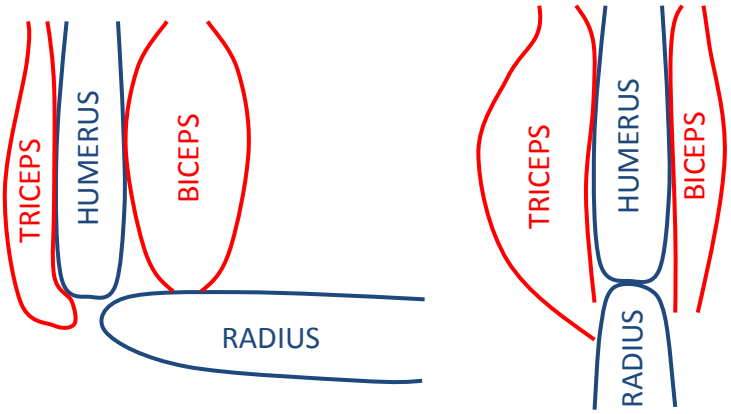
8.2 Muscle action

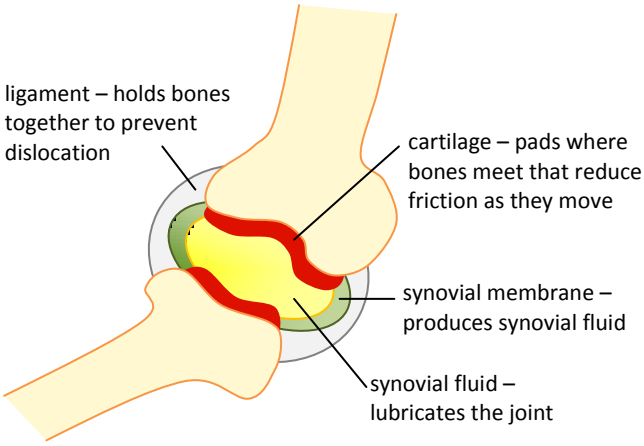
Neuromuscular junctions, types of muscle and the sliding filaments model

Muscles and joints

Muscles can work in **antagonistic** pairs. In order for smooth movement at a muscular junction, such as the elbow, two muscles must be involved. A muscle can only produce a force when it contracts, so if there are two muscles, the bone at the joint can only move smoothly if one muscle contracts, and the other relaxes. Below is a simply diagram showing the behaviour of the biceps and triceps in one arm when the arm is relaxed and when the elbow is bent perpendicularly.



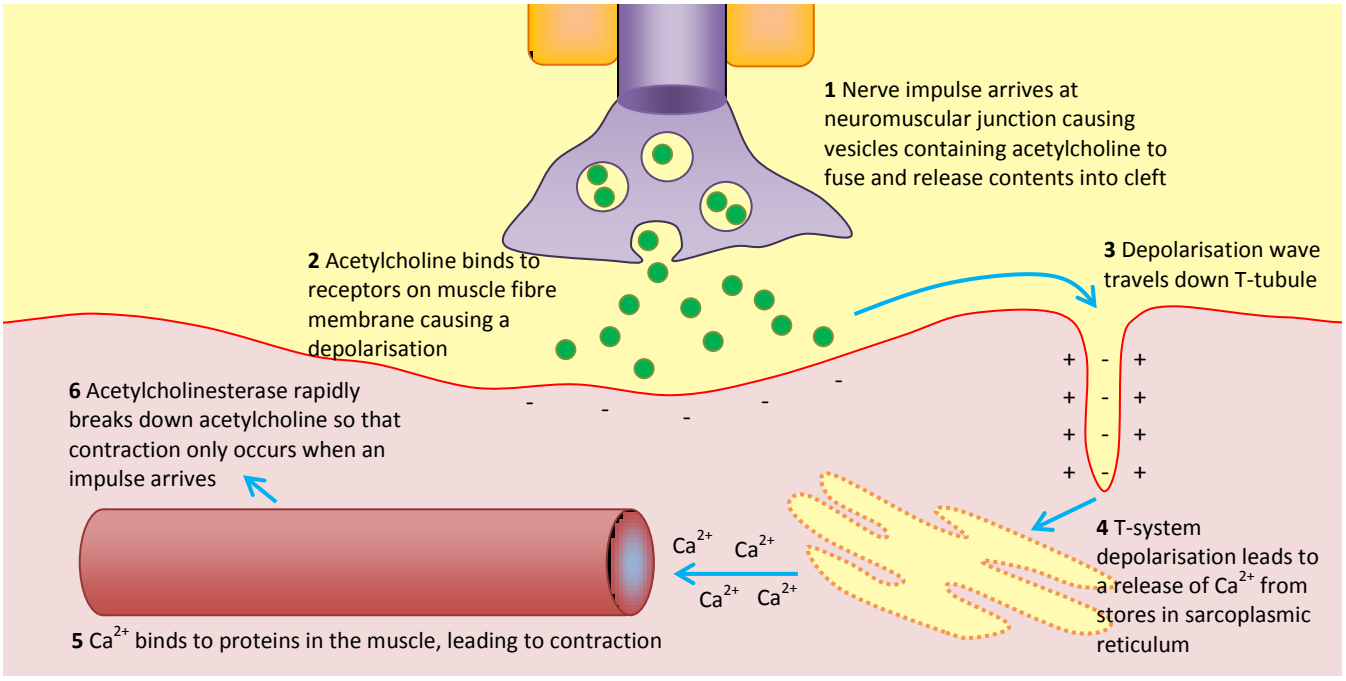
The elbow joint is an example of a **synovial** joint where a lot of movement occurs. These muscles do operate as an antagonistic pair, and although they cannot actively contract, they re-extend when pulled by the opposite antagonistic muscle.



Synovial joints such as the elbow, which is displayed in the diagram to the right, produce **synovial fluid** (from the synovial membrane) which acts as a lubricant for the joint. This is there to ease the movement of the bones at the joint. At the terminus of each bone there is **cartilage** which has the purpose of reducing friction due to movement of the bones. The protective **ligament** casing keeps the bones together when they move.

Neuromuscular junctions

Muscle action is controlled by the nervous system. There are **motor neurones** connected to muscles cells over a junction called a **neuromuscular junction**.



A nerve impulse which arrives at the neuromuscular junction is transmitted across the gap via a method very similar to that of the cholinergic synapse (see 1.4 Synapses for details on the nerve junction, because you are expected to be able to compare similarities and differences between the two) and a small chain of events eventually stimulates a contraction of the muscle:

1. An electrical impulse arrives at the terminus of the motor neurone, where there are vesicles containing the neurotransmitter **acetylcholine**. The action potential triggers the vesicles to move the neurone membrane and fuse, releasing the chemical across the neuromuscular cleft
2. The acetylcholine binds to receptors on the muscle fibre membrane, which triggers a **depolarisation** in the membrane
3. The wave of depolarisation travels along the muscular membrane, until it reaches a tubule of the T-system, called a **T-tubule**, a deep cleft in the **sarcolemma** (muscle fibre membrane)
4. The depolarisation in the T-system sends out a message causing **sarcoplasmic reticulum** (a specialised form of endoplasmic reticulum found only in muscle fibres) to release calcium ions (Ca^{2+}) from its vast stores
5. The calcium moves towards proteins embedded in the muscle, and binds to those proteins, causing a contraction
6. Acetylcholinesterase breaks down acetylcholine into choline and ethanoic acid, so that the neuromuscular junction is not constantly activated, but is only active when a new impulse arrives at the junction

The table below outlines some of the differences and similarities between the neuromuscular junction and the synapse:

Similarities	Differences
both use acetylcholine as the neurotransmitter (provided the synapse in question is the cholinergic synapse)	T-tubules carry the electrical signal quickly into the inside of the muscle cell, whereas at a synaptic junction the message is passed on by the movement of sodium ions
the enzyme acetylcholinesterase is involved in both for breaking down acetylcholine to maintain a concentration gradient and prevent constant impulses being transmitted	the neuromuscular junction is only ever excitatory, whereas synapses can be either excitatory or inhibitory
both are triggered by the arrival of an action potential on the pre-synaptic/motor neurone membrane	the synapse sends a message from neurone-to-neurone, whereas the neuromuscular junction transmits a signal from neurone-to-muscle

Types of muscle

There are three types of muscle:

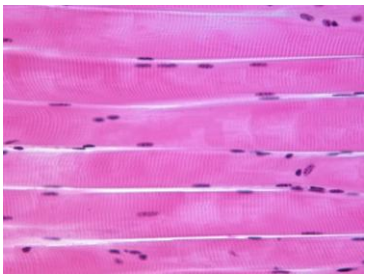
- **skeletal muscle** (also known as striated muscle or *voluntary muscle*)
- **smooth muscle** (also known as *involuntary muscle*)
- **cardiac muscle**

All muscle types are composed of cells that are elongated to form fibres, but the three types above differ significantly in many areas of their structure. The autonomic nervous system is responsible for the control of all involuntary muscle, that includes smooth muscle and cardiac muscle; and the somatic nervous system is responsible for the control of all voluntary muscle – voluntary muscle is also called striated or skeletal muscle.

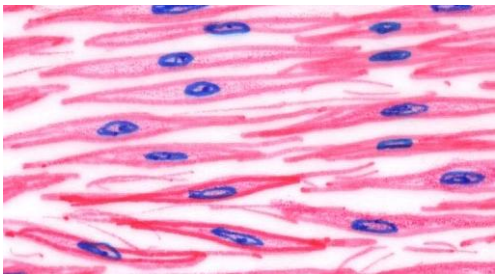
All smooth muscle in the body is *not* under voluntary control. There are many different types of smooth muscle, and it is found all over the body. Smooth muscle can be found surrounding alveoli, the iris of the eye, the walls of the intestine and the walls of arteries and arterioles. Examples of functions of smooth muscle include:

- in the walls of the intestine, bundles of smooth muscle are responsible for **peristalsis** (moving food along the tract)
- in the iris of the eye, groups of the muscle control the intensity of light entering the eye, by contracting their *radial bundles* of muscle to dilate the pupil, or contracting their *circular bundles* of muscle to constrict the pupil

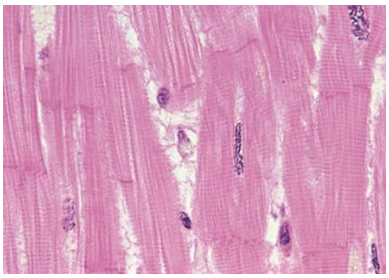
Cardiac muscle is **myogenic**, meaning some of the muscle fibres from atrial and ventricular muscle can contract without receiving a nerve impulse, although nerves from the autonomic nervous system constantly send impulses to the cardiac muscle to regulate heart rate. The contraction and relaxation of the cardiac muscle is repetitive and continuous throughout your entire life. The muscle always contracts powerfully, unless there is a medical problem, and cardiac muscle doesn't fatigue.



Cells of **skeletal muscle** are large cells, long and thin, and are **multinucleated** cells (have many nuclei), and under the light microscope skeletal muscle appears banded (striated) in repetitive strips



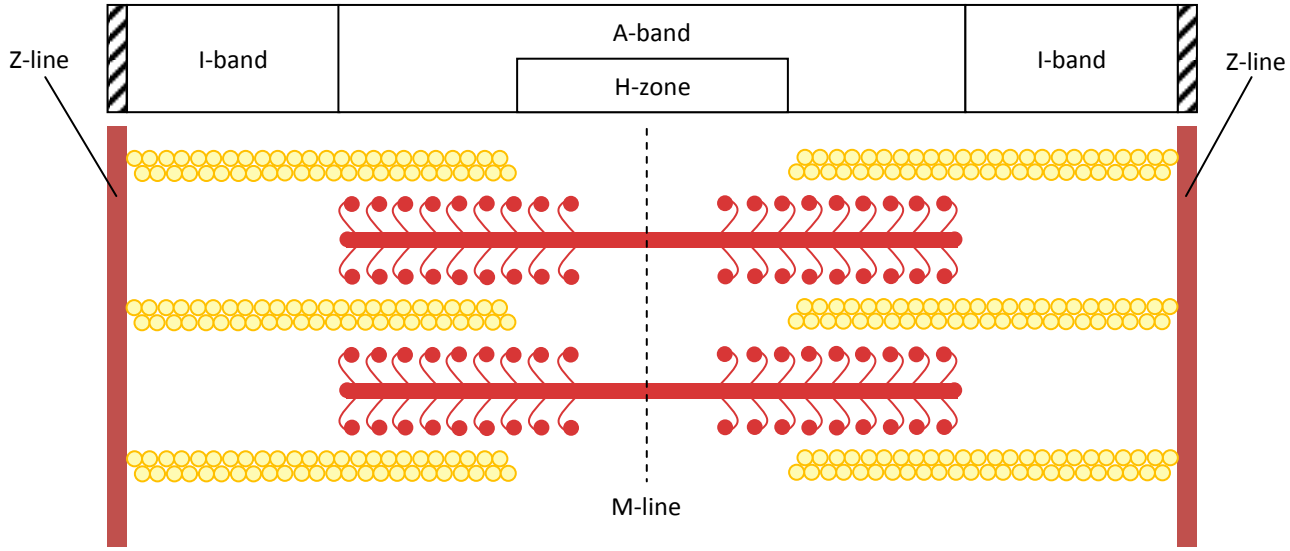
The cells of **smooth muscle** appear spindle-shaped, with small gaps (fenestrations) in between them, and the cells are singly-nucleated, and not striated – they contain small bundles of *actin* and *myosin* and contract very slowly compared to the other two types of muscle

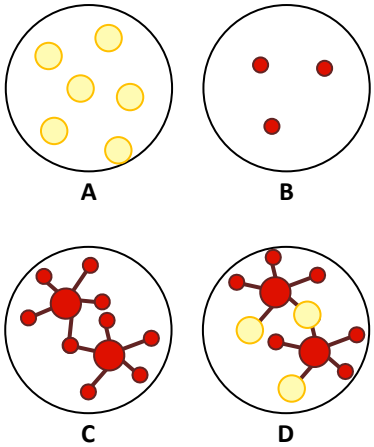


Cardiac muscle cells also appear striated (banded) but are not to be confused with skeletal muscle, and the cells actually have connecting platforms between each other called **intercalated discs**

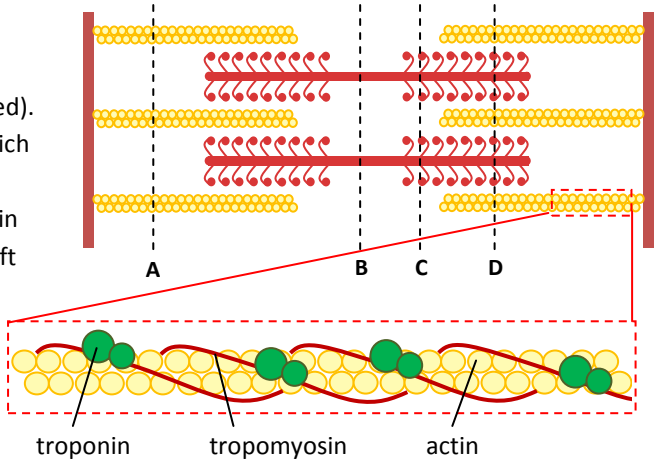
Sliding filament theory of contraction

The action of voluntary muscles leads to the movement of the skeleton at the joints. The appearance of skeletal muscle under the light microscope can be seen above in the image. Each fibre of skeletal muscle is surrounded by a membrane called the **sarcolemma** which contains the muscular cytoplasm (known as the **sarcoplasm**). The fibres make up many **sarcomeres** (one sarcomere is the smallest contractile unit of a muscle, which is seen below). These muscle cells are rich in mitochondria, and have their own specialised endoplasmic reticulum, called *sarcoplasmic reticulum*, which has rich calcium stores for stimulating contracting at the neuromuscular junction. The striated bands of skeletal muscle are separated and given names, which are shown in the diagram below.





The muscle bands are filled primarily with two proteins: **actin** (yellow) and **myosin** (red). There are various 'zones' which give the muscle its banded appearance, that are shown in the diagram above. To the left are cross-sections of various parts of the muscle, and the right shows the thin filament in more detail.



So there are two components of the **sliding filament model**. The *thin filament* consists of two thin strands of actin, a globular protein, coiled around each other. Surrounding them is another rod-shaped protein called **tropomyosin** which coils around the actin. The role of tropomyosin is to reinforce the actin strands. Attached to each molecule of tropomyosin is a molecule of **troponin** – a complex consisting of three polypeptides: one binding to actin, one binding to tropomyosin, and one binding to calcium ions.

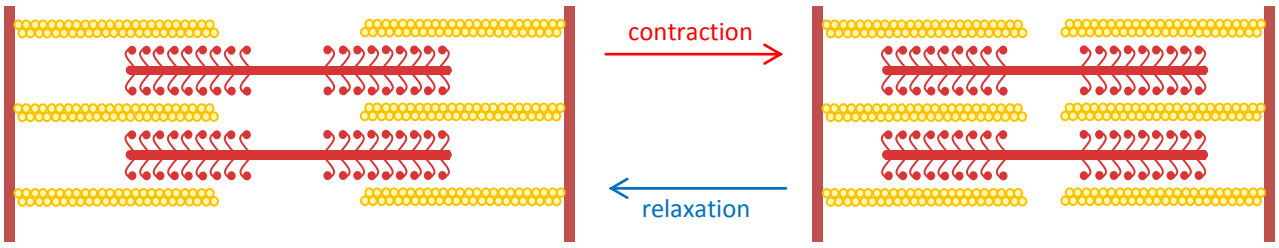
The *thick filament* consists simply of bundles of the protein myosin. There are molecules of myosin along the thin strand which consist of two tails pointing out of the strand at opposite ends, and at each end of the tail is a **myosin head**.

- the **I-band** consists solely of the thin filament (mainly actin), and is on either end of the sarcomere
- the **H-zone** consists solely of the thick filament in the centre of the sarcomere (just myosin)
- the **A-band** comprises both the thin and the thick filaments (the entire sarcomere excluding the I-band)
- the **M-line** is found at the centre of the sarcomere, through the centre of the A-band and H-zone
- the **Z-line** is found at either end of the sarcomere, and separates adjacent sarcomeres (also sometimes known as Z-discs as they are really disc-shaped proteins in the myofibrils which hold the thin filaments in place)

During muscle contraction, this is how the sliding filament theory explains contraction:

1. The binding sites on actin for the myosin heads are covered up by the molecule tropomyosin, but when calcium ions enter the muscle cell and bind to the binding site on troponin, they shift shape slightly, revealing the binding site for the myosin heads on the actin – so when calcium ions are not present, the muscle cannot contract, but as calcium moves into the cell and binds to troponin, myosin is able to bind to the actin molecules
2. After calcium moves into the cell and binds to troponin, revealing the actin binding sites, the myosin heads attach to the surrounding actin (which they have a slight affinity for), forming a **cross-bridge**
3. The myosin heads all have a molecule of ADP and a phosphate attached to them when not active. When the heads bind to the actin, they eject the ADP and phosphate, which releases energy, and they use this energy to bend their heads towards the thin filaments and pull the thin filament towards them (this is the **power stroke**)
4. Then a molecule of ATP replaces the one lost before it on the myosin head, which breaks down the cross-bridge, and the ATP is hydrolysed to give an ADP and a phosphate – returning the myosin back to its original state – and this causes the myosin head to pull back down, releasing the thin filament, which slides back into place
5. So long as there is still calcium present in the muscle cell, the actin binding sites will remain open, and so this cycle can continue for as long as the calcium remains (another resource the cell must have for this to happen is ATP to keep replenishing the lost molecules of ADP and phosphate groups)

The diagram below shows the sarcomere during its relaxed state and during contraction. You can see what happens to the I-band and the H-zone (they both shorten in size as the thin filaments are pulled in by the thick filaments), but notice that the A-band remains the same length, as the length of the thick filament does not change.



In order for the contraction to stop, the calcium ions must be removed from the muscle cell via *active transport*. This is another use for ATP in the muscle cell. Once the calcium break away from the troponin, and exit the cell, the tropomyosin shifts back over the actin to cover the binding sites: this prevents myosin heads from forming cross-bridges there.

It is important to note that during the power stroke, it is not the hydrolysis of ATP that releases the energy needed for the stroke, but actually the release of ADP and phosphate which generates the energy for the power stroke.

ATP is stored quite well in muscle cells, as they have such high energy requirements. ATP is obtainable from *aerobic respiration* and *anaerobic respiration* (although the latter has a much lower net ATP production), and different amounts of ATP are generated depending on the respiratory substrate used.