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Introduction

BTEC National Sport and Exercise Sciences for the Edexcel examination boards is a subject that helps to prepare you for work in the sports industry or for higher education within the fields of sport science and sport.

*BTEC Level 3 National Sport and Exercise Sciences Third Edition* is a comprehensive textbook that covers all mandatory units in the BTEC National Sport and Exercise Sciences qualifications that include:

- National Certificate in Sport and Exercise Sciences
- National Subsidiary Diploma in Sport and Exercise Sciences
- National Diploma in Sport and Exercise Sciences
- National Extended Diploma in Sport and Exercise Sciences

To ensure that you are following the correct pathway for your chosen qualification, please see the table in 'Pathways for BTEC National Sport and Exercise Sciences Qualifications'.

As well as all mandatory units, *BTEC Level 3 National Sport and Exercise Sciences Third Edition* contains many of the more popular optional units that you can take. Some optional units have been provided as PDFs for you to read online or download via Dynamic Learning. For details of these, look for the Dynamic Learning icon on the Contents page. For details about Dynamic Learning and how to access these online units, see the final page of this ebook.

The BTEC National Sport and Exercise Sciences qualifications are all assessed through coursework. You will be given assignments that cover all of the grading criteria for each unit that you are studying. *BTEC Level 3 National Sport and Exercise Sciences Third Edition* will help to show you where you can find the information related to the grading criteria that you are working on, which will help to ensure that you are including the appropriate subject content in your coursework.

Success in this qualification is a combination of your teacher's expertise, your own motivation and ability as a student, and accessibility to the appropriate resources—including a relevant textbook! Written by senior external verifiers and experienced BTEC Sport and Exercise Sciences teachers, *BTEC Level 3 National Sport and Exercise Sciences Third Edition* is highly relevant to your qualification and provides you with resources that will not only support and help you prepare for your assessments, but which will also stretch and challenge you.

Within *BTEC Level 3 National Sport and Exercise Sciences Third Edition* you will find that each unit offers a wide range of learning resources, including:

- **Activities** related to each of the grading criteria to help you to practice assessment activities for your coursework. Each activity has a suggested time-frame so that you will have an idea of how long you need to spend on each.
- **Clear signposting throughout**: each section is clearly signposted with the relevant grading criteria
- **Quick quizzes**: at the end of each learning outcome are a number of short questions to help consolidate your knowledge before you move on to the next section.
- **Learning goals** are placed at the start of each unit to keep you on track with the requirements of the Edexcel BTEC National Sport and Exercise Sciences specification
- **Definition boxes** are provided throughout, giving you clear definitions of complex physiological and technical phrases without you having to look these up in a separate glossary section
- **Useful websites** are suggested at the end of each unit so that you can access these directly to top up your knowledge in important areas of unit content
- **Figures**: Lots of sports photographs and clear illustrations to help bring your learning to life.

*BTEC Level 3 National Sport and Exercise Sciences Third Edition* is written in a clear, highly readable way that will help you to understand and learn about Sport and Exercise Sciences and prepare you and provide information for your assessments in this course.
Pathways for BTEC National Sport and Exercise Sciences Qualifications

To ensure that you are following the correct pathway for the Certificate, Subsidiary Diploma or Diploma in BTEC Sport and Exercise Sciences, please see the table below.

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Selection of three units from choices below

Selection of seven units from choices below

BTEC National for Sport and Exercise Sciences uncorrected first proofs issued by marketing 9/7/2013. This material is © Hodder Education 2013 and should not be redistributed.
### Exercise for Specific Groups

22 Exercise for Specific Groups

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**Note:** Units 17 & 18 are combined within the Edexcel specification

To ensure that you are following the correct pathway for the **Extended Diploma** in BTEC Sport and Exercise Sciences, please see the table below.

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</table>

**Note:** Units 17 & 18 are combined for the Edexcel specification.
2: Sport & Exercise Physiology

2.1 Introduction

Our body allows us to take part in a huge variety of sports and exercises. In order for us to carry out these activities, the body has to undergo a series of changes that provide us with the ability and the energy to carry out these actions.

This unit starts by exploring the responses of the cardiovascular, respiratory and energy systems to the anticipation and initial stress of exercise. There then follows a study of the response of the body after a period of around 20 minutes’ exercise, when a steady state has been achieved. The mechanisms of fatigue are then explored, followed by the methods by which we recover from sports and exercise. A look at the ways in which the body adapts to repeated bouts of aerobic and anaerobic exercise completes the unit.

By the end of this unit you should:

- be able to investigate the initial responses of the body to exercise
- be able to investigate how the body responds to steady-state exercise
- know about fatigue and how the body recovers from exercise
- know how the body adapts to long-term exercise.
### Assessment and grading criteria

<table>
<thead>
<tr>
<th>To achieve a <strong>PASS</strong> grade the evidence must show that the learner is able to:</th>
<th>To achieve a <strong>MERIT</strong> grade the evidence must show that, in addition to the pass criteria, the learner is able to:</th>
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<td><strong>P1</strong> investigate the initial responses of the cardiovascular and respiratory systems to exercise</td>
<td><strong>M1</strong> explain the initial responses of the cardiovascular, respiratory, neuromuscular and energy systems to exercise</td>
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<td><strong>P2</strong> describe the initial responses of the neuromuscular and energy systems to exercise</td>
<td><strong>P3</strong> investigate how the cardiovascular and respiratory systems respond to steady-state exercise</td>
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<td><strong>P4</strong> describe how the neuromuscular and energy systems respond to steady-state exercise</td>
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<td><strong>P6</strong> describe how the cardiovascular and respiratory systems adapt to long-term exercise</td>
<td><strong>P7</strong> describe how the neuromuscular, energy and skeletal systems adapt to long-term exercise.</td>
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<td><strong>P7</strong> describe how the neuromuscular, energy and skeletal systems adapt to long-term exercise.</td>
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<td><strong>D3</strong> analyse how the cardiovascular, respiratory, neuromuscular, energy and skeletal systems adapt to long-term exercise.</td>
<td><strong>D4</strong> analyse how the cardiovascular, respiratory, neuromuscular, energy and skeletal systems adapt to long-term exercise.</td>
<td><strong>D4</strong> analyse how the cardiovascular, respiratory, neuromuscular, energy and skeletal systems adapt to long-term exercise.</td>
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</table>
2.2 The Initial Responses of the Body to Exercise

Exercise
There are two main classifications of the types of exercise that we take part in: aerobic and anaerobic.
- Aerobic exercises use oxygen in the process of supplying energy to the body. These types of exercises are low-intensity and will usually allow us to talk while taking part in them – for example, walking, jogging, cycling and swimming.
- Anaerobic exercises do not use oxygen in the process of supplying energy to the body. These types of exercises are of a high intensity, so we do not have ‘the breath’ to talk while participating – for example, sprinting, high jump, speed swimming and 400m running.

The Cardiovascular System’s Initial Response to Exercise
The cardiovascular system consists of the heart and the blood vessels through which the heart pumps blood around the body. During exercise, a number of changes take place to the cardiovascular system to ensure that the muscles receive the required amounts of oxygen and nutrients. The structure of the cardiovascular system is discussed in more detail in Unit 1: Anatomy for Sport and Exercise.

During exercise, the heart rate needs to be increased in order to ensure that the working muscles receive adequate amounts of nutrients and oxygen, and that waste products are removed. Before you even start exercising there is an increase in your heart rate, called the ‘anticipatory rise’, which occurs because when you think about exercising it stimulates the sympathetic nervous system to release adrenaline. In a trained athlete, the heart rate can increase by up to three times within one minute of starting exercise. As exercise continues, the body becomes warmer, which will also help to increase the heart rate because it increases the speed of the conduction of nerve impulses across the heart.

**Key term**

**Adrenaline (also known as epinephrine):** a hormone released during times of stress which gets the body ready for action, increasing blood pressure, heart rate, and so on.

One of the effects of adrenaline is to make the heart beat faster. Once exercise has started, there is an increase in carbon dioxide and lactic acid in the body, which is detected by chemoreceptors. The chemoreceptors trigger the sympathetic nervous system to increase the release of adrenaline,

Key term

**Chemoreceptor:** a group of cells that detect changes in the chemical environment around them and transmit this message to the brain so that the body can respond accordingly.

**Cardiac Output**
Cardiac output is the amount of blood pumped from the heart every minute and is the product of heart rate and stroke volume.

Cardiac output (litres per minute) = heart rate (bpm) × Stroke volume (litres)
The shorthand for this equation is:

\[ Q = HR \times SV \]

The stroke volume is around 70 to 90 millilitres. It varies depending on a variety of factors. Generally, the fitter you are, the larger your stroke volume is and males tend to have larger stroke volumes than females. At rest, a person's cardiac output is approximately 5 litres per minute, while during exercise it can increase to as much as 30 litres per minute.

**Blood Pressure**

Blood pressure is necessary in order for blood to flow around the body. The pressure is a result of the heart contracting and forcing blood into the blood vessels. Two values are given when a person has their blood pressure taken.

A typical blood pressure for the average adult male is 120/80. The two values correspond to the systolic value (when the heart is contracting) and the diastolic value (when the heart is relaxing). The higher value is the systolic value and the lower is the diastolic value. Blood pressure is measured in milligrams of mercury: mmHg.

The value for a person's blood pressure is determined by the cardiac output (Q), which is a product of stroke volume and heart rate, and the resistance the blood encounters as it flows around the body. This can be put into an equation:

\[ \text{Blood pressure} = Q \times R \]

where \( Q = \text{cardiac output (stroke volume } \times \text{ heart rate)} \) and \( R = \text{resistance to flow} \).

Resistance to blood flow is caused both by the size of the blood vessels through which it travels (the smaller the blood vessel, the greater the resistance) and by the thickness of the blood (the thicker the blood, the greater the resistance).

Changing the resistance to blood flow can alter blood pressure. This is done by involuntary smooth muscles in the arterioles relaxing or contracting in order to alter the diameter of the arterioles. As the smooth muscle contracts, the diameter of the blood vessel gets smaller, so blood pressure is increased. As the smooth muscle relaxes, the diameter of the blood vessel is increased, which decreases the pressure of the blood flowing through it. The same principle can be applied to altering the diameter of water flow through a hose. If you place your finger over part of the opening of the hose, making the diameter smaller, the water will flow out quite forcibly because it is under higher pressure. However, if the water is left to flow unhindered through the end of the hose, it is under lower pressure, and will therefore not ‘spurt’ so far because there is less resistance.

A reduction in blood pressure is detected by baroreceptors in the aorta and the carotid artery.

**Key term**

**Baroreceptor:** a collection of cells that detect a change in blood pressure. They send signals to the brain so that the body can respond appropriately.

This detection is passed to the central nervous system (CNS), which then sends a nervous impulse to the arterioles to constrict. This increases the blood pressure and also has the effect of increasing the heart rate.

When blood pressure is increased, the baroreceptors detect this and signal the CNS, which makes the arterioles dilate and reduces blood pressure.

**Changes to Blood Pressure During the Onset of Exercise**

Exercise has the effect of increasing heart rate, which will result in an increased cardiac output, which will have the effect of increasing blood pressure. This can be seen from the equation:

\[ BP = Q \times R \]

If cardiac output is increased and the resistance to blood flow does not change, then blood pressure will also automatically increase.

A typical blood pressure reading for a person at the onset of exercise would be around 120/80 mmHg.

---

**Fig 2.2** How baroreceptors initiate response to high blood pressure and low blood pressure.
The Respiratory System’s Initial Response to Exercise

The respiratory system is responsible for getting oxygen into the body and getting carbon dioxide out of the body. It is described in detail in Unit 1: Anatomy for Sport and Exercise. The oxygen is used to help produce energy while we take part in sporting activities. The process of creating energy also produces a waste product called carbon dioxide, which needs to be removed from the body.

**Pulmonary Ventilation and Breathing Rate**

The amount of air we breathe in and out per minute is called pulmonary ventilation and is given the symbol $V_e$. Pulmonary ventilation can be worked out using the following equation:

$$V_e = \text{Frequency} \times \text{Tidal volume}$$

Frequency is the number of breaths per minute.

Tidal volume is the volume of air breathed in and out during one breath. At rest, the average breathing rate is around 12 breaths per minute. The average tidal volume is 0.5 litres (this will vary depending on the age, gender and size of a person).

Therefore, the average pulmonary ventilation at rest is:

$$V_e = 12 \times 0.5$$

$$V_e = 6 \text{ litres}$$

When you start to exercise, you need to take more oxygen into your body for it to be used to help produce energy. At the start of exercise, this increased oxygen demand occurs by breathing at a faster rate and breathing in more air and breathing out more air during each breath (i.e. tidal volume increases).

The intercostal muscles are used to aid breathing during exercise.

Key term

**Intercostal muscles**: located between the ribs, there are two types of intercostal muscle – internal and external. They help with inspiration and expiration during exercise.

The external intercostal muscles help with inspiration and the internal intercostal muscles help with expiration. As exercise becomes more strenuous, the abdominal muscles will also help aid expiration.

During anaerobic exercises, such as weightlifting, it is not uncommon for people to perform a Valsalva manoeuvre. This is basically the process of breathing out against a closed glottis or against a closed mouth and nose.

The process of performing the Valsalva manoeuvre while lifting heavy weights helps to stabilise the shoulder girdle and torso. This helps the lifter to move the weight more efficiently. This process produces a
marked increase in blood pressure and reduces blood flow to the thoracic cavity. Therefore, any person suffering with high blood pressure or heart problems should avoid this move.

**Key term**

**Thoracic cavity:** the part of the body that is enclosed by the ribcage and the diaphragm, containing the heart and the lungs.

---

**Student activity 2.1**

In order to find out what happens to the cardiovascular and respiratory systems during the initial stages of exercise, it is necessary to observe someone or take part in exercise and monitor the response of these systems.

**Task 1**

The aim of this activity is to examine what happens to heart rate before and during the onset of exercise. You will need the following equipment:

- Stopwatch or heart rate monitor
- Skipping rope
- Sports clothes
- Bench
- Pen and paper.

Follow the method set out below and record your results in the table; then answer the questions that follow.

- If you have a heart-rate monitor, place it around your chest. If not, find your pulse point, either on your neck or at your wrist.
- Sit quietly for five minutes, then take your resting heart rate. If you have a heart-rate monitor, write down the heart rate that appears on the monitor. If not, feel for your pulse point, then count your heart rate for 30 seconds. Double this figure and write it down.
- Think about what exercise you are about to perform for one minute.
- Record your heart rate after having thought about your exercise.

- Perform step-ups on to a bench for two minutes or skip for two minutes with a skipping rope.
- Immediately after you have finished your exercise, record your heart rate.

1. What happened to your heart rate immediately before you started exercising?
2. What caused this change in your heart rate and why is it necessary?
3. Explain and analyse why there is a difference between your resting heart rate, your pre-exercise heart rate and your post-exercise heart rate.

**Task 2**

- While sitting or lying down, count the number of breaths you breathe in during one minute – try to breathe as normally as possible. Write this number down and then work out your pulmonary ventilation using the equation: $VE = Frequency \times Tidal\ volume$.
- Now take part in some form of exercise, such as skipping or step-ups, for three minutes.
- Immediately after completing your exercise, count the number of breaths you breathe in during one minute, then record your pulmonary ventilation.
- Explain and analyse why there is a difference between your resting pulmonary ventilation rate and your post-exercise pulmonary ventilation rate.

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</table>
Initial Response of the Neuromuscular System

When we want to produce muscle movement, we have to get the message from our brain to our muscles. This communication between the brain and muscle is achieved through nerve impulses. A nerve impulse is an electrical current that runs from the central nervous system (CNS) through nerves and then to the muscle tissue, and results in muscle contraction. The term used to describe the signal travelling from the CNS to the muscle is called an action potential. Nerves that signal muscles to contract are called motor neurones.

Key terms

Central nervous system: consists of the brain and the spinal cord.
Motor neurone: a nerve that signals a muscle to contract.

The neuromuscular junction is the place at which the nerve and muscle meet. The nerve transmits its signal to make the muscle contract in the following manner:

- The pre-synaptic membrane reacts to the signal by its vesicles releasing acetylcholine.
- Acetylcholine diffuses across the gap between the nerve and the muscle (the synaptic cleft) and produces an electrical signal called the excitatory post-synaptic action potential.
- If the excitatory post-synaptic potential is big enough, it will make the muscle tissue contract.
- Once the muscle has carried out its desired movement, the enzyme cholinesterase breaks down the acetylcholine to leave the muscle ready to receive its next signal.

Motor Units

Key term

Motor unit: group of muscle fibres stimulated by one nerve.

As there are so many muscle fibres, a nerve stimulates more than just one fibre. In fact, it has a group of between 15 and 2000 muscle fibres, depending on the muscle it is connected to. This group of muscle fibres is called a motor unit.

When we want to produce muscle movements, we send signals from our CNS to the motor neurones. The strength of the signal determines whether the signal will reach the motor unit. This is called the all-or-nothing principle, which means that if the strength of the nerve signal is large enough, all of the motor unit will contract. And if the strength of the signal is not big enough, no part of the motor unit will contract. When we exercise, especially when we want to exert high levels of force, our motor units produce muscle contraction at different rates. Therefore, you will find that different parts of the muscle are contracting at slightly different times. This has the effect of producing smooth muscle contractions.

Muscle Spindles

A muscle spindle is an organ placed within the muscle which communicates with the CNS. The purpose of the muscle spindle is to detect when the muscle is in a state of contraction. When a muscle is contracted it changes the tension on the muscle spindle. This is relayed to the CNS and the CNS can deal with this information accordingly, by either increasing the contraction of the muscle or relaxing the muscle.
Initial Response of the Energy Systems

The function of energy systems is to produce adenosine triphosphate (ATP). ATP is used to make our muscles contract and therefore allows us to take part in exercise. It is basically a protein (adenosine) with three (tri) phosphates (phosphate) attached to it.

When chemical bonds are broken, energy is released. Therefore, when a phosphate is broken off the ATP to make ADP (adenosine diphosphate – di = two) energy is released, which is used to make the muscles contract.

\[ \text{Adenosine} \rightarrow \text{ATP} \]

![Fig 2.6 Adenosine triphosphate (ATP)]

ATP is not stored in large amounts in skeletal muscle and therefore has to be continually made from ADP for our muscles to continue contracting. There are three energy systems that the body uses to make ATP. They differ in the rate at which they make ATP. At the onset of exercise we will want ATP supplied very quickly. However, if we are on a long walk we do not need such a fast production of ATP, so the body uses a different energy system to make it.

Phosphocreatine Energy System

At the onset of exercise, the energy system that supplies the majority of ATP is the phosphocreatine system (also known as the creatine phosphate system). It supplies ATP much quicker than any other energy system. It produces ATP in the absence of oxygen, and is therefore an anaerobic energy system.

Phosphocreatine (PC) is made up of a phosphate and a creatine molecule. When the bond between the phosphate and the creatine is broken, energy is released which is then used to make the bond between ADP and a phosphate.

PC stores are used for rapid, high-intensity contractions, such as in sprinting or jumping. These stores only last for about ten seconds.

\[ \text{PC} + \text{ADP} \rightarrow \text{ATP} + \text{PC} \]

![Fig 2.7 Phosphocreatine energy system]

Lactic Acid Energy System

Once our PC stores have run out, we use the lactic acid system. This is also known as anaerobic glycolysis, which literally means the breakdown of glucose in the absence of oxygen. When glucose is broken down it is converted into a substance called pyruvate. When there is no oxygen present, the pyruvate is converted into lactic acid. This system produces ATP very quickly, but not as quickly as the PC system:

\[ \text{Glucose} \rightarrow \text{Pyruvate} \rightarrow \text{ATP} + \text{Lactic acid} \]

The lactic acid energy system is the one that is producing the majority of the ATP during high-intensity exercise lasting between 30 seconds and three minutes, such as an 800 m race.

Key learning points

- At the onset of exercise, the various systems respond to try to increase oxygen delivery, energy production and carbon dioxide removal.
- Cardiovascular system: increased heart rate, increased blood pressure, increased cardiac output.
- Respiratory system: increased pulmonary ventilation, increased breathing rate, increased tidal volume.
- Neuromuscular system: increased number of nerve transmissions, skeletal muscular contraction.
- Energy system: ATP production through phosphocreatine energy system and lactic acid energy system.
Task 1
Draw a spider diagram that illustrates the initial responses of the neuromuscular system and energy systems to exercise.

Task 2
Write a report that describes, explains and analyses the initial responses of the neuromuscular system to exercise.

Task 3
Write a report that describes, explains and analyses the initial responses of the energy systems to exercise.

Quick quiz 1
Choose the appropriate term from the following list to answer the questions below:

- Adrenaline
- Synovial fluid
- Pulmonary ventilation
- I2
- Electric current
- Micro-tears
- I20/80
- Valsalva manoeuvre
- Tidal volume
- Skeletal muscle.

1. This is the average number of breaths in and out for a person at rest.
2. This hormone is released before exercise to increase the heart rate.
3. A nerve impulse is an ________?
4. This is the technical term for breaths per minute.
5. This is released into the joints during a warm-up to help increase their range of movement.
6. This is an adult’s average resting blood pressure.
7. The amount of air breathed in and out in one breath.
8. This is performed to help to stabilise the shoulder girdle and torso.
9. These occur in muscle tissue during resistance exercises.
10. Blood is directed here during exercise.

2.3 How the Body Responds to Steady-state Exercise

Once we have been performing continuous exercise for a period of around 20 minutes, our body reaches a ‘steady state’. Continuous exercise includes all forms of exercise that have no stopping periods, such as jogging, swimming or cycling. Examples of non-continuous exercise would be weightlifting, interval training and boxing.

Key term

Steady state: when the body is working at a steady state it means that lactic acid removal is occurring at the same pace as lactic acid production.
Various changes will have occurred in the body to allow this steady state to occur.

**Cardiovascular:**
- Heart rate levels off
- Increased stroke volume
- Vasodilation of blood vessels leading to working muscles
- Blood pressure levels off
- Thermoregulation.

**Respiratory:**
- Tidal volume levels off
- Breathing rate levels off
- Oxygen is unloaded from haemoglobin much more readily.

**Neuromuscular:**
- Increased pliability of muscles
- Increased speed of neural transmissions.

**Energy:**
- Aerobic ATP production.

### Cardiovascular Response to Steady-state Exercise

Heart rate peaks during the first few minutes of exercise and then levels off.

**Stroke Volume**

While exercising, there is an increase in venous return.

**Key term**

**Venous return:** the amount of blood returned to the heart after circulating around the body.

This increased volume of blood has the effect of stretching the cardiac muscle to a greater degree than normal. This stretching has the effect of making the heart contract much more forcibly and thereby pumping out more blood during each contraction, so stroke volume is increased during exercise. This effect is known as Starling’s law.

**Blood Flow**

The average cardiac output is around 5 litres per minute. When this blood is circulated around the body, some organs receive more blood than others. However, during exercise, the working muscles need a greater proportion of blood in order to supply them with energy. The body is able to redirect blood flow by constricting the blood vessels leading to organs that do not require such a large blood flow, and dilating the blood vessels feeding the muscles that do. The process of blood vessels constricting is called vasoconstriction and the process of blood vessels dilating is called vasodilation.

**Key term**

**Constriction:** becoming smaller.

**Dilation:** becoming larger.
Changes to Blood Pressure During Steady-state Exercise

Dilation of the blood vessels feeding the working muscle acts to reduce blood pressure, but this is counteracted by the increase in blood pressure caused by increased cardiac output. Exercise raises systolic pressure, but there is only a slight change in diastolic pressure. Immediately after exercise there is a fall in systolic pressure, as the skeletal muscular pump is no longer pumping blood from the muscles to the heart. This can lead to blood pooling in the muscles and cause the athlete to faint, as not enough blood is being pumped to the brain.

Thermoregulation

Thermoregulation is the process of maintaining a constant body core temperature. In humans this temperature is 37 °C. The skin temperature of the body can vary a great deal. If the core temperature is increased or decreased by 1 °C or more, this will affect an athlete’s physical and mental performance. When exercising, we produce a great deal of excess heat. The cardiovascular system is vitally important in ensuring that we are able to lose this excess heat so that our core temperature does not increase. Excess heat is lost through sweating and dilatation of peripheral blood vessels, so that blood passes close to the surface of the skin. As the sweat evaporates, it cools down the skin surface. This has the effect of cooling the blood as it travels through the blood vessels that are close to the skin surface. When we are exercising at a high intensity in hot conditions, between 15 and 25 per cent of the cardiac output is directed to the skin.

Respiratory Responses

After having peaked in the first few minutes, if exercise remains at the same intensity, tidal volume and breathing rate level off and remain the same until exercise is terminated.

Oxygen Dissociation Curve

Only 1.5 per cent of oxygen is carried in the blood plasma. The majority of oxygen is transported in the blood by haemoglobin. Oxygen reacts with haemoglobin to make oxyhaemoglobin. The reaction of oxygen with haemoglobin is temporary and completely reversible. This means that oxygen can be unloaded from haemoglobin. The binding of oxygen to haemoglobin is dependent on the partial pressure of oxygen. Oxygen combines with haemoglobin in oxygen-rich situations, such as in the lungs.

Oxygen is released by haemoglobin in places where there is little oxygen, such as in exercising muscle. The oxygen dissociation curve is an S-shaped curve that represents the ease with which haemoglobin releases oxygen when it is exposed to tissues of different concentrations of oxygen. The curve starts with a steep rise because haemoglobin has a high affinity for oxygen. This means that when there is a small rise in the partial pressure of oxygen, haemoglobin picks up and binds oxygen to it easily. Thus, in the lungs, the blood is rapidly saturated with oxygen. However, only a small drop in the partial pressure of oxygen results in a large drop in the percentage saturation of haemoglobin. Thus, in exercising muscles, where there is a low partial pressure of oxygen, the haemoglobin readily unloads the oxygen for use by the tissues.

Changes in blood carbon dioxide level and hydrogen ion concentration (pH) cause shifts in the oxygen dissociation curve. These shifts enhance oxygen release in tissues and increase oxygen uptake in the lungs. This is known as the Bohr effect, named after the Danish physiologist, Christian Bohr, who discovered it. During exercise, the blood becomes more acidic because of the increased production of carbon dioxide.
This increase in carbon dioxide and decrease in pH shifts the dissociation curve to the right for a given partial pressure of oxygen, releasing more oxygen to the tissues.

In the lungs, there is a low partial pressure of carbon dioxide and low hydrogen ion concentration, which shifts the dissociation curve to the left for a given partial pressure of oxygen, and therefore enhances oxygen uptake.

As muscles exercise, they also increase in temperature. This has the effect of shifting the curve to the right, which means oxygen is released much more readily. Conversely, a decreased temperature shifts the curve to the left, which increases oxygen uptake.

### Student activity 2.3

During steady-state exercise, the cardiovascular and respiratory systems adapt to the exercise and respond in order to allow us to continue exercising for sustained periods of time.

Work in groups of three or four. You will need the following equipment:

- Electrical sphygmomanometer
- Treadmill or cycle ergometer
- Pen and paper
- Heart-rate monitor
- Stopwatch
- Sports clothes.

Follow the method set out below and record your results in the table; then answer the questions that follow.

- Choose a continuous exercise, such as jogging on a treadmill or cycling on an ergometer.
- Attach the sphygomanometer and heart-rate monitor to the exercising person and record their resting heart rate and blood pressure.
- Record the subject’s resting pulmonary ventilation.
- Your subject should perform aerobic exercise. Try to ensure that they are exercising at the same intensity throughout the duration of the exercise.
- At regular 5-minute intervals, take your subject’s blood pressure, heart rate and pulmonary ventilation (ensuring that they continue to exercise throughout).
- After 25 minutes of exercise, and when the last readings have been taken, your subject can stop exercising.
- After a break of at least 10 minutes, record your subject’s blood pressure, heart rate and pulmonary ventilation.

1. Plot these results on a graph.
2. Examine these results, then write a report that explains and analyses how the cardiovascular and respiratory systems respond to steady-state exercise.

<table>
<thead>
<tr>
<th>Resting</th>
<th>5 mins exercise</th>
<th>10 mins exercise</th>
<th>15 mins exercise</th>
<th>20 mins exercise</th>
<th>25 mins exercise</th>
<th>10 mins recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood pressure (mmHg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Heart rate (bpm)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Pulmonary ventilation (VE)</td>
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</tbody>
</table>
Neuromuscular Response
As more blood is pumped through the muscles and excess heat is generated through exercising, muscle tissue warms up. The warmer the muscle tissue becomes, the more pliable it is.

Key term
Pliable: able to be stretched, shaped or bent.

This means that the muscle tissue is able to stretch to greater lengths without tearing. You can apply this principle to plasticine. If you take a piece of plasticine out of its container and pull it outwards with two hands, the plasticine will quickly break in two. But if you were to warm up the plasticine by rolling it in your hands, and then pull it apart, you would find that it is able to stretch much further without breaking.

As the muscle tissue warms up, the rate at which nervous impulses are sent and received is increased as the heat increases the speed of transmission.

Energy System’s Response
The aerobic energy system provides ATP at a slower rate than the previous two energy systems discussed. It is responsible for producing the majority of our energy while our bodies are at rest or taking part in low-intensity exercise such as jogging. It uses a series of reactions, the first being aerobic glycolysis, as it occurs when oxygen is available to break down glucose. As in the anaerobic energy system, glucose is broken down into pyruvate. Because oxygen is present, pyruvate is not turned into lactic acid, but continues to be broken down through a series of chemical reactions, which include:

- The Krebs Cycle – pyruvate from aerobic glycolysis combines with Coenzyme A (CoA) to form acetyl CoA, which combines and reacts with a number of different compounds to produce ATP, hydrogen and carbon dioxide.
- The Electron Transport Chain – the hydrogen atoms produced from the Krebs Cycle enter this chain and are passed along a chain of electron carriers, eventually combining with oxygen to form ATP and water.

Both the Krebs Cycle and the Electron Transport Chain take place in organelles called mitochondria. The majority of ATP is produced in these organelles, so they are very important for energy production. They are rod-shaped and have an inner and outer membrane. The inner membrane is arranged into many folds that project inwards. These folds are called cristae and provide a large surface area for energy production to take place.

Key learning points 2
When exercising at a steady state, the body undergoes the following responses:

- Cardiovascular responses: HR levels off, increased stroke volume, vasodilation of blood vessels leading to working muscles, BP levels off.
- Respiratory responses: tidal volume levels off, breathing rate levels off, oxygen is unloaded from haemoglobin much more readily.
- Neuromuscular responses: increased pliability of muscles, increased speed of neural transmissions.
- Energy system responses: aerobic ATP production.
2.4 Fatigue and How the Body Recovers from Exercise

Key term

**Fatigue**: tiredness from physical exertion.

We cannot continue to exercise indefinitely because we will eventually fatigue.

Fatigue occurs as a result of a number of factors, including:

- Depletion of energy sources, such as reduced quantities of phosphocreatine, glucose and glycogen
- Effects of waste products, such as increased production of lactic acid and carbon dioxide
- Neuromuscular fatigue, such as depletion of acetylcholine and reduced calcium ion release.

As a result, it is necessary to rest in order to recover and return the body to its pre-exercise state.

Depletion of Energy Sources

In order to exercise, we must break down the energy stored in our body and turn it into ATP. Sources of energy include phosphocreatine, glucose and glycogen. We have only enough phosphocreatine to last us for ten seconds of maximal exercise. We then switch to glucose for energy production. We have around 15 to 20 g of glucose in our bloodstream, around 345 g of glycogen in our muscles, and 90 to 110 g of glycogen stored in our liver. When our blood sugar levels are low, the liver converts either its store of glycogen into glucose or the skeletal muscles’ store of glycogen into glucose. We have only enough glycogen stores to last us for around two hours. So once the body’s stores of glucose and glycogen are used up, we become fatigued and/or have to exercise at a lower intensity.

Effects of Waste Products

Lactic acid is the main by-product of anaerobic glycolysis. Blood always contains a small amount of lactic acid, and during high-intensity exercise this increases greatly. The increased production of lactic acid results in the pH of the blood decreasing. A blood pH of 6.4 or lower affects muscle and neural function and eventually prevents continued exercise.

Onset of blood lactate accumulation (OBLA) is the point at which lactic acid begins to accumulate in the
muscles. It is also known as the anaerobic threshold. OBLA is considered to occur at somewhere between 85 and 90 per cent of your maximum heart rate.

**Neuromuscular Fatigue**

Neuromuscular fatigue means that the muscles are either not able to receive signals from the CNS that stimulate the muscle to contract or that the muscle tissue is unable to function properly.

High-intensity exercise or exercise for long periods of time can eventually interfere with calcium release, which is required for muscle contraction. If no calcium ions are available, the muscle is unable to contract.

Alternatively, transmission of nerve impulses can be affected, as the availability of acetylcholine can be decreased, which prevents the nervous stimulation reaching the muscle tissue/motor unit.

**Recovery Process**

After taking part in any type of exercise, the body has to recover and return to its pre-exercise state.

Excess post-exercise oxygen consumption (EPOC) is also referred to as oxygen debt. EPOC is the total oxygen consumed after exercise in excess of pre-exercise levels. It occurs when the exercise performed is totally or partially anaerobic. As a result, energy is supplied by the anaerobic energy systems, which results in lactic acid production. When the person stops exercising, breathing rate remains elevated so that extra oxygen is breathed in to:

- Break down lactic acid to carbon dioxide and water
- Replenish ATP, phosphocreatine and glycogen
- Pay back any oxygen that has been borrowed from haemoglobin and myoglobin.

After a bout of vigorous exercise, five events must take place before the muscle can operate again:

1. ATP must be replaced.
2. PC stores must be replenished.
3. Lactic acid must be removed.
4. Myoglobin must be replenished with oxygen.
5. Glycogen stores must be replenished.

The replacement of ATP and PC takes around three minutes and the removal of lactic acid takes around 20 minutes after stopping exercise, but the oxygen replenishment of myoglobin and refilling the glycogen stores take between 24 and 48 hours. If the exercise bout was of a very high intensity, it will take longer to recover. However, the fitter you are, the faster you will recover. The faster the debt can be repaid, the sooner the performer can exercise again.

The oxygen debt consists of two separate components:

- Alactacid debt (fast component)
- Lactacid debt (slow component).

**Alactacid Debit**

Alactacid oxygen debt is the process of recovery that does not involve lactic acid. The aerobic energy system is used to produce the ATP required to replenish the PC stores and ATP stores in the body:

\[
\text{ADP} + \text{P} + \text{Oxygen} = \text{ATP}
\]

\[
\text{ATP} + \text{C} + \text{P} = \text{PC} + \text{ADP}
\]

Around 50 per cent of the replenishment occurs during the first 30 seconds, while full recovery occurs at about three minutes.

The alactacid oxygen debt ranges between 2 and 3.5 litres of oxygen. The fitter you are, the greater the debt, because training increases the PC content within the muscle cells. However, the recovery time of a fitter person is reduced because they have enhanced methods of oxygen delivery, such as increased capillarisation and an improved cardiorespiratory system. These increase the rate of ATP production from the aerobic energy system.

**Lactacid Debt**

The lactacid oxygen debt takes much longer to complete and can last for minutes or hours, depending on the severity of the exercise. The process involves oxygen, which is required to break down the lactic acid produced during anaerobic glycolysis into pyruvate. Pyruvate can then enter the aerobic energy system and eventually be broken down into carbon dioxide and water.

\[
\text{Lactic acid} + \text{Oxygen} = \text{Pyruvate}
\]

Lactic acid can also be converted in the liver to glycogen and stored either in the liver or in muscle tissue. Research has shown that an active recovery increases the rate of removal of lactic acid, so walking or slow jogging after a bout of exercise will help to decrease the time it takes to rid the body of lactic acid. An active recovery keeps the heart rate and breathing rate up, which has the effect of increasing the rate of delivery of oxygen to the working muscles. This then helps to rid the body of the lactic acid.

Therefore, a cool-down is very important after any form of activity in order to maximise recovery. Failure to cool down adequately means that the levels of lactic acid will remain elevated. It is thought that this acidity level affects the pain receptors and contributes to the muscle soreness which people may feel some time after having exercised. This muscle
soreness, termed delayed onset of muscle soreness (DOMS), is at its most uncomfortable 36 to 48 hours after exercise has ceased. Muscle glycogen stores must also be restored. This is attained through a high carbohydrate diet and rest. It can take several days to recover muscle glycogen stores, depending on the intensity of the exercise.

Key learning points 3

- Fatigue occurs because of:
  - Depletion of energy sources
  - Accumulation of waste products
  - Lack of calcium ion availability
  - Decreased availability of acetylcholine.
- Recovery after exercise involves taking in excess oxygen in order to return the body to its pre-exercise state.
- Alactic phase of recovery: ATP and PC production takes place in the first few minutes of recovery.
- Lactic phase of recovery: lactic acid is removed and turned into pyruvate and myoglobin; stores of oxygen are repleted and glycogen stores are repleted.
- An active recovery increases the rate of lactic acid removal.

Student activity 2.5

- Place a heart-rate monitor around your chest or take your heart rate by pressing on a pulse point and counting your pulse for one minute. Stand against a wall, then bend your knees and slide down the wall so that your knees are at right angles – you will be in a ‘ski squat’ position.
- After 30 seconds or one minute, count your pulse and remain in the ski squat position.
- You will no doubt feel that your legs are very sore and you cannot maintain this position for very long, but your heart rate has not reached maximal values. You have had to stop this exercise because you have experienced neuromuscular fatigue in your quadriceps muscles!

Task 1
Describe and explain the process involved when a person becomes fatigued through taking part in exercise.

Task 2
You will need the following equipment:
- Stopwatch
- Running track/gym
- Sports clothes.

Follow the method set out below and record your results in the table; then answer the questions that follow.
- Take your resting pulse rate and make a note of it in the results table.

<table>
<thead>
<tr>
<th>Beats per minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting pulse rate</td>
</tr>
<tr>
<td>Immediately after exercise</td>
</tr>
<tr>
<td>1 minute after exercise</td>
</tr>
<tr>
<td>2 minutes after exercise</td>
</tr>
<tr>
<td>3 minutes after exercise</td>
</tr>
<tr>
<td>4 minutes after exercise</td>
</tr>
<tr>
<td>5 minutes after exercise</td>
</tr>
</tbody>
</table>

1. Explain why your heart rate was different from resting levels immediately after exercise had stopped.
2. Explain why your heart rate remained elevated after three minutes of rest.
3. Draw a graph to illustrate the fast and slow components of the recovery process.
4. Write a report that describes and explains the recovery process from exercise participation.
Long-term exercise is also known as chronic exercise and means that a person has been participating in regular exercise for long periods of time (a minimum of eight weeks). This regular participation affects the body in a number of ways that make it more able to cope with the stresses of the exercise. This results in the person being able to exercise at higher intensities and/or for longer periods of time. This process is called adaptation.

### Cardiovascular Adaptations

The main adaptations that occur to the cardiovascular system through endurance training are concerned with increasing the delivery of oxygen to the working muscles. If you were to dissect the heart of a top endurance athlete, you would find that the size of the walls of the left ventricle are markedly thicker than those of a person who does not perform endurance exercise. This adaptation is called cardiac hypertrophy.

Adaptation occurs in the same way that we increase the size of our skeletal muscles – the more we exercise our muscles, the larger or more toned they become. In the same way, the more we exercise our heart through aerobic training, the larger it will become. This will then have the effect of increasing the stroke volume, which is the amount of blood that the heart can pump out per beat. As the heart wall becomes bigger, it can pump more blood per beat, as the thicker wall can contract more forcibly. As the stroke volume is increased, the heart no longer needs to beat as often to get the same amount of blood around the body. This results in a decrease in heart rate which is known as bradycardia.

### Key terms

**Cardiac hypertrophy**: the size of the heart wall becomes thicker and stronger.

**Bradycardia**: decreased resting heart rate.
An average male adult’s heart rate is 70 beats per minute (bpm). However, Lance Armstrong, a Tour de France champion, had a resting heart rate of 30 bpm! As stroke volume increases, cardiac output also increases, so an endurance athlete’s heart can pump more blood per minute than other people’s. However, resting values of cardiac output do not change. An endurance athlete has more capillaries, allowing more blood to travel through them. This process, called capillarisation, aids in the extraction of oxygen. An increase in haemoglobin due to an increase in the number of red blood cells (which contain the haemoglobin) further aids the transport of oxygen. Though haemoglobin content rises, the increase in blood plasma is greater, and consequently the blood haematocrit (ratio of red blood cell volume to total blood volume) is reduced, which lowers viscosity (thickness) and enables the blood to flow more easily.

Strength training produces very few adaptations to the cardiovascular system, as this training does not stress the heart or oxygen delivery and extraction systems for sustained periods of time.

Respiratory Adaptations
The respiratory system deals with taking oxygen into the body and also with helping to remove waste products associated with muscle metabolism. Training reduces the resting respiratory rate and the breathing rate during sub-maximal exercise. Endurance training can also provide a small increase in lung volumes: vital capacity increases slightly, as does tidal volume during maximal exercise. The increased strength of the respiratory muscles is partly responsible for this as it aids lung inflation.

Endurance training also increases the capillarisation around the alveoli in the lungs. This helps to increase the rate of gas exchange in the lungs and, therefore, increase the amount of oxygen entering the blood and the amount of carbon dioxide leaving the blood.

Strength training produces very few adaptations to the respiratory system, as this type of training uses the anaerobic energy systems, whereas the respiratory system is only really concerned with the aerobic energy system.

Neuromuscular and Energy Systems’ adaptations
Endurance training results in an increase in the muscular stores of muscle glycogen. There is increased delivery of oxygen to the muscles through an increase in the concentration of myoglobin and increased capillary density through the muscle. The ability of skeletal muscle to consume oxygen is increased as a direct result of an increase in the number and size of the mitochondria and an increase in the activity and concentration of enzymes involved in the aerobic processes that take place in the mitochondria. As a result, there is greater scope to use glycogen and fat as fuels. Slow-twitch fibres can enlarge by up to 22 per cent, which gives greater potential for aerobic energy production. Hypertrophy of slow-twitch fibres means that there is a corresponding increase in the stores of glycogen and triglycerides. This ensures a continuous supply of energy, enabling exercise to be performed for longer.

These adaptations result in an increased maximal oxygen consumption (VO2 max) being obtained before the anaerobic threshold is reached and fatigue begins.

High-intensity training results in hypertrophy of fast-twitch fibres. There are increased levels of ATP and PC in the muscle and an increased capacity to generate ATP by the PC energy system. This is partly due to the increased activity of the enzymes which break down PC. ATP production by anaerobic glycolysis is increased as a result of enhanced activity of the glycolytic enzymes. There is also an increased ability to break down glycogen in the absence of oxygen.

As lactic acid accumulates, it decreases the pH levels of the blood, making it more acidic. This increased level of hydrogen ions will eventually prevent the glycolytic enzyme functioning. However, anaerobic training increases the buffering capacity of the body and enables it to work for longer in periods of high acidity.

Energy System Adaptation
Aerobic training will increase the number of mitochondria in slow-twitch muscle fibres. This will allow greater production of ATP through the aerobic energy system. Greater amounts of glycogen can be stored in the liver and skeletal muscle. Aerobic training results in an increase in the number of enzymes required for body fat to be broken down, and more body fat is stored in muscle tissue, which means that more fat can be used as an energy source.

Anaerobic or strength training predominantly uses the PC and lactic acid energy system. Chronic anaerobic/strength training increases the body’s tolerance levels to low pH. This means more energy can be produced by the lactic acid energy system, and the increased production of lactic acid can be tolerated for longer.
Skeletal Adaptations

Our skeleton responds to aerobic weight-bearing exercise or resistance exercise by becoming stronger and more able to withstand impact, which means you are less likely to break a bone if you fall over.

Key term

Weight-bearing exercise: this is when we are using our body weight as a form of resistance (e.g. walking, running).

Key learning points 4

- **Adaptations to aerobic exercise:**
  - Cardiovascular system: cardiac hypertrophy, increased SV, decreased resting HR, increased number of capillaries, increased number of red blood cells, decreased haematocrit.
  - Respiratory system: decreased resting breathing rate, increased lung volume, increased vital capacity, increased tidal volume (in maximal exercise), increased strength of respiratory muscles, increased capillarisation around alveoli.
  - Neuromuscular system: increased myoglobin content, increased number of capillaries, increased number of mitochondria, hypertrophy of slow-twitch muscle fibres, increased stores of glycogen, increased stores of fat.
  - Energy systems: increased number of aerobic enzymes, increased breakdown of fat.

- **Adaptations to anaerobic exercise:**
  - Cardiovascular system: no significant adaptations.
  - Respiratory system: no significant adaptations.
  - Neuromuscular: hypertrophy of fast-twitch muscle fibres, increased content of ATP, increased content of PC, increased tolerance to lactic acid.
  - Energy systems: increased number of anaerobic enzymes.
  - Skeletal system: increased strength of bones, increased strength of tendons, increased stretch of ligaments.

Student activity 2.6

Taking part in long-term exercise programmes, such as four 30-minute jogging sessions per week for eight weeks, or a six-week resistance training programme, will produce stimulus to make the body adapt to the exercise so that it is able to perform the activity more readily, with less perceived effort.

**Task 1**

Draw a spider diagram that illustrates how each of the following systems adapts to long-term exercise:
- Cardiovascular
- Respiratory
- Skeletal
- Neuromuscular
- Energy

**Task 2**

Write a report that describes, explains and analyses how the cardiovascular, respiratory, skeletal, neuromuscular and energy systems adapt to long-term exercise.
Quick quiz 4

1. Explain what cardiac hypertrophy is and how this can help an endurance athlete.
2. Explain how capillarisation around the lungs can increase the rate of gas exchange.
3. Explain how the skeletal system adapts to weight-bearing exercises.
4. Describe how the cardiovascular and respiratory system of Paula Radcliff will have adapted through endurance training.
5. Describe how the neuromuscular and skeletal system of Usain Bolt will have adapted through resistance training.

Further reading


Useful websites

www.getbodysmart.com
Free tutorials and quizzes from an American site that looks at human anatomy and physiology, helping you to see the structure of the different body systems.
www.innerbody.com
Free and informative diagrams of the different body systems, including respiratory, cardiovascular, skeletal and muscular
www.instantanatomy.net
Free useful anatomy pictures and information, mainly from a medical viewpoint.