1

Basic units, structure and function: supporting tissues, muscle and nerve

Key terms

connective tissues, articulations, skeletal muscle, neurone, muscle tone

Conceptual overview

This chapter addresses the basic components of structure that are organised to allow movement at joint level. Nerves, muscles and connective tissues work together to produce movement: connective tissues which provide stability and support; skeletal muscle which changes in length and pulls on bones to produce movements at joints; and neurones and nerves which conduct information between the environmental sensors, the control centres for movement and the muscles.

Framework and support: the connective tissues

The overall function of connective tissue is to unite or connect structures in the body, and to give support. Bone is a connective tissue which provides the rigid framework for support. Where bones articulate with each other dense fibrous connective tissue, rich in collagen fibres, surrounds the ends of the bones, allowing movement to occur while maintaining stability. Cartilage, another connective tissue, is also found associated with joints, where it forms a compressible link between two bones, or provides a low-friction surface for smooth movement of one bone on another. Connective tissue attaches muscles to bone, in the form of either a cord (tendon) or a flat sheet (fascia). The connective tissues may be divided into:

- **dense fibrous tissue**;
- **cartilage**;
- **bone**.

Dense fibrous tissue

Dense fibrous connective tissue unites structures in the body while still allowing movement to occur. It has high tensile strength to resist stretching forces. This connective tissue has few cells and is largely made up of fibres of collagen and elastin that give the tissue great strength. The fibres are produced by fibroblast cells that lie in between the fibres (Figure 1.1). The toughness
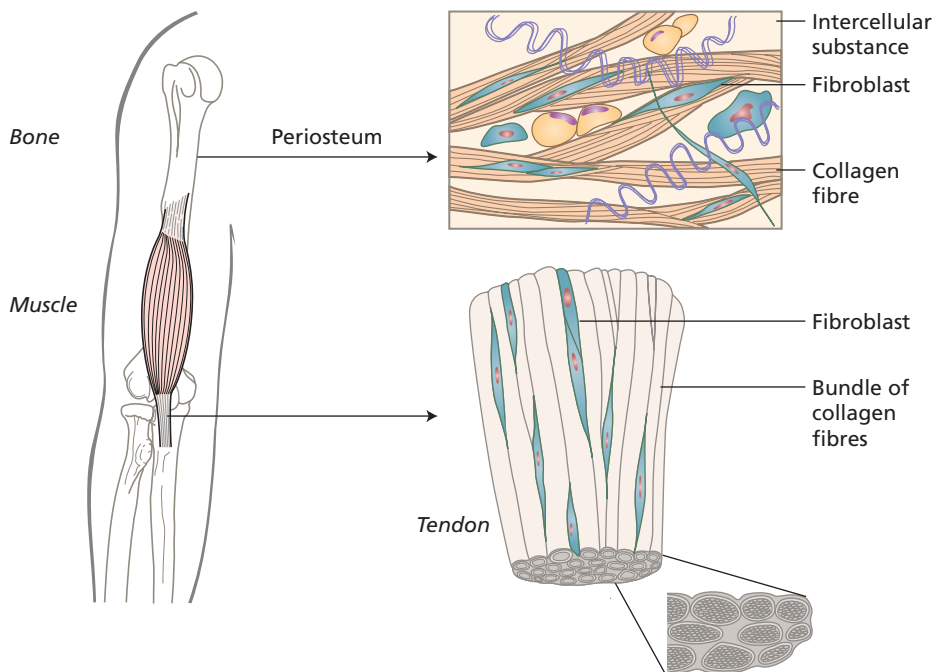

Figure 1.1   Dense fibrous connective tissue seen covering bone as periosteum, and forming the tendon of a skeletal muscle.

of this tissue can be felt when cutting through stewing steak with a blunt knife. The muscle fibres are easily sliced, but the covering of white connective tissue is very tough. Examples of this tissue are as follows:

- The **capsule** surrounding the movable (synovial) joints which binds the bones together (see Figure 1.7).
- **Ligaments** form strong bands that join bone to bone. Ligaments strengthen the joint capsules in particular directions and limit movement.
- **Tendons** unite the contractile fibres of muscle to bone.

   In tendons and ligaments, the collagenous fibres lie in parallel in the direction of greatest stress.

- An **aponeurosis** is a strong flat membrane, with collagen fibres that lie in different directions to form sheets of connective tissue. An aponeurosis can form the attachment of a muscle, such as the oblique abdominal muscles, which meet in the midline of the abdomen (see Chapter 10, Figure 10.6). In the palm of the hand and the sole of the foot an aponeurosis lies deep to the skin and forms a protective layer for the tendons underneath (see Chapter 8, Figure 8.21).
- A **retinaculum** is a band of dense fibrous tissue that binds tendons of muscles and prevents bowstring during movement. An example is the flexor retinaculum of the wrist, which holds the tendons of muscles passing into the hand in position (see Chapter 6, Figure 6.15).
- **Fascia** is a term used for the large areas of dense fibrous tissue that surround the musculature of all the body segments. Fascia is particularly developed in the limbs, where it dips down between the large groups of muscles and attaches to the bone. In some areas, fascia provides a base for the attachment of muscles, for example the thoracolumbar fascia gives attachment to the long muscles of the back (see Chapter 10, Figure 10.6).
- **Periosteum** is the protective covering of bones. Tendons and ligaments blend with the periosteum around bone (see Figure 1.3).
- **Dura** is thick fibrous connective tissue protecting the brain and spinal cord (see Chapter 3, Figure 3.21).

Cartilage

Cartilage is a tissue that can be compressed and has resilience. The cells (chondrocytes) are oval and lie in a ground substance that is not rigid like bone. There is no blood supply to cartilage, so there is a limit to its thickness. The tissue has great resistance to wear, but cannot be repaired when damaged.

   Hyaline cartilage is commonly called gristle. It is smooth and glass-like, forming a low-friction covering to the articular surfaces of joints. In the elderly, the articular cartilage tends to become eroded or calcifies, so that joints become stiff. Hyaline cartilage forms the costal cartilages which join the anterior ends of the ribs to the sternum (Figure 1.2). In the developing foetus, most of the bones are formed in hyaline cartilage. When the cartilaginous model of each bone reaches a critical size for the survival of the cartilage cells, ossification begins.

> **Reflective task**
>
> Look at some large animal bones from the butcher to see the cartilage covering the joint surfaces at the end. Note that it is bluish and looks like glass.
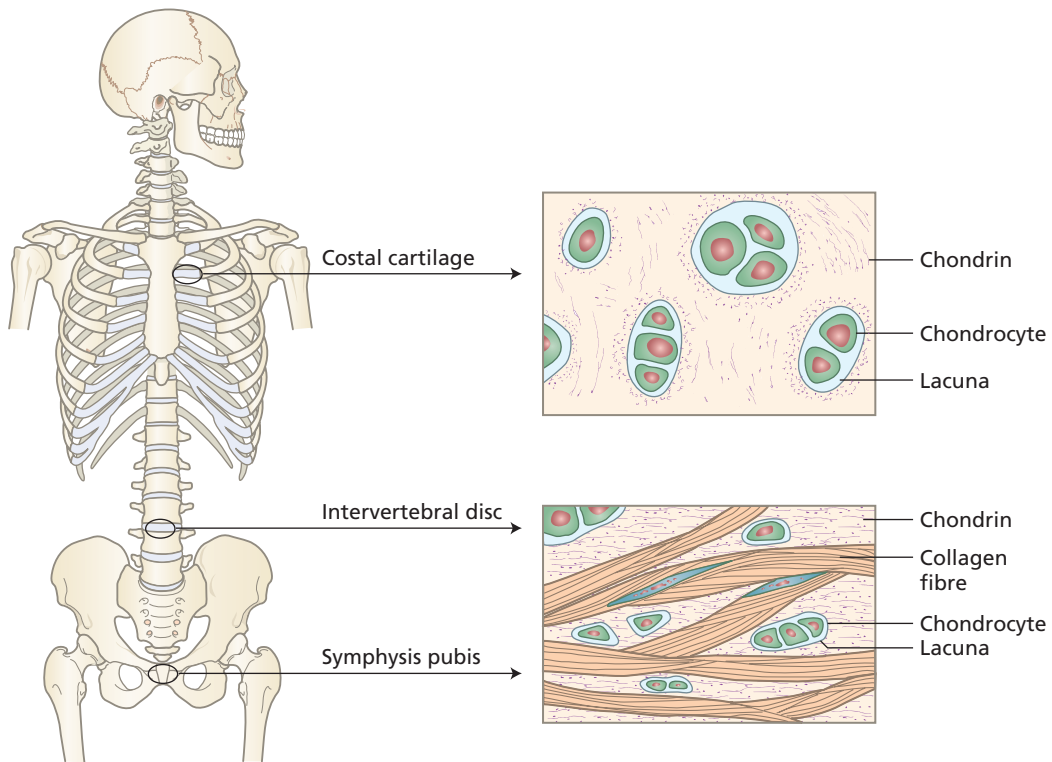
Figure 1.2   Microscopic structure of hyaline and fibrocartilage, location in the skeleton of the trunk.

Fibrocartilage consists of cartilage cells lying in between densely packed collagen fibres (Figure 1.2). The fibres give extra strength to the tissue while retaining its resilience. Examples of where fibrocartilage is found are the discs between the bones of the vertebral column, the pubic symphysis joining the two halves of the pelvis anteriorly, and the menisci in the knee joint.

Bone

Bone is the tissue that forms the rigid supports for the body by containing a large proportion of calcium salts (calcium phosphate and carbonate). It must be remembered that bone is a living tissue composed of cells and an abundant blood supply. It has a greater capacity for repair after damage than any other tissue in the body, except for blood. The strength of bone lies in the thin plates (lamellae), composed of collagen fibres with calcium salts deposited in between. The lamellae lie in parallel, held together by fibres, and the bone cells or **osteocytes** are found in between. Each bone cell lies in a small space or lacuna, and connects with other cells and to blood capillaries by fine channels called canaliculi (Figure 1.3).

In **compact bone**, the lamellae are laid down in concentric rings around a central canal containing blood vessels. Each system of concentric lamellae (known as a Haversian system or an osteon)
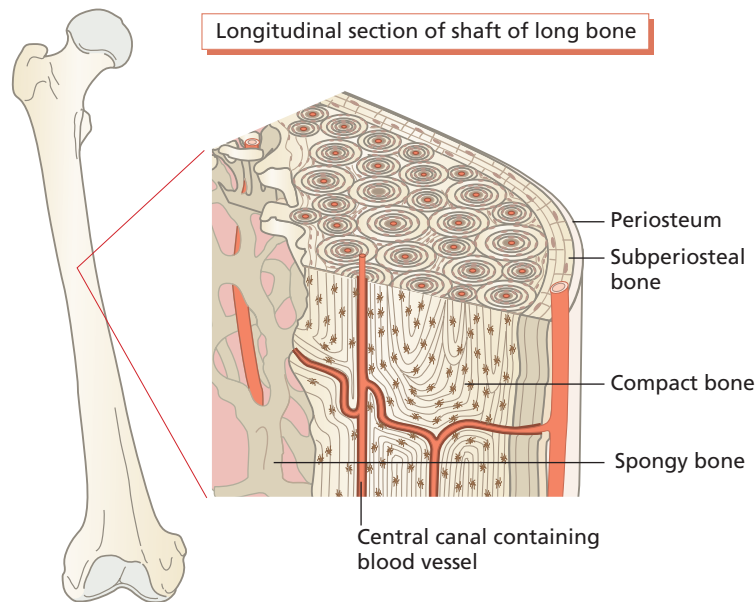
Longitudinal section of shaft of long bone

Periosteum

Subperiosteal bone

Compact bone

Spongy bone

Central canal containing blood vessel

Figure 1.3   A section of the shaft of a long bone.

lies in a longitudinal direction. Many of these systems are closely packed to form the dense compact bone found in the shaft of long bones (Figure 1.3).

Practice note-pad 1A: osteoporosis

Osteoporosis is literally a condition of porous bones, largely due to a depletion of calcium from the body. For a number of reasons, calcium loss exceeds calcium absorption from the diet, causing bone mass to decrease excessively. This leads to fractures occurring as a result of normal mechanical stresses upon the skeleton which it would normally withstand. Spontaneous fractures may also occur.

In **cancellous** or trabeculate bone, the lamellae form plates arranged in different directions to form a mesh. The plates are known as trabeculae and the spaces in between contain blood capillaries. The bone cells lying in the trabeculae communicate with each other and with the spaces by canaliculi. The expanded ends of long bones are filled with cancellous bone covered with a thin layer of compact bone. The central cavity of the shaft of long bones contains bone marrow. This organisation of the two types of bone produces a structure with great rigidity without excessive weight (Figure 1.4). Bone has the capacity to remodel in shape in response to the stresses on it, so that the structure lines of the trabeculae at the ends of the bone follow the lines of force on the bone. For example, the lines of trabeculae at the ends of weight-bearing bones, such as
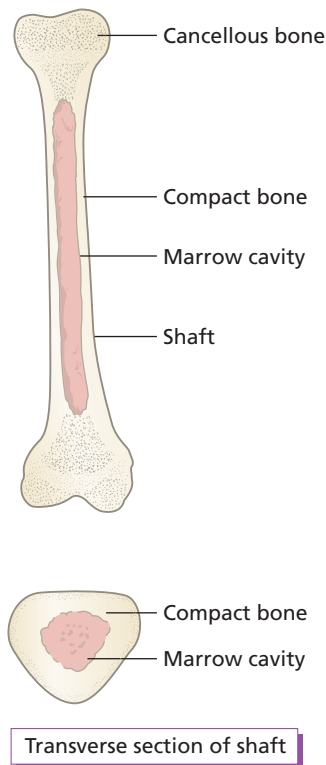
Figure 1.4   Gross structure of long bone: longitudinal and transverse sections.

the femur, provide maximum strength to support the body weight against gravity. Remodelling of bone is achieved by the activity of bone-forming cells known as osteoblasts, and bone-destroying cells known as osteoclasts; both types of cell are found in bone tissue. The calcium salts of bone are constantly interchanging with calcium ions in the blood, under the influence of hormones (parathormone and thyrocalcitonin). Bone is a living, constantly changing connective tissue that provides a rigid framework on which muscles can exert forces to produce movement.

> **Reflective task**
>
> Look at any of the following examples of connective tissue that are available to you:
>
> (1)   Microscopic slides of dense fibrous tissue, cartilage and bone, noting the arrangement of the cellular and fibre content.
> (2)   Dissected material of joints and muscles which include tendons, ligaments, aponeurosis and retinaculum.
> (3)   Fresh butcher's bone: note the pink colour (blood supply), and the central cavity in the shaft of long bones.
> (4)   Fresh red meat to see fibrous connective tissue around muscle.

Articulations

Where the rigid bones of the skeleton meet, connective tissues are organised to bind the bones together and to form joints. It is the joints that allow movement of the segments of the body relative to each other. The joints or articulations between bones can be divided into three types based on the particular connective tissues involved. The three main classes of joint are **fibrous**, **cartilaginous** and **synovial**.

Fibrous joints

Here, the bones are united by dense fibrous connective tissue.

The **sutures** of the skull are fibrous joints that allow no movement between the bones. The edge of each bone is irregular and interlocks with the adjacent bone, a layer of fibrous tissue linking them (Figure 1.5a).

A **syndesmosis** is a joint where the bones are joined by a ligament that allows some movement between the bones. A syndesmosis is found between the radius and the ulna (Figure 1.5b). The interosseous membrane allows movement of the forearm.

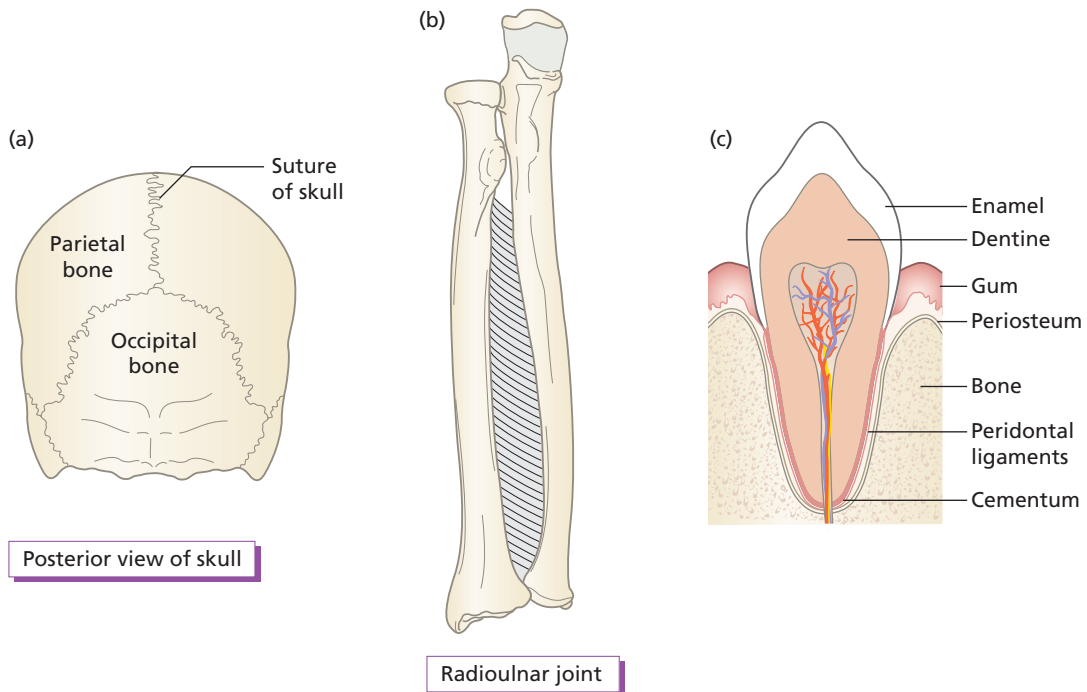A **gomphosis** is a specialised fibrous joint that fixes the teeth in the sockets of the jaw (Figure 1.5c).

(a)

Suture of skull

Parietal bone

Occipital bone

Posterior view of skull

(b)

Radioulnar joint

(c)

Enamel
Dentine
Gum
Periosteum
Bone
Peridontal ligaments
Cementum

Figure 1.5   Fibrous joints: (a) suture between bones of the skull; (b) syndesmosis between the radius and ulna; (c) gomphosis: tooth in socket.

Cartilaginous joints

In these joints the bones are united by cartilage.

A **synchondrosis** or primary cartilaginous joint is a joint where the union is composed of hyaline cartilage. This type of joint is also called primary cartilaginous. The articulation of the first rib with the sternum is by a synchondrosis. During growth of the long bones of the skeleton, there is a synchondrosis between the ends and the shaft of the bone, where temporary cartilage forms the epiphyseal plate. These plates disappear when growth stops and the bone becomes ossified (Figure 1.6a).

A **symphysis** or secondary cartilaginous joint is a joint where the joint surfaces are covered by a thin layer of hyaline cartilage and united by a disc of fibrocartilage. This type of joint (sometimes called secondary cartilaginous) allows a limited amount of movement between the bones by compression of the cartilage. The bodies of the vertebrae articulate by a disc of fibrocartilage (Figure 1.6b). Movement between two vertebrae is small, but when all of the intervertebral discs are compressed in a particular direction, considerable movement of the vertebral column occurs. Little movement occurs at the pubic symphysis, the joint where the right and left halves of the pelvis meet. Movement is probably increased at the pubic symphysis in the late stage of pregnancy and during childbirth, to increase the size of the birth canal.
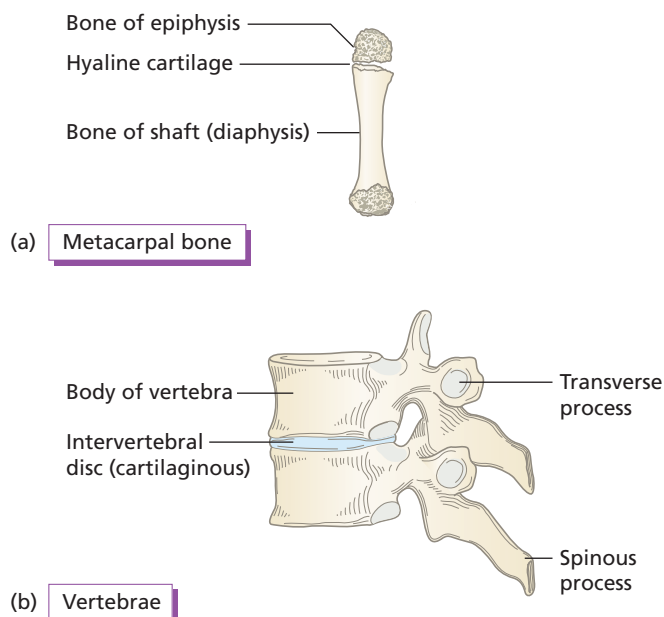
Bone of epiphysis

Hyaline cartilage

Bone of shaft (diaphysis)

(a) Metacarpal bone

Body of vertebra

Intervertebral disc (cartilaginous)

Transverse process

Spinous process

(b) Vertebrae

Figure 1.6   Cartilaginous joints: (a) synchondrosis in a child's metacarpal bone, as seen on X-ray; (b) symphysis between the bodies of two vertebrae.
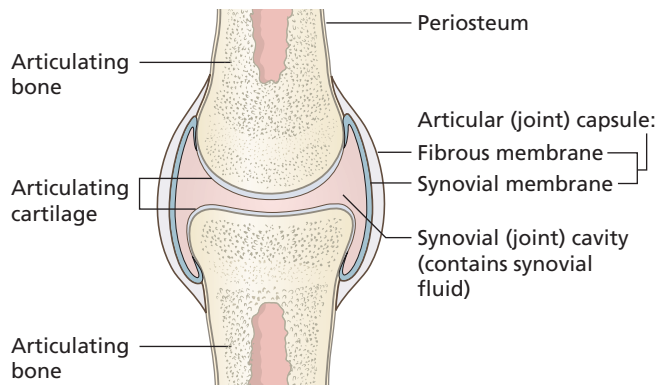
Figure 1.7   Typical synovial joint.

Synovial joints

Synovial joints are the mobile joints of the body. There is a large number of these joints, which show a variety of form and range of movement. The common features of all of them are shown in the section of a typical synovial joint (Figure 1.7) and listed as follows:

- **Hyaline cartilage** covers the ends of the two articulating bones, providing a low-friction surface for movement between them.
- A **capsule** of dense fibrous tissue is attached to the articular margins, or some distance away, on each bone. The capsule surrounds the joint like a sleeve.
- There is a **joint cavity** inside the capsule which allows free movement between the bones.
- **Ligaments**, bands or cords of dense fibrous tissue, join the bones. The ligaments may blend with the capsule or they are attached to the bones close to the joint.
- A **synovial membrane** lines the joint capsule and all non-articular surfaces inside the joint, i.e. any structure within the joint not covered by hyaline cartilage.

One or more bursae are found associated with some of the synovial joints at a point of friction where a muscle, a tendon or the skin rubs against any bony structures. A bursa is a closed sac of fibrous tissue lined by a synovial membrane and containing synovial fluid. The cavity of the bursa sometimes communicates with the joint cavity. Pads of fat, liquid at body temperature, are also present in some joints. Both structures have a protective function.

> **Practice note-pad 1B: osteoarthritis**
>
> Osteoarthritis is a degenerative disease occurring in middle-aged and older people. There is a progressive loss of the articular cartilage in the weight-bearing joints, usually the hip and the knees. Bony outgrowths occur at the margins of the joint and the capsule may become fibrosed. The joints become stiff and painful.

> **Practice note-pad 1C: rheumatoid arthritis**
>
> Rheumatoid arthritis is a systemic disease that can occur at any age (average 40 years) and it is more common in women. The peripheral joints (hands and feet) are affected first, followed by the involvement of other joints. Inflammation of the synovial membrane, bursae and tendon sheaths leads to swelling and pain which may be relieved by drugs. Deformity is the result of erosion of articular cartilage, stretching of the capsule and the rupture of tendons.

All of the large movable joints of the body, for example the shoulder, elbow, wrist, hip, knee and ankle, are synovial joints. The direction and the range of their movements depend on the shape of the articular surfaces and the presence of ligaments and muscles close to the joint. The different types of synovial joint are described in Chapter 2 where the directions of movement at joints are considered.

Skeletal muscle

Skeletal muscle is attached to the bones of the skeleton and produces movement at joints. The basic unit of skeletal muscles is the **muscle fibre**. Muscle fibres are bound together in bundles to form a whole muscle, which is attached to bones by fibrous connective tissue. When **tension** develops in the muscle, the ends are drawn towards the centre of the muscle. In this case, the muscle is contracting in length and a body part moves. Alternatively, a body part may be moved by gravity and/or by an added weight, for example an object held in the hand. Now the tension developed in the muscle may be used to resist movement and hold the object in one position.

In summary, the tension developed allows a muscle:

- to shorten to produce movement;
- to resist movement in response to the force of gravity or an added load.

Furthermore, muscles may develop tension when they are increasing in length. This will be considered in Chapter 2, in the section on types of muscle work.

Both muscle and fibrous connective tissue have elasticity. They can be stretched and return to the original length. The unique function of muscle is the capacity to shorten actively.

> **Reflective task**
>
> - Hold a glass of water in the hand. Feel the activity in the muscles above the elbow by palpating them with the other hand. The tension in the muscles is resisting the weight of the forearm and the water.
> - Lift the glass to the mouth. Feel the muscle activity in the same muscles as they shorten to lift the glass.

Structure and form

The structure of a whole muscle is the combination of muscle and connective tissues, which both contribute to the function of the active muscle. In a whole muscle, groups of contractile muscle fibres are bound together by fibrous connective tissue. Each bundle is called a fasciculus. Further coverings of connective tissue bind the fasciculi together and an outer layer surrounds the whole muscle (Figure 1.8).
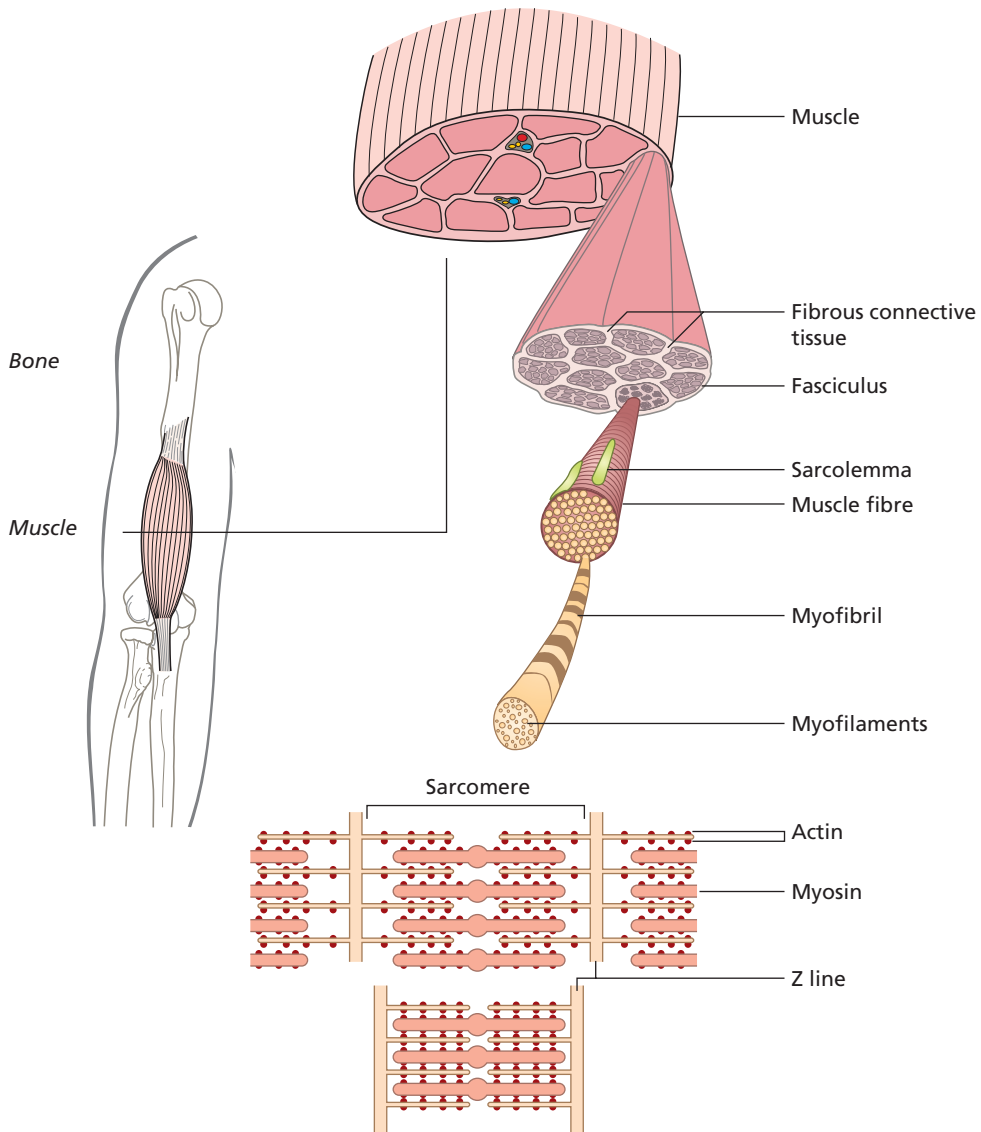
Bone

Muscle

Muscle

Fibrous connective tissue

Fasciculus

Sarcolemma

Muscle fibre

Myofibril

Myofilaments

Sarcomere

Actin

Myosin

Z line

Figure 1.8   Skeletal muscle: the organisation of muscle fibres into a whole muscle, and a sarcomere in the relaxed and the shortened state (as seen by an electron microscope).
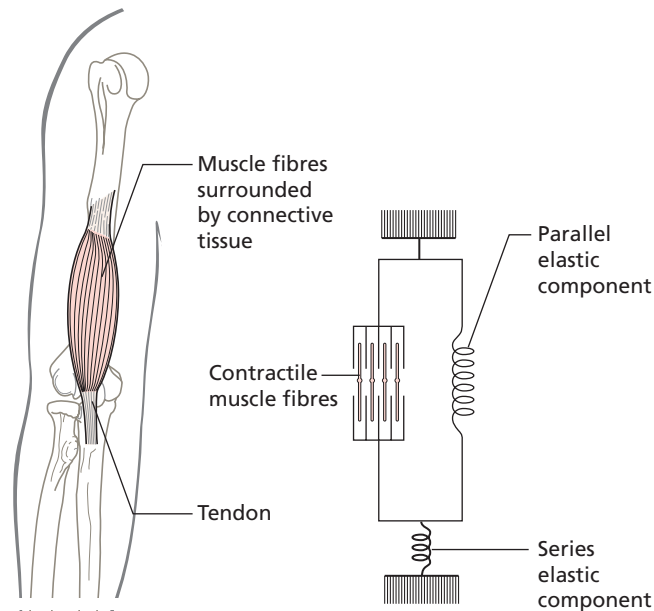
Figure 1.9   Elastic components of muscle.

The total connective tissue element lying in between the contractile muscle fibres is known as the parallel elastic component. The tension that is built up in muscle when it is activated depends on the tension in the muscle fibres and in the parallel elastic component. The fibrous connective tissue, for example a tendon, which links a whole muscle to bone is known as the series elastic component. The initial tension that builds up in an active muscle tightens the series elastic component and then the muscle can shorten. A model of the elastic and contractile parts of a muscle is shown in Figure 1.9. If the connective tissue components lose their elasticity, through lack of use in injury or disease, a muscle may go into contracture. Lively splints are used to maintain elasticity and prevent contracture while the muscle recovers.

The individual muscle fibres lie within a muscle in one of the following two ways:

● Parallel fibres are seen in strap and fusiform muscles (Figure 1.10a, b). These muscles have long fibres which are capable of shortening over the entire length of the muscle, but the result is a less powerful muscle.
● Oblique fibres are seen in pennate muscles. The muscle fibres in these muscles cannot shorten to the same extent as parallel fibres. The advantage of this arrangement, however, is that more muscle fibres can be packed into the whole muscle, so that greater power can be achieved.

The muscles with oblique fibres are known as unipennate, bipennate or multipennate, depending on the particular way in which the muscle fibres are arranged (Figure 1.10c, d). Some of the large muscles of the body combine parallel and oblique arrangements. The deltoid muscle of the shoulder (see Chapter 5, Figure 5.9) has one group of fibres that are multipennate and two groups
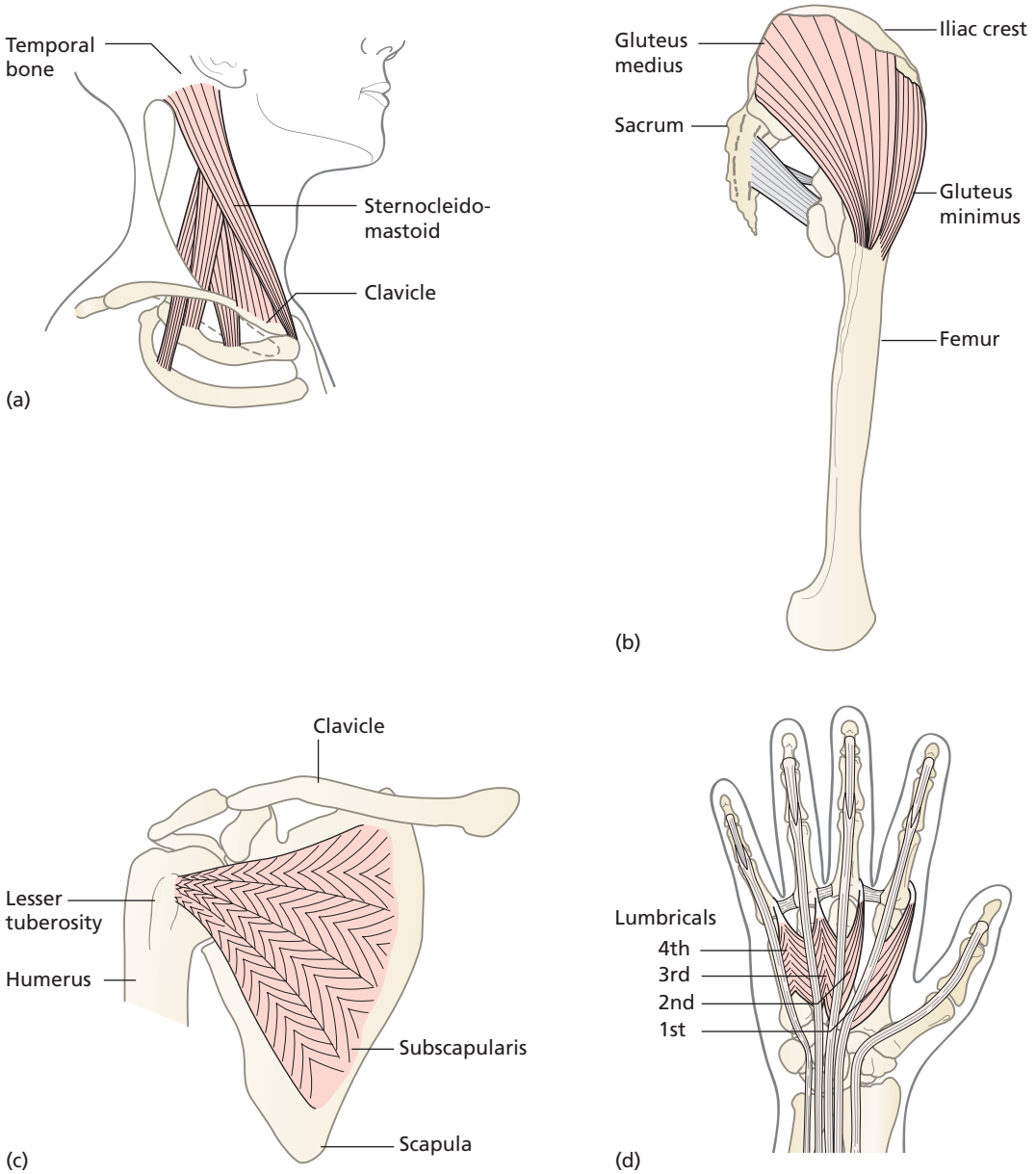
Figure 1.10   Form of whole muscle: parallel fibres (a) strap and (b) fusiform; oblique fibres (c) multipennate and (d) unipennate and bipennate.

that are fusiform, which combines strength to lift the weight of the arm with a wide range of movement. The form of a particular muscle reflects the space available and the demands of range and strength of movement.

Muscles have a limited capacity for repair, although a small area of damage to muscle fibres may regenerate. In more extensive damage, the connective tissue responds by producing more collagen fibres and a scar is formed. An intact nerve and adequate blood supply are essential for muscle function. If these are interrupted the muscle may never recover. Movement can then only be restored by other muscles taking over the functions of the damaged muscles.

Microscopic structure

A muscle fibre can just be seen with the naked eye. Each muscle fibre is an elongated cell with many nuclei surrounded by a strong outer membrane, the sarcolemma. If one fibre is viewed under a light microscope, the nuclei can be seen close to the membrane around the fibre. The chief constituent of the fibre is several hundreds of myofibrils, strands of protein extending from one end of the fibre to the other (Figure 1.8). The arrangement of the two main proteins, actin and myosin, that form each myofibril presents a banded appearance. The light and dark bands in adjacent myofibrils coincide, so that the whole muscle fibre is striated.

The electron microscope reveals the detail of the cross-striations in each myofibril. A repeating unit, known as the sarcomere, is revealed along the length of the myofibril. Each sarcomere links to the next one at a disc called the Z-line. The thin filaments of actin are attached to the Z-line and project towards the centre of the sarcomere. The thicker myosin filaments lie in between the actin strands. The darkest bands of the myofibril are where the actin and myosin overlap in the sarcomere.

The arrangement of the myosin molecules in the thick myosin filaments forms cross-bridges that link with special sites on the active filaments when the muscle fibre is activated. The result of this linking is to allow the filaments to slide past one another, so that each sarcomere becomes shorter. This, in turn, means that the myofibril is shorter, and since all the myofibrils respond together, the muscle fibre shortens.

Reflective task

Look at Figure 1.8, starting at the bottom, to identify the details of the structure of a muscle: (1) sarcomeres lie end to end to form a myofibril; (2) myofibrils are packed tightly together inside a muscle fibre; (3) muscle fibres are bound together in a fasciculus; and (4) fasciculi are bound to form a whole muscle.

In active muscles, the energy required to develop tension is released by chemical reactions. Most of these reactions occur in structures called **mitochondria** (Figure 1.11). All cells have mitochondria, but they are more abundant in muscle fibres where they lie adjacent to the myofibrils. The breakdown of adenosine triphosphate (ATP) and a 'back-up' phosphocreatine provide a high level of energy output in the muscle. The store of ATP is replenished in the mitochondria using oxygen and glucose brought by the blood in the network of capillaries surrounding muscle fibres (Figure 1.11). In this way, the muscle fibres have a continuous supply of energy, as long as the supply of oxygen is maintained (aerobic metabolism). Glycogen is another source of energy that
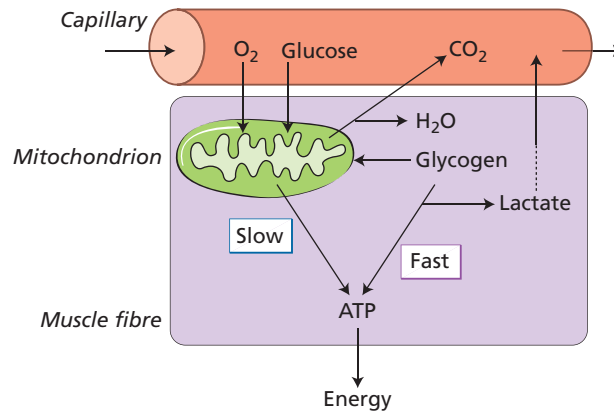
Figure 1.11   Energy for muscle contraction (simplified). The 'slow' pathway predominates in type I fibres, where ATP is replenished by aerobic reactions to provide the energy for long periods of low-level activity. The 'fast' pathway predominates in type II fibres, where glycogen provides energy without oxygen for short bursts of high-level activity.

is stored in muscle fibres. When there is insufficient oxygen to replenish ATP by oxidative reactions, energy is released from breakdown of glycogen to maintain the ATP levels. This occurs during a short burst of high-level muscle activity.

Adaptation of muscles to functional use

Not all muscle fibres in one muscle are the same. Two main types have been distinguished:

- **Slow** fibres, known as type I fibres, are red because they contain myoglobin which stores oxygen, like the haemoglobin in the blood, and they are surrounded by many capillaries. Energy supply for the slow fibres (called SO) is mainly from oxidative reactions. The slow fibres respond to stimulation with a slow twitch and they are resistant to fatigue.
- **Fast** fibres, known as type II fibres, are white with no myoglobin and have fewer capillaries per fibre. Energy is derived mainly from the breakdown of glucose and stored glycogen without oxygen. The fast fibres (called FG) respond with a fast twitch, but they are easily fatigued when the glycogen stores are used up.

Slow fibres are adapted for sustained postural activity, while the fast fibres are recruited for rapid intense bursts of activity, for example running, cycling and kitchen tasks such as cutting bread and chopping vegetables.

Skeletal muscle shows a remarkable capacity to adapt its structure to functional use. Both the relative proportion of slow and fast fibres and the number of sarcomeres in the myofibrils can change over time.

Muscle strength and bulk is increased by progressive resistance training programmes using weights or strength-training machines. The added strength is due to an increase in the number and size of the myofibrils, particularly in the fast muscle fibres which hypertrophy most readily.

Less increase occurs in the slow fibre type. There is little evidence that similar training pro-grammes can strengthen the muscles of patients with chronic degenerative disorders of the neuromuscular system. Any change may depend on the number of remaining intact fibres. For these patients, improvement in stamina rather than strength will be more useful for daily living in any case. Training for endurance in healthy young adults has the effect of changes in some fast fibres, which become more like slow fibres. The presence of these type IIA or FGO fibres increases the length of time that the muscle can perform movement without fatigue.

Studies of the effects of ageing have shown a progressive decrease in the size of fast fibres with fewer changes in slow fibres. These changes are most likely to be the response to a less active life. Fast fibres can increase in size in elderly people, so that exercise programmes are beneficial when there are no pathological changes present.

Muscles also change the number of sarcomeres in the myofibrils if a muscle is held in a short-ened or lengthened position, for example by a plaster cast. Sarcomeres are lost in the shortened position and added in the lengthened position. This is an adaptation to changes in the functional length of the muscle. Any benefit, however, may be overridden by the changes in the muscle which lead to muscle contracture.

Practice note-pad 1D: myopathies

Neuromuscular disorders that are myopathic originate in the muscle, and may be inherited or acquired. There is muscle weakness in the proximal muscles, which is slowly progressive with muscle wasting.

Duchenne muscular dystrophy is an inherited myopathy that affects boys only. There is a rapid progression of muscle weakness that begins in childhood.

Acquired myopathy can result from infections, or endocrine disorders, or as a complica-tion of steroid drug treatment.

Basic units of the nervous system

The functions of the nervous system in movement are: to conduct motor commands from the brain to the muscles; to regulate the activity in the cardiovascular and respiratory systems which supply the muscles with essential nutrients and oxygen; and to monitor changes in the environ-ment that affect movement.

The properties of **neurones** are:

- excitation: neurones generate impulses in response to stimulation;
- conduction of impulses between neurones (in one direction only).

Neurones are organised in networks or centres in the brain and the spinal cord. Activity in one centre is directed to a particular end, for example the location of a specific sensation. The output from one processing centre is then conducted to one or many other centres in a series of opera-tions, for example from motor centres in the brain to the spinal cord. Information can also be conducted in parallel between processing centres.

The properties of neural networks are:

- processing of activity directed to a particular end;
- relay of the output of processing to other centres in the nervous system.

   This section is primarily concerned with the structure and the activity in the basic units of the nervous system, the neurones. Neural processing in specific centres in the central nervous system will be considered in Section III.

The neurone: excitation and conduction

Each neurone has a **cell body** and numerous processes extending outwards from the cell. The processes are living structures and their membrane is continuous with that of the cell body (Figure 1.12). (Think of the cell body like a conker with spines projecting out in all directions.) The
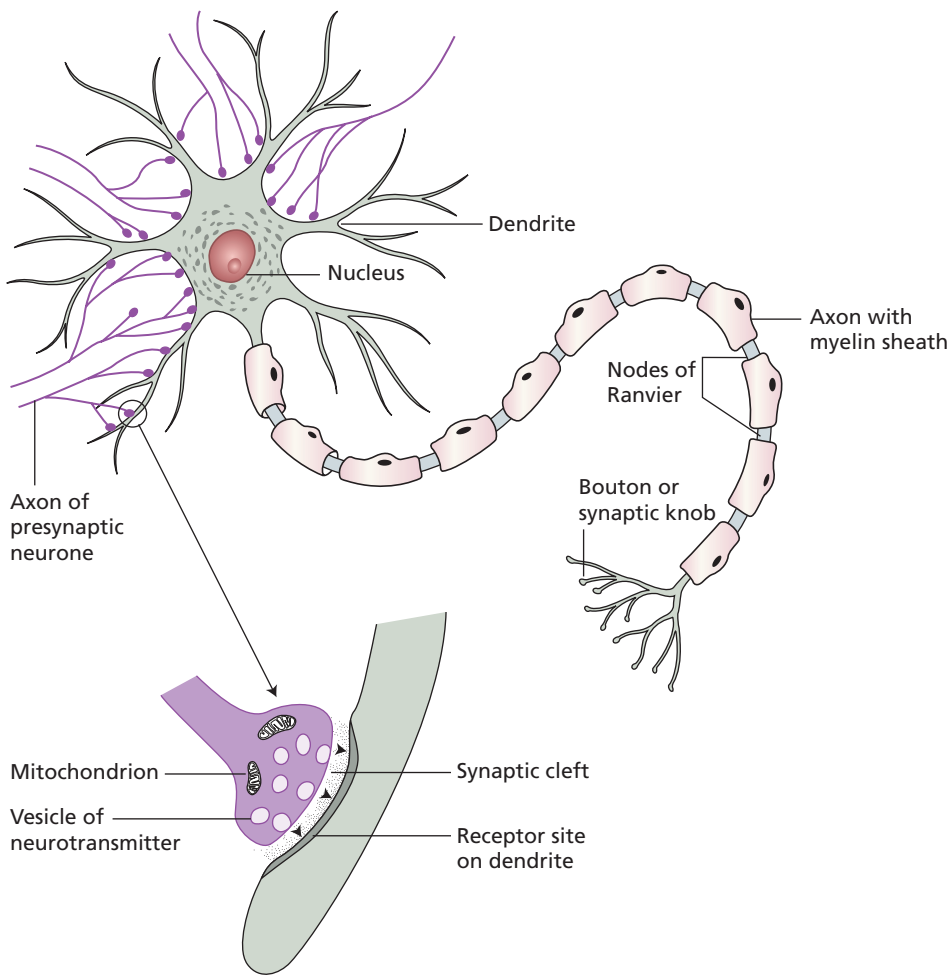

Figure 1.12   Neurone and synapse; synaptic cleft enlarged.

projections vary in length: short processes are called **dendrites**, and each neurone has one long process, the **axon**. The dendrites are adapted to receive signals or impulses and pass them on to the cell body. Some neurones, particularly in the brain, have thousands of complex branching dendrites, so that signals from a large number of other neurones can be received.

The axon is the output end of every neurone. The length of an axon varies from a few millimetres to 1 m. Cell bodies of motor neurones in the spinal cord in the lower back have long axons that extend down the leg to supply the muscles of the foot. The axon may be surrounded by a sheath of **myelin**, a fatty material, which increases the rate at which impulses are conducted down the axon. The myelin is laid down between layers of membrane of Schwann cells that wrap around the axon. Gaps in the myelin occur between successive Schwann cells forming nodes of Ranvier (Figure 1.12).

At the end of the neurone the axon branches, and each branch is swollen to form a bouton or synaptic knob. The boutons lie near a dendrite or cell body of another neurone. A typical motor neurone may have as many as 10 000 boutons on its surface which originate from other neurones. Axons also terminate on muscle fibres at a neuromuscular junction, on some blood vessels and in glands.

Practice note-pad 1E: multiple sclerosis (MS)

In multiple sclerosis, changes in the myelin sheath around axons result in the formation of plaques, which affects the rate of conduction of nerve impulses. Axons in the central nervous system (brain and spinal cord) are affected, while those in the peripheral nervous system are not. The visual system seems to be most sensitive to plaque formation. Disturbance of both movement and sensation occurs. Fatigue and cognitive impairment are other common features that affect function. The number of plaques and their sites vary between individuals and with time in the same individual, so that the disease sometimes follows a course of relapse and remission. In some individuals there is progressive deterioration.

An impulse is a localised change in the membrane of a neurone. When a neurone is excited, the membrane over a small area allows charged particles (ions) to pass across the membrane, a process known as depolarisation, and an impulse is generated. The area of depolarisation then moves to the adjacent area and the impulse travels down the membrane in one direction only. Each impulse is the same size, like a morse code of dots only, but the signals carried can be varied by the rate and pattern of the impulses conducted along the neurone.

A **synapse** is the junction where impulses pass from one neurone to the next. Impulses always travel in one direction at a synapse, i.e. from the axon of one neurone to the dendrites and cell body of the next neurone. This ensures the one-way traffic in the nervous system.

When an impulse arrives at the end of the axon, a chemical is released from the boutons into the gaps between them and the next neurone. The chemical is known as a neurotransmitter and the gap is the synaptic cleft (Figure 1.12). Each molecule of the neurotransmitter has to match special protein molecules, known as receptor sites, on the next neurone. When the transmitter locks on to the receptor site, the combination triggers the depolarisation of the membrane of the second neurone and impulses are conducted down it. Next, the transmitter substance is broken down by enzymes, taken up again by the boutons, re-formed and stored.

Each neurone has a threshold level of stimulation. The level of excitation reaching a neurone must be sufficient to depolarise the membrane, so that impulses are generated. Some impulses reaching a neurone affect the membrane in such a way that no impulses are propagated, this is known as **inhibition**. The source of inhibitory effects may be the presence of small neurones, the activity of which always produces inhibition, or the release of different transmitter substance from the boutons of the axon. The mechanism of inhibition will be discussed in more detail in Chapter 12.

Various transmitter substances have been identified in the nervous system. These include acetylcholine, adrenaline, dopamine and serotonin. Acetylcholine is the neurotransmitter released at most of the synapses in the pathways involved in movement, and also at the neuromuscular junctions. Drugs that prevent the release of acetylcholine at synapses are used as relaxants for muscles, for example in abdominal surgery.

Neuroplasticity

Neuroplasticity infers the human brain is capable of change as a result of our experiences and environment and that the brain is plastic in nature. The total number of neurones in the brain decreases after early adult life. Despite this loss, the brain retains its capacity to learn new skills and to use knowledge in different ways. For example, traumatic brain injury destroys neurones, either by direct damage to the neurones or as a result of reduced blood flow to the affected area of the brain. Recovery and rehabilitation may produce a, sometimes remarkable, return of function. It would appear that activity associated with a specific function can move to a different anatomical location within the brain. This suggests that the nervous system has the capacity to be modified and new connections can be made, although the reasons are not entirely understood.

Biochemical changes have been explored as a possible explanation for the plasticity of neurones. During the early development of the basic networks of the brain, protein substances called nerve growth factors (NGFs) are present, but these are absent in the adult brain. Attempts to reintroduce NGFs in patients with degenerative diseases of the nervous system have been largely unsuccessful.

Evidence from animal experiments has demonstrated that structural changes in neurones can occur in a damaged area in some parts of the brain. These changes include new synaptic connections made by undamaged neurones and the sprouting of the axons to form synapses at sites that were previously activated by injured axons. The time when the fibres make new connections coincides with the return of function.

Current knowledge supports some plasticity of neurones in response to learning new skills and after injury. The cell body of each neurone is relatively fixed, but the synaptic connections that it makes with other neurones can be modified.

Motor and sensory neurones

So far, the structure and properties of a typical neurone have been described. Electrochemical changes in the dendrites and cell body result in impulses that are propagated in one direction only, down the axon. In the organisation of the nervous system, the cell bodies of neurones lie in the central nervous system (brain and spinal cord) and the axons lie in the peripheral nerves that leave it to be distributed to all parts of the body.

Motor (efferent) neurones carry impulses away from the central nervous system to all parts of the body, or from the brain down to the spinal cord.
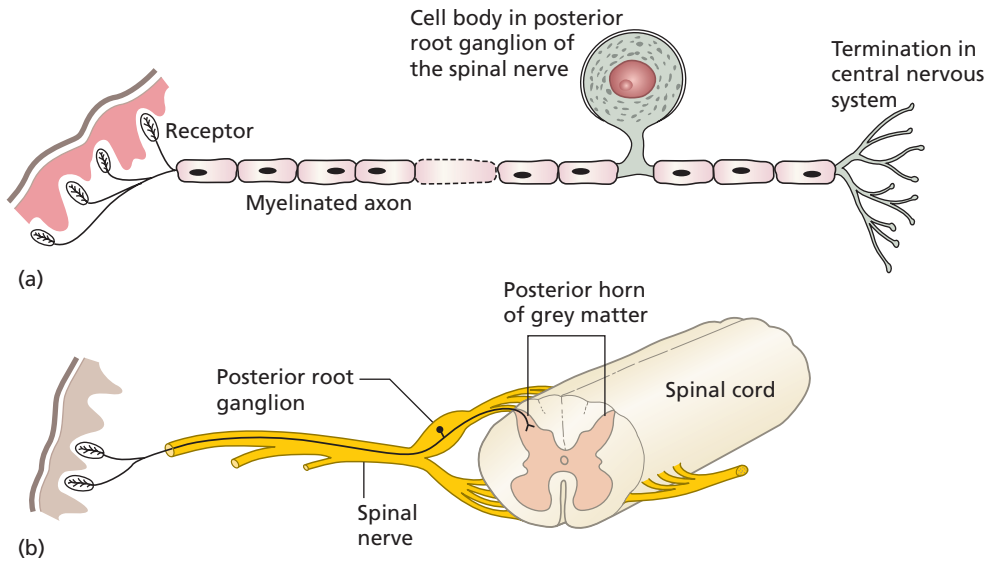
Figure 1.13   Sensory neurones: (a) typical sensory neurone; (b) the position of a sensory neurone in a spinal nerve and the spinal cord.

Sensory (afferent) neurones develop in a different way. The cell bodies of the sensory neurones are found in ganglia just outside the spinal cord. There are no synaptic junctions on the cell bodies, and the axon divides into two almost immediately after it leaves the cell. The two branches formed by this division are a long process in a peripheral nerve that ends in a specialised sensory receptor, for example in the skin or a muscle, and a short process that enters the spinal cord and terminates in the central nervous system.

Figure 1.13a shows the arrangement of a typical sensory neurone. It is sometimes called 'pseudounipolar', since it has one axon but appears to be bipolar. Compare this with the multipolar motor neurone shown in Figure 1.12. Figure 1.13b shows the position of a sensory neurone in relation to the spinal cord, a spinal nerve and its branches. Note the cell body lying in a ganglion (swelling) and the axon entering the spinal cord. Sensory neurones carry impulses from the body towards the central nervous system, or from the spinal cord up to the brain.

Interneurones are those which lie only in the central nervous system and their axons do not extend into the nerves leaving it.

The motor unit

The motor neurones in the spinal cord, which activate the skeletal muscles, lie in a central H-shaped core of grey matter. These lower motor neurones are found in the anterior (ventral) limb of the grey matter. Neurones that activate a particular group of muscles lie together and form a motor neurone pool (Figure 1.14). The axons of these neurones lie in spinal nerves that branch to form the nerve supplying the muscle. There are fewer motor neurones in the pool than muscle fibres in the muscle, and therefore each neurone must supply a number of muscle fibres.
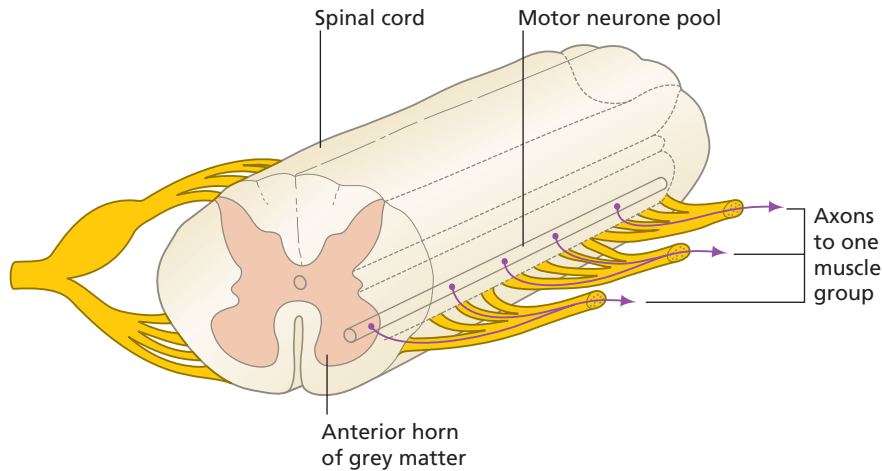
Spinal cord   Motor neurone pool

Axons
to one
muscle
group

Anterior horn
of grey matter

Figure 1.14   Motor neurone pool in the spinal cord.

Practice note-pad 1F: peripheral neuropathies

Neuromuscular disorders that are neurogenic originate in the nerve supply to the muscles, either in the spinal cord, in the nerve roots or in the peripheral nerves (see Chapter 4). Neuropathies of peripheral nerves affect sensory and motor axons, usually commencing distally, and are known as 'glove and stocking'. Muscle weakness and sensory loss occur. Peripheral neuropathy can occur as a complication of diabetes that is not under control.

   Guillain–Barré syndrome is an acute peripheral neuropathy that affects motor axons. It usually follows a viral infection, and the resulting motor weakness involves the trunk and proximal limb muscles, mainly in the lower limbs. Recovery is nearly always complete unless there is severe involvement of the respiratory muscles or axonal damage.

A **motor unit** consists of one motor neurone in the anterior horn of the spinal cord, its axon and all the muscle fibres innervated by the branches of the axon (Figure 1.15). The number of muscle fibres in one motor unit depends on the function of the muscle rather than its size. Muscles performing large, strong movements have motor units with a large number of muscle fibres. For example, the large muscle of the calf has approximately 1900 muscle fibres in each motor unit. In muscles that perform fine precision movements, the motor units have a small number of muscle fibres (e.g. up to 100 in the muscles of the hand). The muscle fibres of one motor unit do not necessarily lie together in the muscle, but may be scattered in different fasciculi. The number of motor units that are active in a muscle at any one time determines the level of performance of the muscle.

   There are two types of motor unit:

- **Low-threshold** motor units supplying slow type I muscle fibres are involved in the sustained muscle activity that holds the posture of the body. The number of active motor units remains
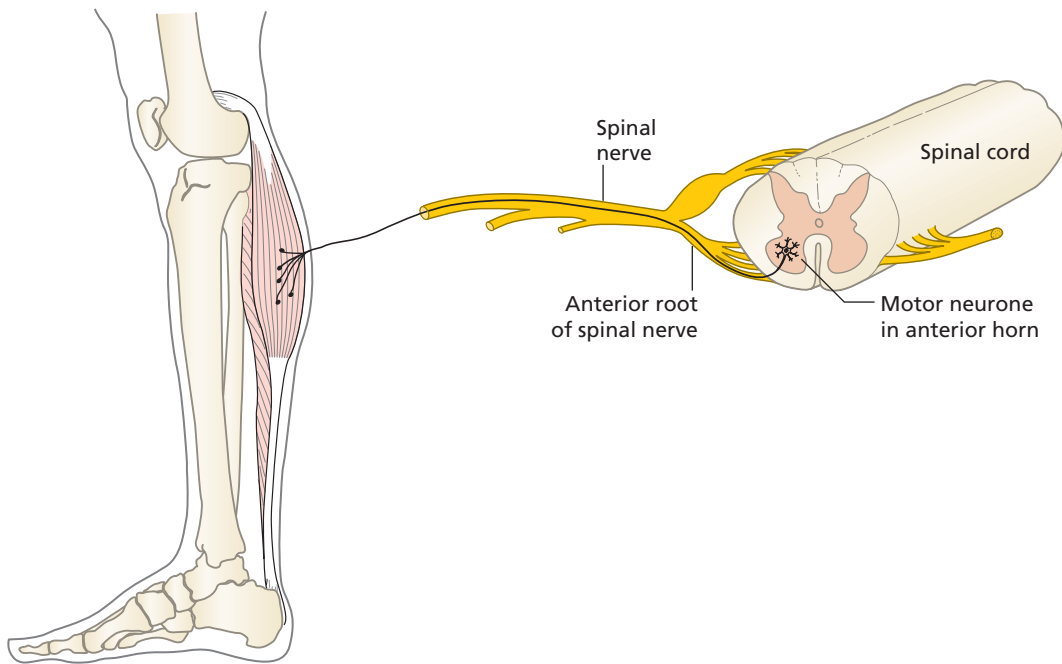
Figure 1.15 Motor unit.

constant, but activity changes between all the low-threshold neurones. The slow type I muscle fibres do not fatigue easily and the activity is maintained over long periods.

- **High-threshold** motor units with large-diameter axons supplying fast type II muscle fibres are involved in fast, active movements, which move the parts of the body from one position to another. These motor units soon fatigue, but they are adapted for fast, strong movements such as running and jumping.

In a strong purposeful movement, such as pushing forwards on a door, the motor units are activated or recruited in a particular order. The slow units are active at the start of the movement and then the fast units become active as the movement reaches its peak.

All muscle activity includes a combination of slow and fast motor units. The slow units contribute more to the background postural activity, while the fast units play a greater part in rapid phasic movements. In manipulative activities the shoulder muscles have sustained postural activity to hold the limb steady, while the hand performs rapid precision movements, such as writing, sewing or using a tool.

Practice note-pad 1G: motor neurone diseases

These are progressive disorders of the motor neurones in the spinal cord. Muscle weakness and fatigue of the muscles of the limbs and the trunk occur, which become generalised to affect swallowing and speech. There is no sensory loss. Depending on the sub-type, onset is usually around the age of 40 years, with rapid deterioration over 3–5 years.

Receptors

Receptors are specialised structures that respond to a stimulus and generate nerve impulses in sensory neurones. They are collectively the source of the sensory information that is transmitted into the central nervous system. While there is awareness of some receptor stimulation, a large amount of sensory processing and the resulting response occurs below consciousness. I can feel the pressure of the fingertips on the computer keys as I write and hear my mobile phone when it rings. At the same time, I am unaware of the receptors in the muscles in the neck and the balance part of the ear responding to changes in the position of the head so that my posture is adjusted to keep my eyes on the keyboard.

A system of receptors that respond to a specific stimulus is known as the **modality** of sensation, for example tactile modality. Several receptors of the same type may give input into one sensory neurone. The area covered by all the receptors activating one sensory axon is called a **receptive field**. There may be overlap in receptive fields, so that stimulation of one point may excite more than one sensory neurone (Figure 1.16). In the fingertips, for example, where the receptive fields are small and there is great overlap, a stimulus such as a pin prick can be very precisely interpreted.

When a receptor is stimulated, the membrane of the receptor ending is depolarised and impulses are generated. If the same stimulus continues for some time, the rate of firing of impulses falls and may stop, even though the stimulus is still present. This is known as **adaptation** of receptors. Different receptors adapt at different rates.

Slow-adapting receptors continue to produce impulses at the same rate all the time the stimulus is applied. The function of these receptors is to give continuous monitoring of background sensory information. Receptors found in muscles and joints are slow adapting. People are unaware of most of the activity of slow-adapting receptors.

Fast-adapting receptors generate a short burst of impulses in response to the stimulus, but activity ceases if the stimulus continues at the same level. Sensation from these receptors usually reaches consciousness. Touch receptors in the skin are fast adapting. When a person puts clothes on, he or she feels the clothes at first, and then is no longer aware of them. If the strength of stimulus changes, e.g. a belt becomes tighter, another burst of impulses is generated and the change is sensed.

Adaptation of receptors allows the nervous system to process the changing features of the environment inside and outside the body, while information of unchanging features is reduced.
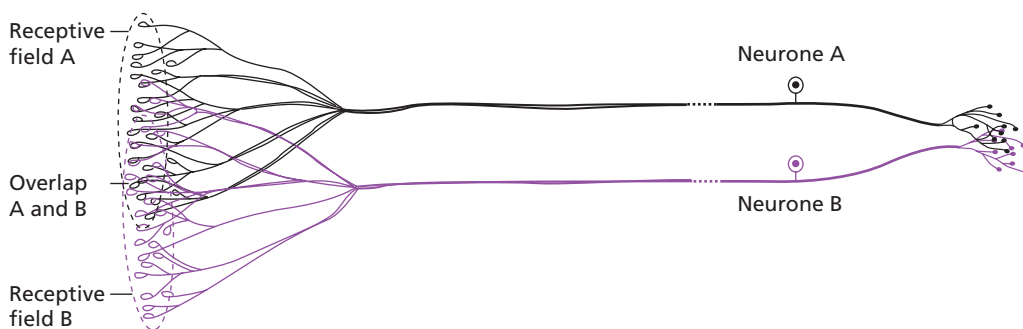

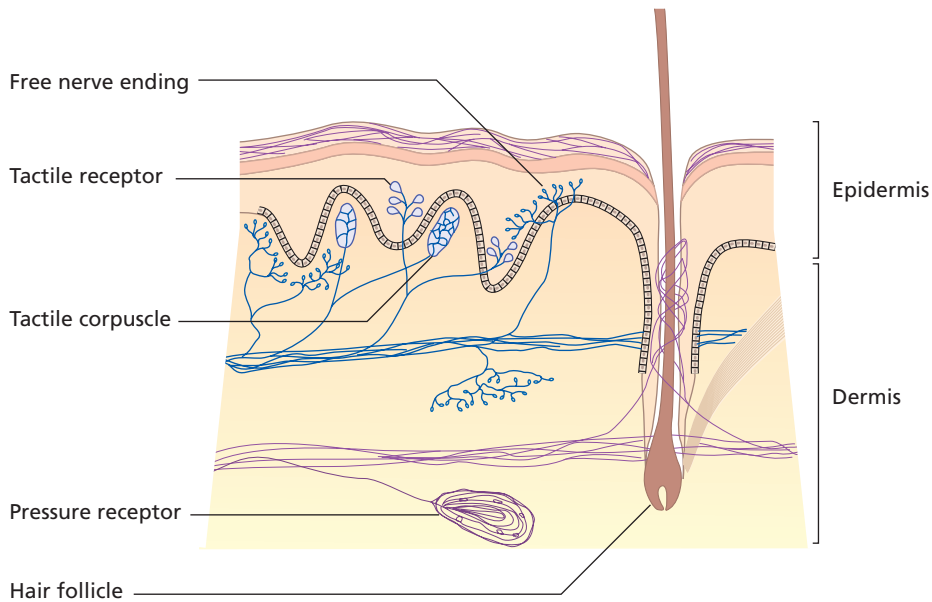**Figure 1.16**   Receptors in the receptive fields of two neurones.

Free nerve ending

Tactile receptor

Epidermis

Tactile corpuscle

Dermis

Pressure receptor

Hair follicle

Figure 1.17   Section of the skin showing receptors.

Cutaneous receptors

Three types of receptor are found in the skin: thermoreceptors responding to temperature; nociceptors activated by noxious stimuli, which result in the perception of pain; and mechanoreceptors sensing touch and pressure (Figure 1.17).

Mechanoreceptors in the skin play a role in the regulation of movement. The sole of the foot has a high density of mechanoreceptors. These pressure sensors provide information about foot contact with the base of support, which is an important component of the maintenance of balance, both in standing and during movement. The jogger or athlete running along rough terrain in poor visibility relies on information from the soles of the feet to prevent tripping and falling. The palm of the hand and the fingertips also have a large number of mechanoreceptors. Writing with a pen, dressing and handling coins are all activites heavily dependent on information from the skin of the hand. The importance of these receptors is even greater when we cannot see the object, for example when doing up a back fastening on a skirt.

Nociceptors detect tissue damage that we perceive as pain. The noxious stimulus may be mechanical, thermal or the chemical products from damaged tissues. They should not be called pain receptors because pain is a perception, not a stimulus (see Chapter 11).

Proprioceptors

Proprioceptors lie in skeletal muscles, tendons and joints. They collectively signal the relative positions of the body parts. There are three types of proprioceptor: muscle spindles lying in parallel in between skeletal muscles fibres; Golgi tendon organs found at the junction between a muscle and its tendon; and joint receptors associated with the synovial joints.

A **muscle spindle** has a capsule of connective tissue enclosing 5–14 specialised small muscle fibres known as intrafusal fibres. The central part of these intrafusal fibres of the spindle contains the nuclei and is non-contractile. Wound round this central area is the primary sensory ending, called the annulospiral ending. The main stimulus for the activation of muscle spindles is a change in length of the muscle.

A **Golgi tendon organ** is found at the junction between the muscle fibres and the tendon in a skeletal muscle. A spindle-shaped capsule of connective tissue containing collagen strands encloses the nerve ending. Increase in tension in the muscle pulls on the collagen fibres in the tendon organ and stimulates the nerve ending. In a muscle there are fewer tendon organs than muscle spindles.

Joint receptors are found in all the synovial joints lying in the capsule and ligaments. Some of the receptors are free nerve endings and others are encapsulated in a similar way to those found in the skin. These receptors are activated by the changing angulation of a joint during movement.

The cutaneous, muscle and joint receptors are collectively known as somatosensory receptors. They contribute to the sense of limb position (body scheme) and the sense of movement of body parts. The function of proprioceptors in the regulation of movement will be considered in Chapter 12.

Muscle tone

The functional activity of the muscles of the body depends on nervous stimulation and the conduction of impulses to and from the muscles. A muscle cannot function without its nerve supply. Even when we are at rest, there is low level nervous activity in the muscles. If a person feels their own muscles or those of a partner, the muscles are not limp but 'lively'. This is known as **muscle tone**. A low level of muscle tone is present in a relaxed conscious person. Even when the body is asleep some muscle tone is present, except in periods of deep sleep. Muscle tone has also been described as the state of readiness of the body musculature for the performance of movement. Postural tone allows people to hold static postures. For example, in many self-care activities, the muscles around the shoulder hold the hand close to the head while the hand combs the hair or cleans the teeth. In this position, it is important to resist any tendency for the shoulder muscles to lengthen and allow the limb to fall down.

Postural tone originates in the proprioceptors (muscle spindles) lying in parallel with the skeletal muscle fibres. When there is a change in length of a muscle, the spindles are stimulated. Impulses pass in sensory neurones to the spinal cord where they synapse with the lower motor neurones of the same muscle. These are large-diameter motor neurones, known as skeletomotor neurones. There are two types of skeletomotor neurone corresponding to the fast type II muscle fibres and the slow type I muscle fibres. The response in these muscle fibres restores the muscle to its original length. The pathway of this muscle stretch reflex is shown in Figure 1.18. Note that it is a monosynaptic reflex with no interneurones involved in the spinal cord.

> **Reflective task**
>
> Feel the muscles around the shoulder of another person while the arm is hanging by his or her side. The muscles are not limp, but they are 'lively'. Now ask the person to lift his or her arm sideways to the horizontal and hold the position. Feel the muscles again, and notice that they are more lively, the tone of the muscles has increased.
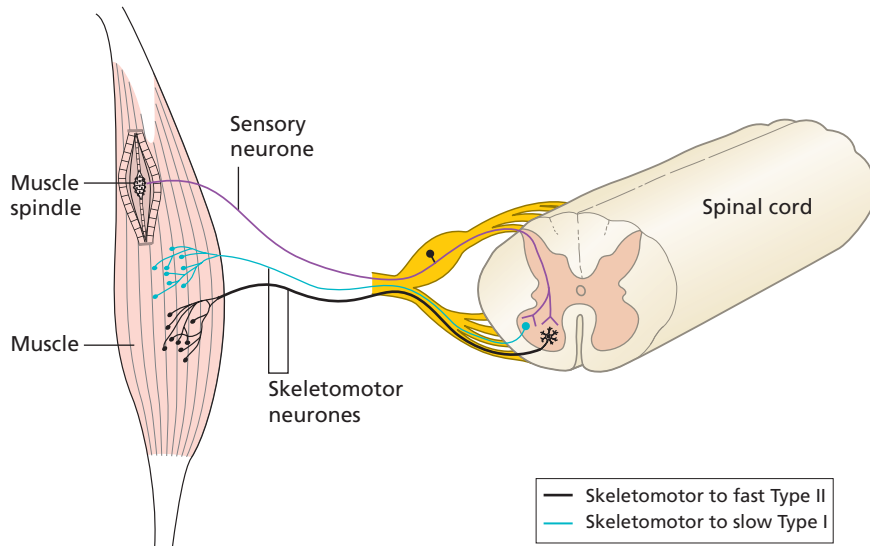
Figure 1.18 Pathway of the muscle stretch reflex showing skeletomotor neurones.
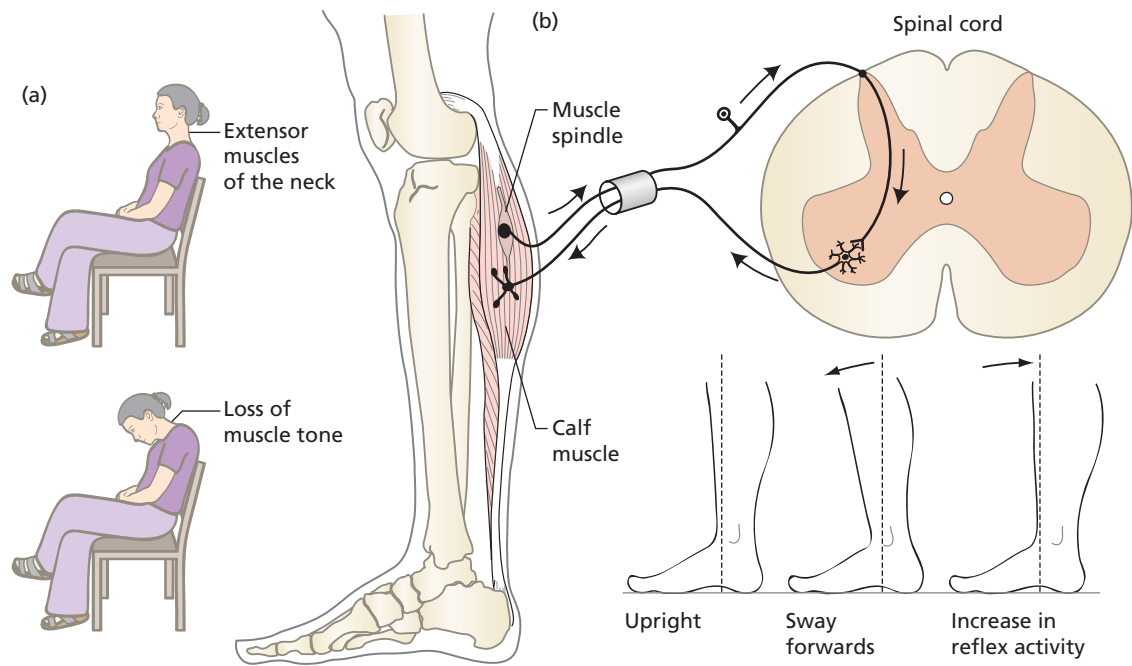

Figure 1.19 Examples of postural tone: (a) the head in sitting; (b) calf muscles in standing.

When a person stands upright, the background level of stretch reflex activity increases in the antigravity muscles of the neck, trunk and lower limbs, which prevents the body from collapsing in response to the pull of gravity. In sitting upright the head is held up by the activity in the muscles at the back of the neck to prevent the head from falling forwards (Figure 1.19a). In standing, the tendency for the body to sway forwards is counteracted by activity in the muscles of the calf (Figure 1.19b). When postural tone is too high or too low, for example in many neurological conditions, movement is affected. A person with low tone has difficulty in maintaining balance while performing fast and accurate movement. In the presence of high tone, movements overshoot and the performance of fine motor skills is impaired.

Summary

This chapter has addressed the structure and properties of the basic units of the musculoskeletal and nervous systems:

- The connective tissues provide support for the whole body.
- Bone forms the rigid framework and has a remarkable capacity for repair after injury.
- Fibrous connective tissue binds and attaches bones to each other as well as joining muscle to bone. Fibrous tissue contains collagen strands which have both tensile strength and elasticity.
- Cartilage also joins some bones and forms the low-friction surface for the articulating surfaces of bones at the movable joints of the body.
- Bones articulate at joints which allow varying degrees of movement. Fibrous and cartilaginous joints show limited movement together with a high level of stability. The greatest movement occurs in the synovial joints.
- The stability of these joints depends on the shape of the articulating surfaces, the number and the strength of the ligaments that join the bones, and the presence of short muscles close to the joint. The joints with a structure that provides poor stability usually have a wide range of movement.
- Skeletal muscle changes in length in response to nervous stimulation to produce movement of bones at their articulations.
- Active muscle also resists change in length in response to the force of gravity or an added load. The strength of a muscle depends on the number and size of the individual muscle fibres.
- Two main types of muscle fibre are found in all muscles. Slow fibres are adapted for sustained activity and are resistant to fatigue. Fast fibres have rapid response times, but they are easily fatigued. The relative proportion of slow and fast fibres in a muscle depends on its functional use and can change over time.
- The neurones of the nervous system are specialised to: respond to stimulation; conduct information to and from the muscles and the organs of the body; and integrate information from different sources in neural networks found in the central nervous system.
- Receptors are specialised endings of neurones which respond to specific stimuli.
- Cutaneous receptors respond to changes in the external environment. Those in the hand and the foot are important for sensory information about the surfaces in contact with them, for example objects held in the hand and the texture of the supporting surface in the foot.
- Proprioceptors, lying in the muscles, tendons and joints, collectively respond to changes in the length and tension in muscles, and the angulation of joints. The nervous system processes

the information from the proprioceptors to provide knowledge of the position and movement of the parts of the body.

- Muscle tone is the force with which skeletal muscles resist changes in length and hold a position.
- The neural background to muscle tone is the muscle stretch reflex, a monosynaptic pathway from and to the same muscle via the spinal cord. Postural tone is important to counteract the force of gravity in upright standing.