance and more rapid rates of recovery post-exercise. Weight-bearing exercises (e.g. running) significantly influence VO_2 max levels, while non-weight-bearing (e.g. swimming) have comparatively less influence.
Anaerobic threshold (% of VO_2 max)	Continued high volume and intensity of endurance exercise is further likely to improve an athlete's anaerobic threshold. This is when the blood concentration of lactate and hydrogen ions increase as the body's requirements become more reliant on the lactate energy system to meet the intensity demands of the exercise. Athletes with a high VO_2 max who undertake regular intensive exercise can tolerate increasingly higher levels of blood lactate than athletes with a lower VO_2 max.
Anaerobic power	This can be increased by either sprint (or speed) training or power training. Maximal sprint or power training overloads ATP-PC and lactate energy systems and can be measured using sprint tests. This enhances anaerobic metabolic capacity of the muscles being trained, allowing an athlete to train and perform at higher intensities.
Strength (1RM)	Strength training results in structural and functional adaptations to the body (muscle tissue in particular). These adaptations depend on the amount of training undertaken, but the strength, measured by 1RM, will have increased for the muscle group in question and so the 1RM can be used to measure adaptations over time.
Muscular endurance (15RM)	The level of adaptation can be measured in the ability of the muscle to contract repeatedly for 15 repetitions at a given weight or resistance.

VO_2 max tests can be done in a laboratory to measure cardiovascular fitness improvements

PAUSE POINT Explain how persistence with training can be measured and demonstrate an increase in fitness over time.

Hint Depending on the type of training, which measurement or test might you use to determine fitness level increases?

Extend Can training increase two or more body system measurements during the same period? Justify your answer.

Assessment practice 1.3

Finlay, the rugby player featured in Assessment practice 1.1, has now undergone three months of rugby training since he completed his initial eight-week fitness programme at the gym. The rugby training includes:

- 4 × weekly session of rugby drills
- 2 × strength and power sessions per week
- 1 × intense sprint interval session per week
- 1 × 45 minute continuous run (low intensity) per week.

1 Testing shows that Finlay's resting heart rate has dropped further. Explain how the rugby training has contributed to this.

2 Why might Finlay now be less conscious of his previously fractured femur? How might his rugby training have strengthened his bones further?

Finlay decided to attempt the one-minute press-up test. Upon completion of his fitness training programme at the gym, Finlay completed 38 press-ups. Now he can complete 63.

3 Analyse Finlay's rugby training and suggest a possible explanation for his ability to increase his press-up count to his current performance level.

D Environmental factors and sport and exercise performance

Elite athletes compete and train around the world so need to cope with numerous environmental conditions. Altitude and temperature vary greatly depending on location. For example, golfers could be in Dubai playing in 40°C heat one week and in near freezing conditions in Scotland the next. But these environmental factors can also have an effect on responses to training.

High altitude

Altitude is the measure of elevation above sea level. As altitude increases, atmospheric pressure decreases, leading to a fall in oxygen pressure. Today, it is common for athletes to not only compete but also train at altitude, enabling the body to become more efficient at absorbing oxygen. This is known as **acclimatisation**.

Decreases in oxygen pressure cause the body's chemoreceptors to become more responsive to an increase in carbon dioxide. This leads to an increase in ventilation as the brain attempts to restore gaseous exchange to a normal level. As oxygen is less available at high altitude, this results in lower than normal haemoglobin saturation levels in the blood. At 5000 metres above sea level the oxygen saturation in blood is approximately 70 per cent (compared to 98 per cent at sea level). If an athlete has not acclimatised, the lack of oxygen may seriously impair physical activity. However, most people can ascend to 2400 metres above sea level without difficulty.

Responses of body systems to high altitude

- **Hypoxia** occurs when the body is deprived of oxygen. At high altitude, the demands of the cardiovascular and respiratory systems are increased. Without acclimatisation the body's tissue may become hypoxic and deprived of adequate oxygen.
- **Increased breathing rate** (hyperventilation) involves increased ventilation of the lungs caused by impaired gaseous exchange in the lungs.

- **Increased heart rate** (possible tachycardia) – tachycardia is a resting heart rate above normal (more than 100 beats per minute). High altitude causes only a minimal reduction in resting stroke volume, but a decrease in maximal heart rate response lowers cardiac output.
- **Reduced VO_2 max** – there is an estimated reduction in VO_2 max of 2 per cent for every 300 metres above 1500 metres above sea level. This drop in VO_2 max means an athlete's oxygen uptake decreases which will (without acclimatisation) adversely affect performance, particularly during endurance events.
- **Altitude sickness** – an illness brought on by an ascent to high altitude and characterised by a shortage of oxygen leading to hyperventilation, exhaustion and nausea.

Adaptations of the body systems to high altitude

During acclimatisation, generally over a period of two or more weeks, there is an increase in red blood cell count and haemoglobin concentration. This is caused by an increase in the manufacture of red blood cells in bone marrow to carry more oxygen to muscles. Other changes also take place:

- **capillarisation** – to counteract the lower concentrations of oxygen in the blood, the number of small blood vessels in the body increases to ensure that all available oxygen is used efficiently
- **increased mitochondria** – altitude causes an increase in the myoglobin and mitochondria within cells
- **oxidative enzymes** – altitude causes an increase in oxidative enzymes in mitochondria. This allows Type I and Type IIa muscle fibres to process increased levels of oxygen for use with the aerobic energy system.

Acclimatisation during training may not always be possible, so there are alternative training options that promote equivalent adaptations to enhance sport and exercise performance at sea level.

- **Hypoxic (altitude) chambers** – these are used to simulate the effects of high altitude on the human body.
- **Sleep high, train low** – the body adapts to sleeping at high altitude with low oxygen levels, while training at a low altitude where the oxygen levels are much higher. This allows the body to benefit from the benefits of being at high altitude (increase in blood cell production) without interfering with a training programme.
- **Aerobic performance** – exercise performance (aerobic) is enhanced due to the red blood cells becoming more efficient at uploading oxygen to tissues.
- **Anaerobic performance** – exercise performance (anaerobic) is enhanced due to an increase in OBLA because of changes in the acid/alkali balance in the blood.

Hypoxic or altitude chambers can be used to help athletes acclimatise while training at sea level

Discussion

Do you consider altitude training to be performance enhancing? What are the differences between altitude training and blood doping?

Key term

Homeostatic response – the body's attempts to maintain a condition of balance within its internal environment, such as its temperature, even when faced with external changes or challenges.

Thermoregulation

The body's thermoregulatory system enables a **homeostatic response** to temperature changes. During exercise, the metabolic rate can increase twenty-fold and this increase in energy consumption raises body temperature significantly.

The body tackles this via the hypothalamus, the body's thermostat. The hypothalamus contains the central point within the body for temperature regulation. A group of specialised neurons at the base of the brain helps regulate body temperature within a narrow band around 37°C. The hypothalamus receives a generous blood supply allowing it to monitor body temperature and initiate a response when temperature changes.

The body loses heat through a combination of:

- **convection** – the process of water or air flowing over the skin and carrying away body heat
- **conduction** – involves heat moving from or to the body from its surrounding air. The faster cooler air moves around the body, the greater the quantity of heat conducted from the body
- **radiation** – the transfer of heat from one object to another without contact. Through radiation, an athlete radiates heat towards cooler objects. The closer the two temperatures (the athlete and the object), the less heat the athlete loses. At rest, radiation is the main method of losing body heat
- **evaporation** – water vaporisation lost through breathing or sweating transfers heat from the body to the surrounding environment – this is the body's major defence against overheating. In response to overheating, the sweat glands secrete lots of saline solution (NaCl dissolved in water) forming sweat. The cooling process occurs when sweat reaches the surface of the skin and evaporates.

Excessive heat

There are two main responses that the body makes to excessive heat during sport and exercise performance.

- **Hyperthermia** – this occurs when the body cannot lose excess heat. Early symptoms include excessive sweating, headache, nausea, dizziness and hyperventilation. Overexposure to hot and humid conditions can lead to normal heat loss processes becoming ineffective. A core temperature greater than 40°C increases metabolic rate, increasing heat production. The skin becomes hot and dry and the temperature rise risks organ damage. To combat this, cool the body in water and administer fluids.
- **Dehydration** – excessive water loss. When water output exceeds intake, the body has a negative fluid balance. A serious consequence is a lowering of blood plasma levels leading to inadequate blood volume to maintain cardiovascular function. It is avoided by drinking plenty of water. When a large amount of water is lost through perspiration, causing possible salt depletion, it is vital to maintain electrolyte balance. This can cause further symptoms including tiredness, irritability, fainting, cramps and loss of performance.

Competitors in the Marathon des Sables need to avoid hyperthermia or dehydration

During sport and exercise performance, the body can respond and adapt to excessive heat in various ways, including:

- **increased sweat production** – to enable the loss of excess heat the body increases its sweat production, allowing greater evaporation. However, it is important you remain properly hydrated and that electrolyte levels remain stable
- **reduced electrolyte concentration due to sweating** – during excessive periods of sweating, electrolytes are lost and must be replaced. Failure to do so may lead to inhibited nervous function and, in extreme cases, can be fatal
- **increased blood plasma volume or earlier onset of sweating** – a benefit of heat acclimatisation is an increase in blood plasma volume. Just as altitude training stimulates the body to produce more red blood cells, training in locations with a high temperature stimulates the body to produce more plasma. The result is a greater cardiac output, and higher VO_2 max
- **reduced aerobic and anaerobic performance** – the body cools down by circulating blood through the skin. This diverts blood from the muscles, which in turn increases heart rate. If the temperature is high the body needs to circulate more blood to the skin, depriving muscles of much-needed oxygen and nutrients. This will have an impact on both aerobic and anaerobic performance.

Extreme cold

The body has several methods for reducing heat loss during sport and exercise performance in extreme cold conditions:

- **vasoconstriction** reduces the amount of convection heat transfer from the skin and concentrates the remaining heat in and around the body's core (its vital organs)
- **shivering** is a response to feeling cold. When the core body temperature drops, a shivering reflex is triggered to maintain homeostasis. Skeletal muscles will shake in small movements, creating warmth by expending kinetic energy
- **shivering thermogenesis** is the fastest thermogenic process a static body can produce and involves a series of involuntary muscle contractions producing heat in response to a cold environment. The conversion of chemical energy of ATP into **kinetic** energy causes some of this kinetic energy to be transferred as heat
- **non-shivering thermogenesis** occurs in brown adipose tissue and involves a series of complex cellular reactions which enable energy from free fatty acids to be dissipated within the body as heat.

Key term

Kinetic – relating to or resulting from motion.

The main effects of extreme cold on the body during sport and exercise performance are:

- **hypothermia** – a condition where low body temperature results from prolonged exposure to cold. Breathing, blood pressure and heart rate decrease and drowsiness sets in. If uncorrected, hypothermia can be fatal as body temperature approaches 29°C. Hypothermia develops if the rate of heat loss from your body exceeds the rate at which the body is producing heat
- **frostbite** – this is damage to skin and tissue caused by prolonged exposure to freezing temperatures. The body responds to cold temperatures by vasoconstriction and blood flow to the extremities (hands, feet, ears, nose and lips) slows down, so that blood flow to vital organs can be increased. The tissues in these extremities are deprived of oxygen and the fluid in the tissues freezes into ice crystals causing severe cellular damage. If blood flow cannot be restored quickly, the tissue will die and will need to be removed through surgery.

PAUSE POINT Do you think the type of clothing worn is important when training in hot or cold climates?

Hint Clothing will impact thermoregulation levels in hot and cold climates.

Extend Research the types of sports clothing and how they help thermoregulation in different climates.

Assessment practice 1.4

Consider Amy, the cyclist in Assessment practice 1.2. The climate was different on each stage of the cycling event. During Stage 1 the temperature reached 32°C with 95 per cent humidity. During Stage 3 it was much cooler and, near the coast, the temperature dropped to 10°C with an added wind chill factor.

- Analyse how thermoregulation allows Amy to maintain her core body temperature while cycling in the different conditions.

Further reading and resources

Books

Brooks, D. (2004) *The Complete Book of Personal Training*, Champaign, IL: Human Kinetics.

Coulson, M. (2013) *The Complete Guide to Personal Training*, London: Bloomsbury.

Katch, V., McArdle, W. and Katch, F, I. (2011) *Essentials of Exercise Physiology*, 4th edition, Philadelphia, PA: Lippincott Williams & Wilkins.

Vander, A., Sherman, J. and Luciano, D. (2014) *Human Physiology: The Mechanisms of Body Function*, 7th edition, Boston, MA: McGraw Hill.

Websites

www.eis2win.co.uk – English Institute of Sport: information about the nutritional principles used by the EIS to improve athlete performance.

www.uksca.org.uk – UK Strength and Conditioning Association: information and advice about how to become an accredited strength and conditioning coach.

www.bases.org.uk – British Association of Sport and Exercise Sciences: news and other information about sport and exercise sciences.

THINK FUTURE

Isobel Graham
Personal trainer

When I started my Level 3 BTEC Sport and Exercise Sciences course, I soon took an interest in how the body works and adapts to fitness training and programming. I knew that when I finished I wanted to be a personal trainer, so I took a Level 2 gym instructors award. The content of the BTEC course, especially the exercise physiology, helped me pass the exam. Not long after gaining my Level 2 qualification, I got a part-time job at a local health club while continuing my studies at college.

When I completed the BTEC course, I was able to enrol on a Level 3 Personal Trainer course. This took me approximately 12 months to complete and it was hard work, but I'm now a fully qualified advanced personal trainer and have a list of clients that I train at the same health club, some of whom are competition athletes.

The job is very rewarding and, in addition to all the required specialist knowledge, it's vital to have a good rapport with your clients. It's important to make people feel comfortable and good about themselves. Their health, well-being and achievements are a reflection of my efforts, so I'm very proud of my clients and all they've accomplished in the gym.

Personal training is my dream job. I realised early on in my BTEC course that this was what I wanted to do, and that focus helped me to complete the BTEC and all subsequent courses. I make a good living and I'm just about to put a deposit down on a flat. Would I change anything? Not a thing!

Focusing your skills

Fitness knowledge

Use your knowledge and expertise to the best of your ability and provide the best service you can when developing individual training programmes.

- A personal trainer needs excellent knowledge of how the body moves and functions. This specialised knowledge is based on human anatomy, physiology, psychology, nutrition and exercise programming.
- You are a mixture of coach and teacher to your clients, and must blend long-term goals and motivational techniques into a training programme.
- You will need to develop individual training programmes, all of which are different. This will require the utmost planning, coordination and organisation.

Conducting health monitoring tests

You must follow the correct protocol when undertaking health monitoring tests. These tests give a good indication of a client's level of fitness and whether your programming is having an impact.

- Treat your clients with courtesy and respect. Emphasise that your clients' results are confidential and will not be passed to anyone else without their consent.
- Conduct tests in a suitable environment and in a professional manner. Explain what you are doing and maintain an air of calm authority throughout.
- Upon completion of any test, explain the results and discuss the role they will play in developing any future training programme.
- Ensure the testing area is left exactly as you found it and all equipment is safely stowed away.

Getting ready for assessment

This section has been written to help you do your best when you take your assessment task. Read through it carefully and ask your tutor if there is anything you are still not sure about.

Worked example

Question 1

Adnan has returned to football after a three-year break. He needs to improve his general fitness so he decides to undertake a 12-week training programme at his local gym. His fitness instructor gives him the following programme.

Day	Training task(s)
Monday	20–30 mins running on a treadmill (10–12 km/h)
Tuesday	Resistance machines (upper body)
Thursday	15–20 mins rowing (24–28 strokes per minute); 15–20 mins cycling
Friday	Resistance machines (lower body)
Saturday	20–30 mins cross-country running

(a) Explain how Adnan's fitness training programme might increase his bone strength and/or density. [3]

Look carefully at how the question is set out to see how many points need to be included in your answer.

Adnan's training involves weight-bearing exercises which are known to strengthen bones. He will also use resistance machines which make bones more dense and able to support more weight. This is helped by calcium in the diet.

This answer demonstrates a basic understanding of skeletal adaptations to exercise. Although the learner has not mentioned osteoblast activity, they have shown their knowledge that weight-bearing and resistance exercises strengthen bone tissue and mentioned the role calcium plays in the process. 2 marks awarded.

Upon successful completion of the 12-week training programme, a series of health monitoring tests reveal that Adnan's resting heart rate has dropped from 88 bpm to 77 bpm, and show a significant improvement in his VO_2 max, from 35.2 ml/kg/min to 40.01 ml/kg/min.

(b) Explain why Adnan's fitness training programme has caused a reduction in his resting heart rate and a rise in his VO_2 max value. [5]

Due to the amount of cardiovascular exercise Adnan was doing over 12 weeks, this exercise would have led to cardiac hypertrophy. This means that the heart muscle tissue will have enlarged due to the exercise undertaken. This increase in heart muscle size means the stroke volume would have increased. If the cardiac output stayed the same, then the resting heart rate can reduce. This will have made Adnan fitter and he would have found the cardiovascular exercise easier by week 12.

Adnan's VO_2 max would have increased because of capillarisation. This means that the number of capillaries would have increase in his tissues (due to cardiovascular training) so his blood would be able to deliver more oxygen to the working muscles. This is why his VO_2 max increased.

This answer demonstrates a good understanding of cardiovascular and respiratory adaptation to training and the specific relevance to the client's requirements. The learner takes into account his current level of fitness and explains how the adaptations work in terms of the client's performance. 4 marks awarded.

When Adnan trained his larger muscle groups (chest, back and legs) he used weights of 25, 30, 35 and 40 kg on the resistance machines.

(c) Explain how Adnan's nervous system can control the force generated by his muscles to allow him to use the various weight levels on the resistance machines. [4]

Muscle spindles and Golgi tendon organs provide the information about the intensity of exercise, allowing Adnan to carry out strong and coordinated movement patterns.

This answer demonstrates a basic understanding of the nervous system's adaptations to exercise. Although the learner has not mentioned the process of nervous inhibition, the knowledge of how weight training involves the use of muscle spindles and Golgi tendons is described, but it could be explained in further detail. 2 marks awarded.

Question 2

Gemma is a triathlete who took part in a 1.5 km swim, 50 km cycle ride and 10 km run. Gemma consumed plenty of calories in the form of balanced meals leading up to the event. She consumed carbohydrate gels at hourly intervals during the triathlon, along with plenty of fluids.

(a) Explain why Gemma consumed carbohydrate gels during the triathlon. [3]

Gemma is using mostly the aerobic energy system to complete the triathlon which utilises carbohydrates, fats and proteins extracted from the diet for resynthesising ATP. The aerobic system produces more ATP than any other energy system but does so at a slower rate and is therefore less suitable for intense exercise but ideal for the steady state of a triathlon. The aerobic systems consist of three processes or stages, each of which produce ATP. They are aerobic glycolysis, the Krebs cycle and the electron transport chain. The carbohydrate gels keeps the aerobic energy system continually fuelled with blood glucose to allow for completion of the event and prevents fatigue.

This answer demonstrates an excellent understanding of energy systems and explains why the consumption of carbohydrate gels was important for the triathlon. 3 marks awarded.

(b) The final 5 km of the cycle component was executed on a 3 per cent gradient. Towards the end of this, Gemma's legs started to feel sore. In terms of energy systems, what accounts for this muscle soreness and why did it occur? [3]

The gradient means that Gemma had to work harder on the cycle component. If the gradient was very steep then her muscles would have needed more than the aerobic energy system, and would need to have used the lactate system which makes muscles sore.

This answer demonstrates only a basic understanding of energy systems. The learner identified that the lactate system was engaged to an increasing level at a gradient, but failed to explain what caused muscle soreness (hydrogen ions) or the fact that all energy systems operate at the same time but to differing degrees. 1 mark awarded.

After 6 km of the running stage, Gemma had to climb a steep gradient for 200 m. At the top of the hill Gemma felt breathless, had to slow her running rate significantly and needed to breathe deeply for several minutes.

(c) Explain why Gemma needed to breathe deeply despite slowing her running rate significantly. [3]

The gradient meant that Gemma was working at the limits of her aerobic energy system and probably utilising more of the lactate system. This would produce large volumes of CO_2 in the blood which needs to be expelled. If it doesn't then Gemma will have to stop. The best way to get rid of CO_2 is to breath deeper. Once the breathing rate returns to normal then the excess CO_2 has been expelled.

This answer demonstrates a good understanding of energy systems and the issues surrounding waste products in the blood. The learner understands the basic mechanics of how the body rids itself of excess carbon dioxide. 2 marks awarded.