Key concepts
- The muscular system is organized into discrete muscles, which work as antagonistic pairs.
- Skeletal muscle tissue acts with the bones of the skeleton to produce movements.
- In muscle, contraction results from the movement of actin filaments against myosin filaments.
- ATP is required for muscle contraction.

Learning Objectives
1. Use the KEY TERMS to compile a glossary for this topic.

Muscle Structure
- Recall the distinguishing features and roles of cardiac muscle, smooth muscle, and skeletal muscle tissue.
- Describe the ultrastructure of skeletal muscle, including:
  - The organization of the muscle into bundles of fibers.
  - The organization of the fibers (cells) into bundles of smaller myofibrils.
  - The composition and arrangement of the filaments within each myofibril.
- Describe the organization of the body's musculature into functional groups. Recognize major muscle groups and their functions. Explain the functional significance of muscles as antagonistic pairs.

The Physiology of Muscle Contraction
- Recognize a sarcomere as a complete contractile unit. Relate the structure of the sarcomere to the distribution of actin and myosin within the myofibril.
- Describe the sliding-filament hypothesis of muscle contraction. Identify the role of calcium ions (Ca²⁺), the troponin-tropomyosin complex, and ATP. Recognize that contraction of a muscle fiber is an all-or-nothing event.
- Describe the structure and function of the neuromuscular junction, including the role of acetylcholine (Ach), the T-tubules, and the sarcoplasmic reticulum.
- Describe the structural differences between fast twitch and slow twitch muscle fibers. Explain the physiological basis of these differences.

The Functioning Muscle
- Explain how joints, with muscles, bring about specific movements of the skeleton. With reference to muscles and their activity, define the terms origin and insertion. Distinguish between isotonic and isometric contractions and explain how muscle tone is achieved and maintained.
- Describe movements of the skeleton, including extension, flexion, rotation, abduction, adduction, and circumduction.
- Explain how muscles as a whole produce graded responses by (1) changing the frequency of stimulation (to tetany) or (2) by recruitment of motor units.
- Identify sources of energy for muscle contraction. Compare aerobic and anaerobic pathways as sources of ATP for muscle contraction.
- Explain muscle fatigue and relate it to the increase in blood lactate, depletion of carbohydrate supplies, and decreased pH. Explain how these changes provide the stimulus for increased breathing (and heart) rates.
- Define the term oxygen debt and explain how it is repaid after intense exercise.
- Discuss the effects of exercise, inactivity, and aging on muscle.
Muscles of the Human Body

The muscles of the human body occur as groups which work together to achieve an outcome. For example, the raising of the forearm is achieved by the contraction of the biceps brachii and the brachialis. This muscle group is sometimes referred to simply as the biceps. Similarly, the abdominals is used to refer to the muscle layers covering the body’s anterior midsection. Muscle groups are divided between the head, trunk, upper and lower arms, thorax and midsection, and upper and lower legs, each with anterior and posterior muscles. Some common muscle groupings are illustrated below.

**Muscle Groups**

**Word list:**
- Facial muscles, pectorals, obliques (abdominal group), rectus abdominis (abdominal group), trapezius, latissimus dorsi, deltoid, biceps, triceps, gluteals, quadriceps, hamstrings, gastrocnemius

- **a.** Facial
- **b.** Deltoid
- **c.** Trapezius
- **d.** Pectoralis Major
- **e.** Triceps
- **f.** Biceps
- **g.** Latissimus Dorsi
- **h.** Oblique (Lateral Abdominal Muscles)
- **i.** Glutes
- **j.** Rectus Abdominis
- **k.** Hamstring
- **l.** Quadriceps
- **m.** Gastrocnemius

**Head Muscles**

Head muscles are divided into the facial muscles, which make expressions, and the chewing muscles. Facial muscles are inserted into soft tissues (e.g. skin) and enable a range of facial expressions.

**Smiling** involves about 12 muscles. Major muscles involved include:
- Zygomaticus major raises the corners of the mouth and produces the cheek dimples
- Zygomaticus minor raises the upper edges of the lips
- Levator anguli oris raises the upper lip to show the canine teeth.

**Frowning** involves about 11 muscles. Muscles involved include:
- Procerus pulls the skin between the eyebrows down towards the nose producing the “frowner’s fold”
- Depressor anguli oris pulls the corners of the mouth down to form the lips into an inverted U.

Related activities: Muscle Structure and Function
Muscle Fascicles and Muscle Structure

Skeletal muscles consist of fascicles (bundles of muscle fibers surrounded by connective tissue layer). The arrangement of fascicles varies, producing a variety of muscle structures.

- **Convergent**
  Muscle fascicles that converge to a single insertion tendon.
  Example: pectoralis major (pectoral muscle)

- **Fusiform**
  A modification of parallel which results in a muscle with an expanded midsection.
  Example: biceps brachii

- **Parallel**
  Muscle fascicles run parallel to the long axis of the muscle.
  Example: extensor digitorum longus

- **Circular**
  Muscle fascicles arranged in concentric rings.
  Examples: muscles around the mouth and eyes.

- **Pennate (feather)**
  Muscle fascicles are attached obliquely to a central tendon. May be multipennate, bipennate or unipennate.

- **Multipennate**
  Muscle fascicles insert into the tendon from several sides.
  Example: rectus femoris

- **Bipennate**
  Muscle fascicles insert into opposite sides of the tendon.
  Example: rectus femoris (one of four muscles of the quadriceps)

- **Unipennate**
  Muscle fascicles insert into only one side of the tendon.
  Example: extensor digitorum longus of the lower leg

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1. On the previous page, use the word list to label the muscle groups on the figure:

2. Which major muscles group(s) would be used to carry out the following movements:
   
   (a) Raise the lower leg (i.e. tibia and fibula) towards the buttocks: **Calf** (Gastrocnemius + Soleus)
   
   (b) Bring the upper leg forward (i.e. the femur) as in taking a step: **Quads**
   
   (c) Rotate the wrist: **Bicep Brachii** w/ **supinator/pronator** forearm muscles
   
   (d) Raise the arm from the side of the body up over the head: **Deltoid**

3. What is the unusual feature of facial muscles? They have their own origin on the bone, but are inserted into soft tissue (not another bone).

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4. On the photos on the previous page identify and label the facial muscles mentioned using the following shorthand:
   
   zygomaticus major (ZMa), zygomaticus minor (ZMi), levator anguli oris (LAO), procerus (P), depressor anguli oris (DAO)

5. Describe the difference between parallel and fusiform muscle structure: **Parallel**: fascicles run parallel to the axis of the muscle (axis of force generation).
   
   **Fusiform**: subcategory of parallel => muscle is wider, shaped cylinder in the middle, tapering at the ends (spindle shaped). Force is concentrated into a smaller area.
Skeletal muscle (also called striated or voluntary muscle) is organized into bundles of muscle cells or fibers. Each fiber is a single cell with many nuclei, and each fiber is itself a bundle of smaller myofibrils arranged lengthwise. Each myofibril is in turn composed of two kinds of myofilaments (thick and thin), which overlap to form light and dark bands. The alternation of these light and dark bands gives skeletal muscle its striated or striped appearance. The sarcomere, bounded by the dark Z lines, forms one complete contractile unit. Muscle fibers are innervated by the branches of motor neurons, each of which terminates in a specialized cholinergic synapse called the neuromuscular junction (or motor end plate). A motor neuron and all the fibers it innervates (which may be a few or several hundred) are called a motor unit. Graded responses in the muscle as a whole are achieved by varying the number of motor units active at any one time (recruitment of motor units).

Longitudinal Section of a Sarcomere

- I band (light)
- A band (dark)
- Z lines

The photograph of a sarcomere (above) shows the banding pattern arising as a result of the highly organized arrangement of thin and thick filaments. It is represented schematically in longitudinal section and cross section.

The Neuromuscular Junction

Above: Axon terminals of a motor neuron supplying a muscle. The branches of the axon terminate on the sarcolemma of a fiber at regions called the neuromuscular junction (or motor end plate). Each fiber receives a branch of an axon, but one axon may supply many muscle fibers.

Left: Diagrammatic representation of part of a neuromuscular junction.
The banding pattern of myofibrils

Within a myofibril, the thin filaments, held together by the Z lines, project in both directions. The arrival of an action potential sets in motion a series of events that cause the thick and thin filaments to slide past each other. This is called **contraction** and it results in shortening of the muscle fiber and is accompanied by a visible change in the appearance of the myofibril: the I band and the sarcomere shorten and H zone shortens or disappears (below).

![Banding Pattern of Myofibrils](image)

**Relaxed**

- **Z line**
- **H zone**
- **I band**
- **A band**
- **Maximally contracted**

The response of a single muscle fiber to stimulation is to contract maximally or not at all; its response is referred to as the **all-or-none law of muscle contraction**. If the stimulus is not strong enough to produce an action potential, the muscle fiber will not respond. However, skeletal muscles as a whole are able to produce varying levels of contractile force. These are called **graded responses**.

**Duchenne muscular dystrophy** is an X-linked disorder caused by a mutation in the gene DMD, which codes for the protein **dystrophin**. The disease causes a rapid deterioration of muscle, eventually leading to loss of function and death. It is the most prevalent type of muscular dystrophy and affects only males. Dystrophin is an important structural component within muscle tissue and it connects muscle fibers to the extracellular matrix through a protein complex on the sarcolemma. The absence of dystrophin allows excess calcium to penetrate the sarcolemma (the fiber's plasma membrane). This damages the sarcolemma, and eventually results in the death of the cell. Muscle fibers die and are replaced with adipose and connective tissue.

1. Describe the neuromuscular junction: N.S. is a specialized **synapse** formed where a motor neuron terminates on the sarcolemma and consists of the axon terminal (synaptic end bulb) of the region of the sarcolemma it makes contact with.

   **Overlap pattern of the thick & thin filaments (dark = overlap)**

2. Explain the cause of the banding pattern visible in striated muscle:

   - **Overlap pattern of the thick & thin filaments**

3. Explain the change in appearance of a myofibril during contraction with reference to the following:

   - The I band: **becomes narrower as more filaments overlap**
   - The H zone: **appears as the overlap becomes maximal**
   - The sarcomere: **shortens progressively as the overlap becomes maximal**

4. Describe the purpose of the connective tissue sheaths surrounding the muscle and its fascicles: They protect the muscle from friction & give structural integrity to the muscle.

5. Explain what is meant by the all-or-none response of a muscle fiber: **Refers to the way muscle fiber contracts maximally or not at all**.

6. Explain why the inability to produce dystrophin leads to a loss of muscle function: **Without dystrophin there is no structural link between muscle fibers of the extracellular matrix.**
The Sliding Filament Theory

The previous activity described how muscle contraction is achieved by the thick and thin muscle filaments sliding past one another. This sliding is possible because of the structure and arrangement of the thick and thin filaments. The ends of the thick myosin filaments are studded with heads or cross bridges that can link to the thin filaments next to them. The thin filaments contain the protein actin, but also a regulatory protein complex. When the cross bridges of the thick filaments connect to the thin filaments, a shape change moves one filament past the other. Two things are necessary for cross bridge formation: calcium ions, which are released from the sarcoplasmic reticulum when the muscle receives an action potential, and ATP, which is hydrolyzed by ATPase enzymes on the myosin. When cross bridges attach and detach in sarcomeres throughout the muscle cell, the cell shortens. Although a muscle fiber responds to an action potential by contracting maximally, skeletal muscles as a whole can produce varying levels of contractile force. These graded responses are achieved by changing the frequency of stimulation (frequency summation) and by changing the number and size of motor units recruited (multiple fiber summation). Maximal contractions of a muscle are achieved when nerve impulses arrive at the muscle at a rapid rate and a large number of motor units are active at once.

The Sliding Filament Theory

Muscle contraction requires calcium ions ($Ca^{2+}$) and energy (in the form of ATP) in order for the thick and thin filaments to slide past each other. The steps are:

1. The binding sites on the actin molecule (to which myosin 'heads' will locate) are blocked by a complex of two protein molecules: troponin and troponyosin.

2. Prior to muscle contraction, ATP binds to the heads of the myosin molecules, priming them in an erect high energy state. Arrival of an action potential causes a release of $Ca^{2+}$ from the sarcoplasmic reticulum. The $Ca^{2+}$ binds to the troponin and causes the blocking complex to move so that the myosin binding sites on the actin filament become exposed.

3. The heads of the cross-bridging myosin molecules attach to the binding sites on the actin filament. Release of energy from the hydrolysis of ATP accompanies the cross bridge formation.

4. The energy released from ATP hydrolysis causes a change in shape of the myosin cross bridge, resulting in a bending action (the power stroke). This causes the actin filaments to slide past the myosin filaments towards the center of the sarcomere.

5. (Not illustrated). Fresh ATP attaches to the myosin molecules, releasing them from the binding sites and repriming them for a repeat movement. They become attached further along the actin chain as long as ATP and $Ca^{2+}$ are available.

1. Match the following chemicals with their functional role in muscle movement (draw a line between matching pairs):

   (a) Myosin
   (b) Actin
   (c) Calcium ions
   (d) Troponin-troponyosin
   (e) ATP

   Bind to the actin molecule in a way that prevents myosin head from forming a cross bridge

   Supplies energy for the flexing of the myosin 'head' (power stroke)

   Has a moveable head that provides a power stroke when activated

   Two protein molecules twisted in a helix shape that form the thin filament of a myofibril

   Bind to the blocking molecules, causing them to move and expose the myosin binding site

2. Describe the two ways in which a muscle as a whole can produce contractions of varying force:

   (a) By changing the frequency of stimulation, so that fibers receive impulses at a greater rate (frequency summation).

   (b) By changing the # or size of motor units recruited, so max motor units = max contraction.

3. (a) Identify the two things necessary for cross bridge formation: Calcium ions + ATP

   (b) Explain where each of these comes from: $Ca^{2+}$ from storage in S.R.

   ATP is in the muscle fiber & is hydrolyzed by ATPase enzyme on the myosin.
We are familiar with the many different bodily movements achievable through the action of muscles. Contractions in which the length of the muscle shortens in the usual way are called *isotonic contractions*: the muscle shortens and movement occurs. When a muscle contracts against something immovable and does not shorten the contraction is called *isometric*. Skeletal muscles are attached to bones by tough connective tissue structures called *tendons*. They always have at least two attachments: the *origin* and the *insertion*. They create movement of body parts when they contract across *joints*. The type and degree of movement achieved depends on how much movement the joint allows and where the muscle is located in relation to the joint. Some common types of body movements are described below (left panel). Because muscles can only pull and not push, most body movements are achieved through the action of opposing sets of muscles (below, right panel).

**The Action of Antagonistic Muscles**

The skeleton works as a system of levers. The joint acts as a *fulcrum* (or pivot), the muscles exert the *force*, and the weight of the bone being moved represents the *load*. The flexion (bending) and extension (unbending) of limbs is caused by the action of *antagonistic muscles*. Antagonistic muscles work in pairs and their actions oppose each other. During movement of a limb, muscles other than those primarily responsible for the movement may be involved to fine tune the movement.

Every coordinated movement in the body requires the application of muscle force. This is accomplished by the action of agonists, antagonists, and synergists. The opposing action of agonists and antagonists (working constantly at a low level) also produces muscle tone. Note that either muscle in an antagonistic pair can act as the agonist or prime mover, depending on the particular movement (for example, flexion or extension).

**Movement at Joints**

The synovial joints of the skeleton allow free movement in one or more planes. The articulating bone ends are separated by a joint cavity containing lubricating synovial fluid. Two types of synovial joint, the shoulder ball and socket joint and the hinge joint of the elbow, are illustrated below.

**Periodicals:**

Related Activities: Joints

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Types of Body Movement

Flexion decreases the angle of the joint and brings two bones closer together. Extension is its opposite. Extension more than 180° is called hyperextension.

Rotation is movement of a bone around its longitudinal axis. It is a common movement of ball and socket joints and the movement of the atlas around the axis.

Abduction is a movement away from the midline, whereas adduction describes movement towards the midline. The terms also apply to opening and closing the fingers.

1. Describe the role of each of the following muscles in moving a limb:
   (a) Prime mover: **the muscle primarily responsible for the movement**
   (b) Antagonist: **the muscle that opposes the prime, relaxed when prime contracts**
   (c) Synergist: **assists the prime mover by fine-tuning the direction of the limb movement**

2. Explain why the muscles that cause movement of body parts tend to operate as antagonistic pairs: **muscles can only contract or relax, only pull to produce movement, two muscles must act as antagonistic pairs to move bones to and from different positions.**

3. Describe the relationship between muscles and joints. Using appropriate terminology, explain how antagonistic muscles act together to raise and lower a limb:
   **Origin (less moveable) + insertion (more moveable), when muscle contracts, insertion is moving towards the origin. To raise a limb, flexor (agonist) contracts pulling the limb up (extensor/antagonist relaxed), vice-versa.**

4. Explain the role of joints in the movement of body parts: **Bones are rigid, movement thus has to occur at the joints. Degree of movement also depends on the mobility/type of joint.**

5. (a) Identify the insertion for the biceps brachii during flexion of the forearm: **Radius (radial tuberosity)**
   (b) Identify the insertion of the brachialis muscle during flexion of the forearm: **Ulna**
   (c) Identify the antagonist during flexion of the forearm: **Triceps**
   (d) Given its insertion, describe the forearm movement during which the biceps brachii is the prime mover:
      **Rotation of ulna on radius**

6. (a) Describe a forearm movement in which the brachialis is the antagonist: **Elbow extension**
   (b) Identify the prime mover in this movement: **Triceps**

7. (a) Describe the actions that take place in the neck when you nod your head up and down as if saying "yes":
      **Flexion and extension**
   (b) Describe the action being performed when a person sticks out their thumb to hitch a ride: **Abduction (away from body)**
Exercise places an immediate demand on the body's energy supply systems. During exercise, the metabolic rate of the muscles increases by up to 20 times and the body's systems must respond appropriately to maintain homeostasis. The ability to exercise for any given length of time depends on maintaining adequate supplies of ATP to the muscles. There are three energy systems to do this: the ATP-CP system, the glycolytic system, and the oxidative system. The ultimate sources of energy for ATP generation in muscle via these systems are glucose, and stores of glycogen and triglycerides. Prolonged intense exercise utilizes the oxidative system, and relies on a constant supply of oxygen to the tissues. The VO2 is the amount of oxygen (expressed as a volume) used by muscles during a specified interval for cell metabolism and energy production. VO2max is the maximum volume of oxygen that can be delivered and used per minute and therefore represents an individual's upper limit of aerobic metabolism. VO2max is used as a measure of fitness, and is high in trained athletes. At some percentage of VO2max (the anaerobic threshold) the body is unable to meet its energy demands aerobically and an oxygen debt is incurred.

The ATP-CP system

The simplest of the energy systems is the ATP-CP system. CP or creatine phosphate is a high energy compound that stores energy sufficient for brief periods of muscular effort. Energy released from the breakdown of CP is not used directly to accomplish cellular work. Instead it rebuilds ATP to maintain a relatively constant supply. This process is anaerobic, occurs very rapidly, and is accomplished without any special structures in the cell.

CP levels decline steadily as it is used to replenish depleted ATP levels. The ATP-CP system maintains energy levels for 3-15 seconds. Beyond this, the muscle must rely on other processes for ATP generation.

The glycolytic system

ATP can also be provided by glycolysis. The ATP yield from glycolysis is low (only net 2 ATP per molecule of glucose), but it produces ATP rapidly and does not require oxygen. The fuel for the glycolytic system is glucose in the blood, or glycogen, which is stored in the muscle or liver and broken down to glucose-6-phosphate. Pyruvate is reduced to lactate, regenerating NAD+ and allowing further glycolysis.

Glycolysis provides ATP for exercise for just a few minutes. Its main limitation is that it causes an accumulation of H+ (because protons are not being removed via mitochondrial respiration) and lactate (C3H3O3) in the tissues. These changes lead to impairment of muscle function.

The Oxidative System

In the oxidative system, glucose is completely broken down to yield around 36 molecules of ATP. This process uses oxygen and occurs in the mitochondria. Aerobic metabolism has a high energy yield and is the primary method of energy production during sustained high activity. It relies on a continued supply of oxygen and therefore on the body's ability to deliver oxygen to the muscles. The fuels for aerobic respiration are glucose, stored glycogen, or stored triglycerides. Triglycerides provide free fatty acids, which are oxidized in the mitochondria by the successive removal of two-carbon fragments (a process called beta-oxidation). These two carbon units enter the Krebs cycle as acetyl coenzyme A (acetyl CoA).

Related activities: Muscle Physiology and Performance, Muscle Fatigue
The graph above illustrates the principle of oxygen debt. In the graph, the energy demands of aerobic exercise require 3 L of oxygen per minute. The rate of oxygen uptake increases immediately exercise starts, but the full requirement is not met until six minutes later. The oxygen deficit is the amount of oxygen needed (for aerobic energy supply) but not supplied by breathing. During the first six minutes, energy is supplied largely from anaerobic pathways: the ATP-CP and glycolytic systems. After exercise, oxygen uptake per minute does not drop immediately to resting level. The extra oxygen that is taken in despite the drop in energy demand is the oxygen debt. The oxygen debt is used to replace oxygen reserves, restore creatine phosphate, and oxidize the lactic acid or convert it to glucose.

1. Explain why the supply of energy through the glycolytic system is limited: **Lactic acid quickly builds up as a waste product which inhibits glycogen breakdown and impedes muscular contraction so time period of its use is limited.**

2. Summarize the features of the three energy systems in the table below:

<table>
<thead>
<tr>
<th>ATP-CP system</th>
<th>Glycolytic system</th>
<th>Oxidative system</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP supplied by: Breakdown of C.P</td>
<td>Anaerobic breakdown of Glycogen</td>
<td>Complete (oxidative phase)</td>
</tr>
<tr>
<td>Duration of ATP supply: 3-15 sec</td>
<td>Few minutes</td>
<td>Prolonged but dependent on the ability to supply adequate oxygen to muscles</td>
</tr>
</tbody>
</table>

3. Study the graph and explanatory paragraph above, then identify and describe what is represented by:

(a) The shaded region A: **Oxygen deficit**: amount of oxygen needed for aerobic supply but not supplied by breathing (builds up)

(b) The shaded region B: **Oxygen debt**: the extra oxygen required (taken in) despite the drop in energy demand. The debt is used to replace oxygen reserves, restore C.P, break down lactic acid

4. With respect to the graph above, explain why the rate of oxygen uptake does not immediately return to its resting level after exercise stops:

   **90% of the extra oxygen required to restore oxygen at energy levels (the oxygen debt).**

5. The rate of oxygen uptake increases immediately exercise starts. Explain how the oxygen supply from outside the body to the cells is increased during exercise:

   **By the rate & depth of breathing (increasing gas exchange) or increasing blood flow (heart beating faster).**

6. Lactic acid levels in the blood continue to rise for a time after exercise has stopped. Explain why this occurs:

   **Lactic acid is transported in the blood from muscles to the liver where it can be fully metabolized or oxidized to CO₂ + H₂O.**
Muscle fatigue refers to the decline in a muscle's ability to maintain force in a prolonged or repeated contraction. It is a normal result of vigorous exercise but the reasons for it are complex. Muscles can fatigue because of shortage of fuel or because of the accumulation of metabolites, which interfere with the activity of calcium in the muscle. Contrary to older thinking, muscle fatigue is not caused by the toxic effects of lactic acid accumulation in oxygen-starved muscle. In fact, lactate formed during exercise is an important source of fuel (through conversion to glucose) and delays fatigue and metabolic acidosis during moderate activity by acting as a buffer. However, during sustained exhausting exercise, more of the muscle’s energy needs must be met by glycolysis, and this leads to the metabolic changes (including accumulation of lactate and phosphate) that contribute to fatigue. Accumulated lactate is metabolized within the muscle itself or transported to the liver and converted back into glucose.

At rest
- Muscles produce a surplus of ATP
  - This extra energy is stored in CP (creatine phosphate) and glycogen

During moderate activity
- ATP requirements are met by the aerobic metabolism of glycogen and lipids.
- There is no proton accumulation in the cell

During peak activity
- Effort is limited by ATP. ATP production is ultimately limited by availability of oxygen.
- During short-term, intense activity, more of the muscle's ATP needs must be met by glycolysis. This leads to an increase in H⁺.
- Removal of H⁺ is slow because mitochondrial respiration is hampered. Lactate may accumulate and is coincident with metabolic acidosis but not the cause of it.
- Muscle contraction is impaired (fatigue).

The complex causes of muscle fatigue
- During intense exercise, oxygen is limited and more of the muscle's energy needs must be met through anaerobic metabolism. The effects of this are:
  - An increase in H⁺ (acidosis) because protons are not being removed via the mitochondrial electron transport system.
  - Lactate accumulates faster than it can be oxidized.
  - Accumulation of phosphate (Pi) from breakdown of ATP and creatine phosphate.
- These metabolic changes lead to a fall in ATP and impaired calcium release from the sarcoplasmic reticulum (SR), both of which contribute to muscle fatigue.

1. Explain the mechanism by which lactate accumulation is associated with muscle fatigue: Lactic acid accumulation in muscle tissue results in lowered pH, inhibition of cellular activity.
2. Identify the two physiological changes in the muscle that ultimately result in a decline in muscle performance:
   (a) Fall in ATP production
   (b) Fall in Ca²⁺ release/stores
3. Suggest why the reasons for fatigue in a long distance race are different to those in a 100 m sprint:
   - Marathon: ATP continues to be produced aerobically until all energy stores are exhausted. Sprint: ATP anaerobically until oxygen debt can be replenished.
The overall effect of aerobic training on muscle is improved oxidative function and better endurance. Regardless of the type of training, some of our ability to perform different types of activity depends on our genetic make-up. This is particularly true of aspects of muscle physiology, such as the relative proportions of different fiber types in the skeletal muscles. Muscle fibers are primarily of two types: fast twitch (FT) or slow twitch (ST). Fast twitch fibers predominate during anaerobic, explosive activity, whereas slow twitch fibers predominate during endurance activity. In the table below, note the difference in the degree to which the two fiber types show fatigue (a decrease in the capacity to do work). Training can increase fiber size and, to some extent, the makeup of the fiber, but not the proportion of ST to FT, which is genetically determined.

### Fast vs Slow Twitch Muscle

<table>
<thead>
<tr>
<th>Feature</th>
<th>Fast Twitch</th>
<th>Slow Twitch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>White</td>
<td>Red</td>
</tr>
<tr>
<td>Diameter</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Contraction rate</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>ATP production</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>Metabolism</td>
<td>Anaerobic</td>
<td>Aerobic</td>
</tr>
<tr>
<td>Rate of fatigue</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>Power</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Slow twitch fibers appear light colored when stained with a myofibrillar ATPase stain.

Type II fast twitch fibers are classified further according to their metabolism:
- Type IIa (intermediate) = some oxidative capacity
- Type IIb = fast glycolytic only

There are two basic types of muscle fibers: slow twitch (type I) and fast twitch (type II) fibers. Both fiber types generally produce the same force per contraction, but fast twitch fibers produce that force at a higher rate. Low twitch fibers contain more mitochondria and myoglobin than fast twitch fibers, so they are more efficient at using oxygen to generate ATP without lactate build up. In this way, they can fuel repeated muscle contractions such as those required for endurance events.

1. Explain three ways in which aerobic (endurance) training improves the oxidative function of muscle:

   (a) Improved oxidation of glycogen → increased capacity of muscle to generate ATP aerobically.

   (b) Increased myoglobin content in muscle, which stores O₂ and aids in the delivery to the mitochondria.

   (c) An increase in the # of capillaries surrounding each muscle fiber. Endurance trained men have 5%-10% more capillaries than sedentary men.

2. Contrast the properties of fast and slow twitch skeletal muscle fibers, identifying how these properties contribute to their performance in different conditions:

   **Fast Twitch:** large, pale fibers w/ rapid contraction rates, rapid ATP production, work anaerobically, fatigue quickly = perfect for short bursts of activity where max force is needed.

   **Slow Twitch:** Darker due to the presence of myoglobin, small in diameter, slower ATP production, aerobic, fatigue slowly = endurance activities.
INSTRUCTIONS: Test your vocabulary by matching each term to its definition, as identified by its preceding letter code.

- **Actin (thin filament)**
  - A. Muscle cell containing a bundle of myofibrils.

- **Antagonistic pair**
  - B. Muscle that is primarily responsible for a specific movement and produces most of the force required.

- **Blood lactate**
  - C. Name given to a pair of muscles whose actions oppose each other, when one contracts the other relaxes (e.g., the biceps and triceps).

- **Cardiac muscle**
  - D. The muscle fibre that predominates during aerobic, endurance activity. They contain more mitochondria and myoglobin than fast twitch fibre types.

- **Cross bridge**
  - E. The decline in a muscle's ability to maintain force in a prolonged or repeated contraction. It is the normal result of vigorous exercise.

- **Fast twitch**
  - F. An actin binding protein important in muscle contraction by regulating the binding of myosin.

- **Filament (=myofilament)**
  - G. A protein found in the thick myofilaments of the sarcomere of muscle.

- **Muscle fatigue**
  - H. The filaments that make up the myofilibril can be thick or thin. Thin filaments consist primarily of the protein actin. Thick filaments consist primarily of the protein myosin.

- **Muscle fiber**
  - I. The amount of lactate in the blood. Its presence is a result of anaerobic metabolism when oxygen delivery to the tissues is insufficient to support metabolic demands (e.g., periods of strenuous exercise).

- **Myofibril**
  - J. A cumulative deficit of oxygen resulting from intense exercise. The oxygen deficit is made up during the recovery (rest) period.

- **Neuromuscular junction**
  - K. A contractile protein found in muscle cells.

- **Oxygen debt**
  - L. Specialized structure of muscle cells. Composed of two kinds of myofilaments (thick and thin). A bundle of these make up a muscle fiber.

- **Prime mover**
  - M. The contractile element of the fiber, it is contained between two Z membranes.

- **Sarcomere**
  - N. Specialized smooth endoplasmic reticulum found around myofibrils in skeletal muscle fibres. It stores and releases calcium ions required for muscle contraction.

- **Sarcoplasmic reticulum**
  - O. The junction between a motor neuron and a skeletal muscle fiber. It is a specialized cholinergic synapse.

- **Skeletal (=striated) muscle**
  - P. A complex of three proteins that bind to tropomyosin and help regulate muscle contraction by causing tropomyosin to either block or unblock the attachment of myosin to actin.

- **Sliding filament hypothesis**
  - Q. The theory of how thin and thick filaments slide past each other to produce muscles contraction.

- **Slow twitch**
  - R. The muscle responsible for automatic movements such as peristalsis. It is not under conscious control. Cells are spindle shaped with one central nucleus.

- **Smooth muscle**
  - S. The temporary linkage of actin and myosin filaments during muscle contraction.

- **Tropomyosin**
  - T. Specialized striated muscle that does not fatigue. It is found only in the walls of the heart and is not under conscious control (involuntary muscle).

- **Troponin**
  - U. The muscle fibre that predominates during anaerobic, explosive activity. It contains less mitochondria and myoglobin than slow twitch fibre types.

- **Muscle that is attached to the skeleton and responsible for the movement of bone around joints or movement of some organs, e.g., the eyes.**
  - V.