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CHAPTER 1

Body mechanics

By the end of this chapter you should be able to:

1 show an awareness of the *basic bone structure* of the human body in terms of bones, ligaments, tendons, muscles and joints;

2 apply the *principle of moments* and the concept of *mechanical advantage* to bones acting as levers;

3 make a simple analysis of the *forces* involved in standing, bending and lifting;

4 show an awareness of the importance of *correct body posture*, particularly when lifting;

5 describe the magnitudes and directions of forces between the body and the ground when standing, walking and running.

The human body

The study of the human body from a mechanical perspective allows us to analyse techniques for sports and to help prevent injuries to the back or limbs. It also enables informed assistance to those who have sustained back injury, for example, or who suffer from bad posture.

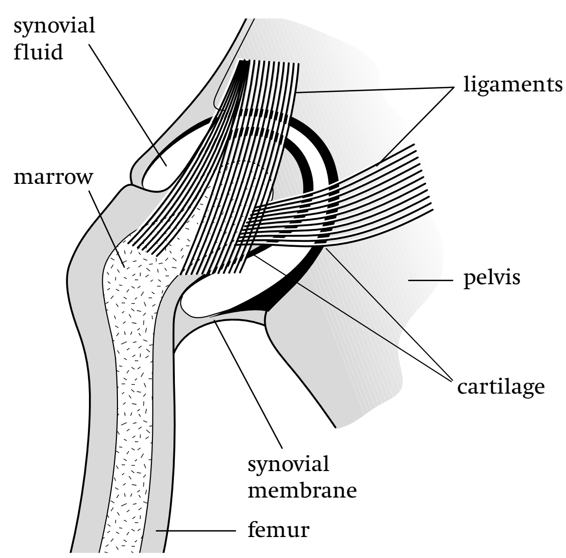
So, here we shall be interested mainly in the muscles and skeleton of the body. Movement of the body involves bones, muscles, ligaments and joints.

Bones

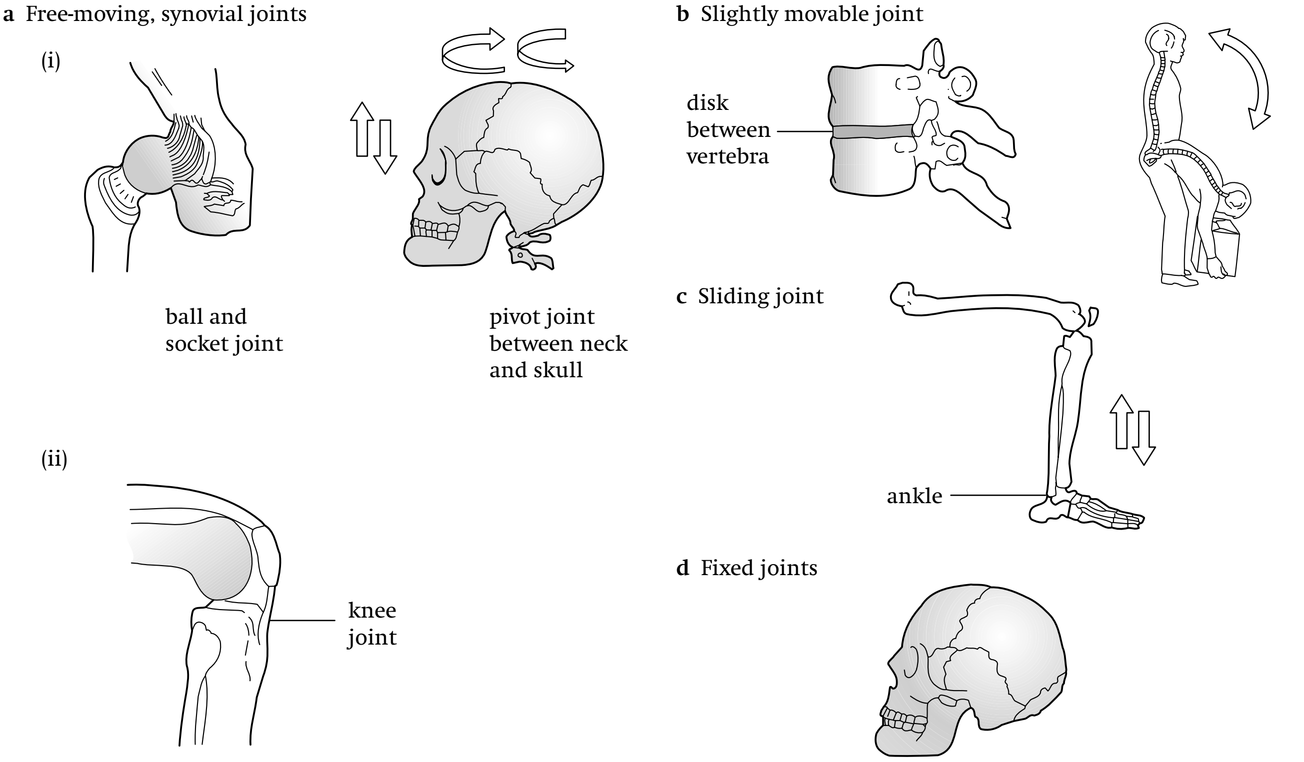
The adult human body has 206 bones. **Bones** are not inanimate structures but living organs that serve several functions. In physical terms they give rigidity and mechanical structure; this is their prime purpose. Bones have a structure of collagen fibres, which have a rubbery nature, and bone mineral. However, bone itself is not very flexible, and the movement of the skeleton is accomplished by **joints**, which are regions where two or more bones come together. The bone surfaces at a joint are covered in cartilage (gristle) and separated from each other by a **synovial cavity** containing a fluid. Where a joint does permit movement, the bones are held together by **ligaments** (*figure 1.1*). Joints are classified into four main types, **free-moving**, **slightly movable**, **sliding** and **fixed**, as shown in *figure 1.2*.

Muscles

Muscles are attached to bones by tough elastic **tendons**. There are three different types of muscle; the main one for movement of the skeleton is the voluntary or skeletal muscle. The other two types of



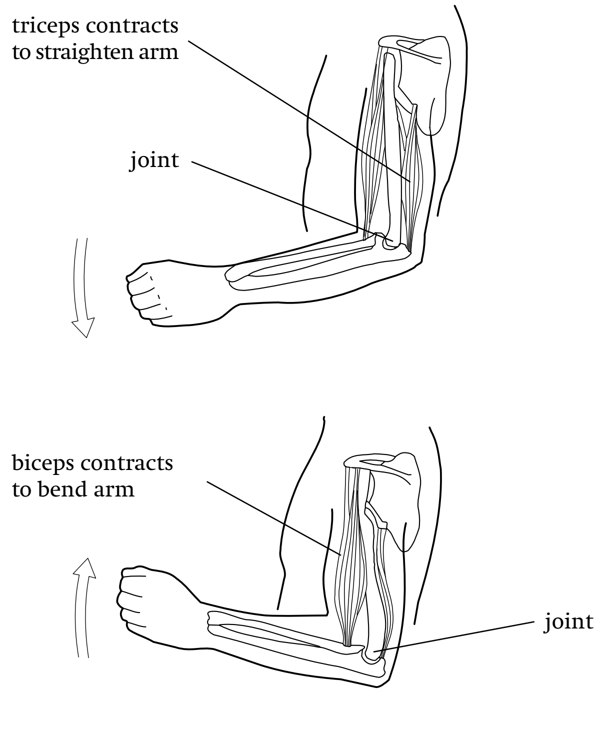
● **Figure 1.1** A hip joint: the ligaments, shown as fine lines, hold the joint together.



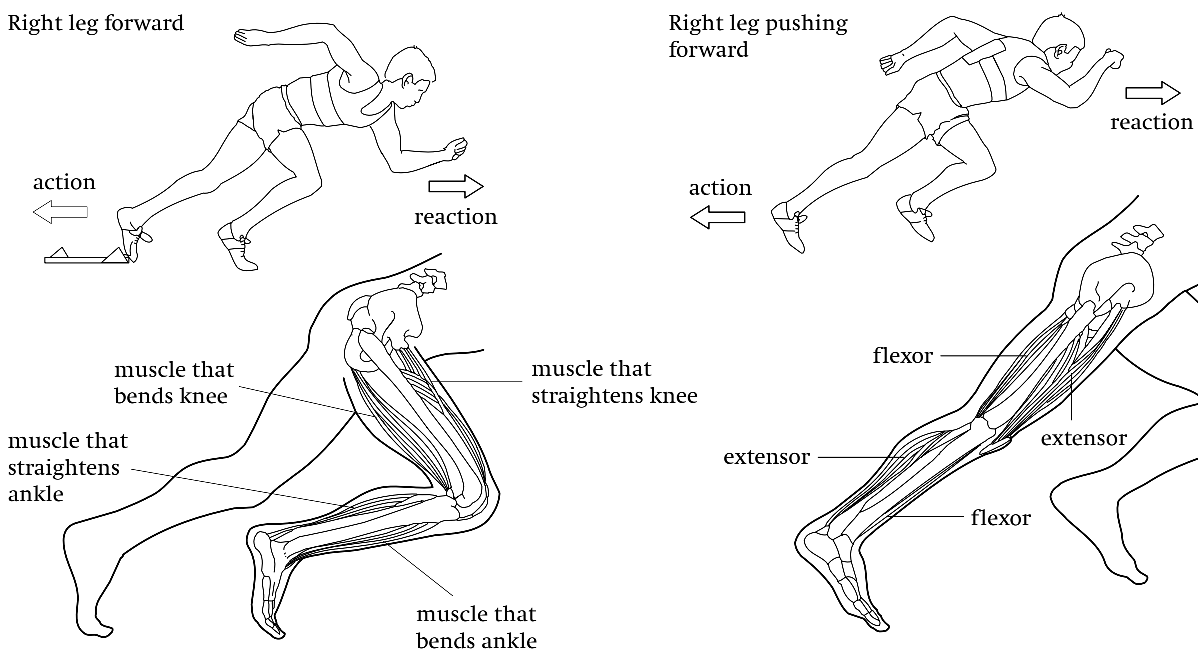
● **Figure 1.2** Types of joint. **a** Free-moving, synovial joints comprise (i) joints that allow movement in several directions and (ii) joints that allow movement in one direction only. **b** An example of a **slightly movable** joint is the joint between two vertebrae. **c** The ankle is a sliding joint. **d** The joints of the skull, movable at birth, become **fixed** joints.

muscle are the involuntary muscles found in the heart and in the blood vessels and alimentary canal. The importance of voluntary muscle is its ability to contract very readily when stimulated.

Muscles can only contract, i.e become shorter and thicker. In doing so, they pull on the bones to which they are attached. When a muscle relaxes, it no longer exerts a pulling force; it returns to its original length. Muscles cannot be lengthened beyond this, so they are incapable of exerting a pushing force. Therefore several muscles are required for the control of a joint with a wide range of movement. Muscles often act in pairs, as at a hinge joint, where one muscle moves the bone one way and another muscle moves the bone the other way. A pair of muscles that have opposite effects is called **antagonistic**; such a pair is the biceps and triceps, which raise and lower the forearm (*figure 1.3*). The muscle that bends or flexes a joint is called a **flexor** and the muscle that straightens or extends a joint is called an **extensor**. *Figure 1.4* shows the muscular action in a runner's legs.



● **Figure 1.3** The biceps and triceps are antagonistic muscles.



● **Figure 1.4** Flexor and extensor muscles in a runner's legs.

SAQ 1.1

Muscles cannot lengthen yet apparently we use them to push against objects. Explain how the muscles and joint of the elbow allow this to occur. Use *figure 1.3* to help in your answer: imagine that you are starting to push a supermarket trolley, for example.

The human body as a machine

A **machine** is designed to enable a small force to produce a large force (or vice versa) or to enable a force acting at one point to produce a force at another point. A **lever** is one of the simplest machines. The input force, known as the **effort**, is applied at a certain distance from the fulcrum or pivot; the output force or **load** is usually at a different distance from the fulcrum. The **mechanical advantage** (MA) of a lever (or any other machine) is defined as load L divided by effort E:

$$\text{MA} = \frac{\text{load}}{\text{effort}} = \frac{L}{E}$$

Levers found in the human body can be divided into three types, class 1, class 2 and class 3:

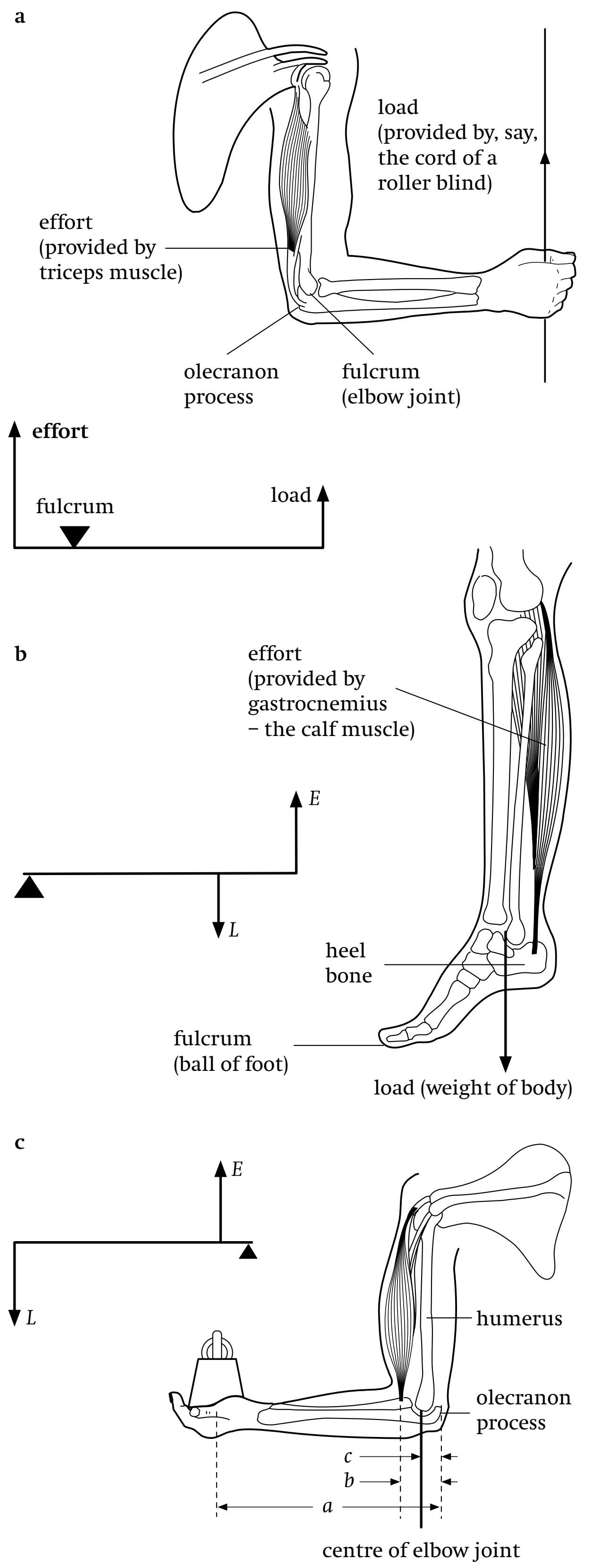
- **Class 1** The fulcrum is between the effort and the load (*figure 1.5a* overleaf). When a cord is pulled the effort (provided by the shortening of the triceps) is actually greater than the load, so the MA is less than 1. Of course, levers in this class commonly have MA values equal to 1 or greater than 1.
- **Class 2** The load is between the effort and the fulcrum (*figure 1.5b*). When we stand on our toes the ball of our foot acts as the fulcrum. The effort needed to counteract the weight of the body is supplied by the calf muscle. The MA for this class of levers is greater than 1.
- **Class 3** The effort is between the fulcrum and the load (*figure 1.5c*). The forearm, when the biceps is shortening, acts as a class 3 lever. The MA for this class of levers is less than 1.

In order to make calculations involving levers, we need to define the turning effect, or **moment**, of a force about any point:

$$\text{moment} = \text{force} \times \text{perpendicular distance}$$

The **perpendicular distance** is measured between the line of action of the force and the point in question. Usually this point is described as the fulcrum (or pivot) only when it is actually the site of a hinge or joint.

The **principle of moments** states that in equilibrium the total clockwise moment about any point equals the total anticlockwise moment about that point.



● **Figure 1.5** Levers. **a** Class 1 lever, load and effort on opposite sides of the fulcrum; **b** class 2 lever, load and effort on same side of the fulcrum, effort further than load, MA > 1; **c** class 3 lever, load and effort on same side of the fulcrum, effort nearer than load, MA < 1.

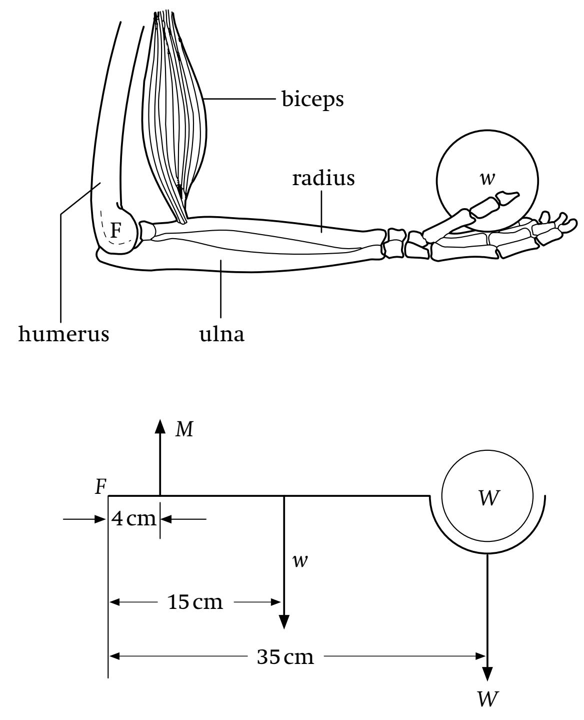
Worked example

Consider a mass of 5 kg held with forearm at right angles to the upper arm. It is possible using the principle of moments to calculate the muscular force of contraction M exerted by the biceps (*figure 1.6*). The following data are needed: the distance of M from the fulcrum F is 4 cm; the load W is exerted at a distance of 35 cm from F; the forearm has a mass of 1.5 kg, weight w, and a centre of mass that is 15 cm from the fulcrum. The acceleration due to gravity, g, is 9.8 m s^{-2} (or N kg^{-1}).

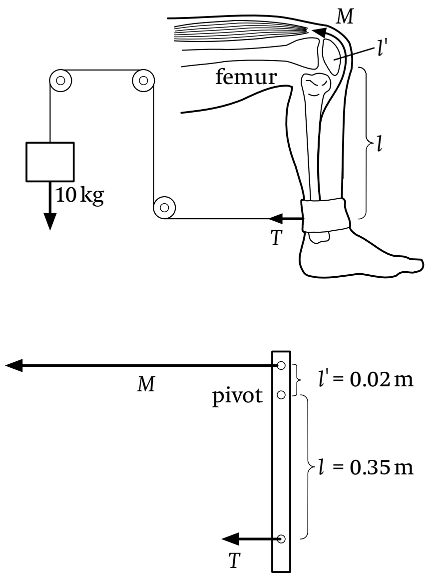
Taking moments about F gives us

$$M \times 4 = 5 \times 9.8 \times 35 + 1.5 \times 9.8 \times 15$$
$$M = 484\,\text{N}$$

This is approximately ten times the load. The reason is that the biceps exerts its force on the forearm at a point close to the elbow. This makes it much less effective in producing a rotation than forces exerted further from the elbow, such as the weight of the forearm and the load. To compensate, the biceps must exert a much larger force than would be necessary if it were attached further from the elbow.



● **Figure 1.6** For the worked example, above.



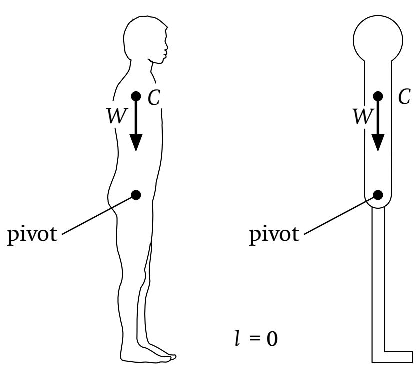
● **Figure 1.7** For *SAQ 1.2*. The muscular force *M* acts over the kneecap at a perpendicular distance *l'* from the pivot.

SAQ 1.2

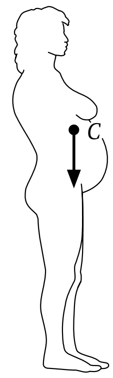
An exercise device is used to strengthen the leg muscles (*figure 1.7*). Calculate the force *M* exerted by the muscle in the upper leg when moving the foot forward to lift the weight shown.

Standing, bending and lifting

The mechanics of the spine can be investigated by treating the spine approximately as a rigid rod. We can then apply Newton's first law (a body in equilibrium experiences no net force) and/or the principle of moments and deduce the forces involved in standing, bending and lifting.



● **Figure 1.8** Standing.

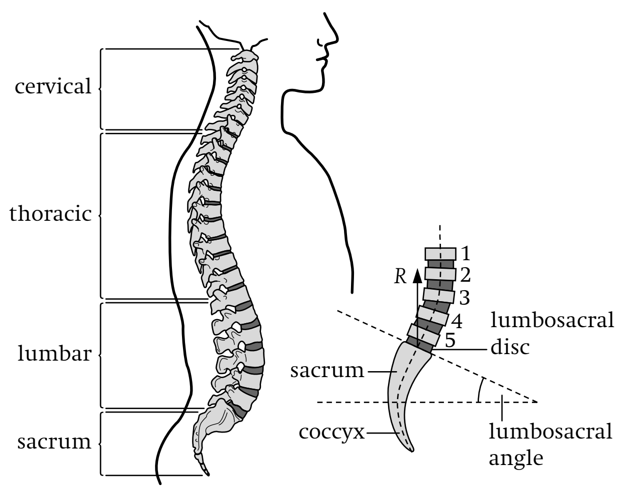


● **Figure 1.9** In pregnancy the spine has to be tilted back to keep the centre of gravity over the middle of the foot.

Standing

When a person stands erect, as shown in *figure 1.8*, the weight of the upper body, *w*, is directly over the legs and little force is exerted by the back and leg muscles. Most of the body's weight is supported by the skeleton and not by muscle action. A vertical line from the centre of gravity of the upper body, *C*, passes through the middle of the foot. An overweight, or pregnant, condition leads to a forward shift in the centre of gravity *C*, moving the vertical projection of it forward to the ball of the foot, where the balance is less stable. To compensate the person may need to tip slightly backwards (*figure 1.9*).

The backbone or spine consists of 33 vertebrae of which nine are fused together to make the sacrum and the coccyx (*figure 1.10*). The sacrum is attached firmly to the pelvic girdle. The other 24 vertebrae are separate and are covered with



● **Figure 1.10**

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cartilage; in between each are discs, tough fibrous pads. The discs allow some bending of the spine and cushion the bones from compression by the body's weight. The pressure on a disc in normal movement remains constant but if it increases to about 10^7 Pa then the disc will rupture.

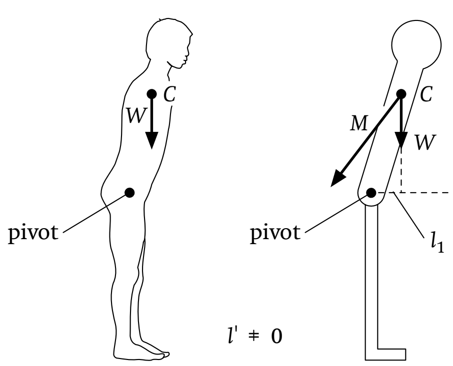
When you are standing upright then the lumbrosacral disc, the disc next to the sacrum, lies at an angle to the horizontal of 40° (*figure 1.10*). The weight of the head, trunk and arms, about 0.6 times the total body weight T, acts via this disc on the sacrum and pelvis. Thus by Newton's third law, to every action there is an equal and opposite reaction, the reaction R of the pelvis and sacrum on the rest of the spine is also $0.6T$. This reaction can be resolved to give the forces parallel and perpendicular to the direction of the spine where it meets the pelvis (*figure 1.10*).

compressive force = $R \cos 40° = 0.46T$
shear force = $R \sin 40° = 0.39T$

If T is 700 N then R = 420 N and its components are a compressive force of 322 N and a shear force, across the lumbrosacral disc, of 270 N.

Bending and lifting

A range of muscles links the vertebrae of the spine to the pelvis. The spine can be considered as a more or less rigid structure pivoting at the lumbrosacral joint (*figure 1.11*). As mentioned above, the sacrum is attached firmly to the pelvic girdle and the top part of the pelvic girdle is attached to the muscles involved in bending and lifting.



● **Figure 1.11** Bending. The pivot is the lumbroscral joint. The perpendicular distance of the upper body weight W from the fulcrum is l'.

The weight of the head, trunk and arms, which, as mentioned above, is 0.6 of the total body weight, acts at the centre of gravity of the upper body C. This point is about two-thirds the length t of the trunk from the buttocks. To a reasonable approximation, the resultant M of the forces exerted by the spinal muscles also acts at C and at an angle of 10° to the spine.

Suppose that the body is bent at an angle of 60° to the vertical (*figure 1.12a*). If a typical body mass of 70 kg is taken then the upper body weight W is $0.6 \times 70 \times 9.8 = 412$ N. The muscular force M can be found by balancing the moments of the forces about the pivot:

$$M \times 0.67t \sin 10° = W \times 0.67t \sin 60°$$

Thus

$$M = \frac{412 \sin 60°}{\sin 10°} = 2055\,\text{N}$$

Resolving forces parallel to the spinal column we obtain for the reaction force S of the pelvis on the spine (*figure 1.12b*)

$$S = M \cos 10° + W \cos 60° = 2230\,\text{N}$$

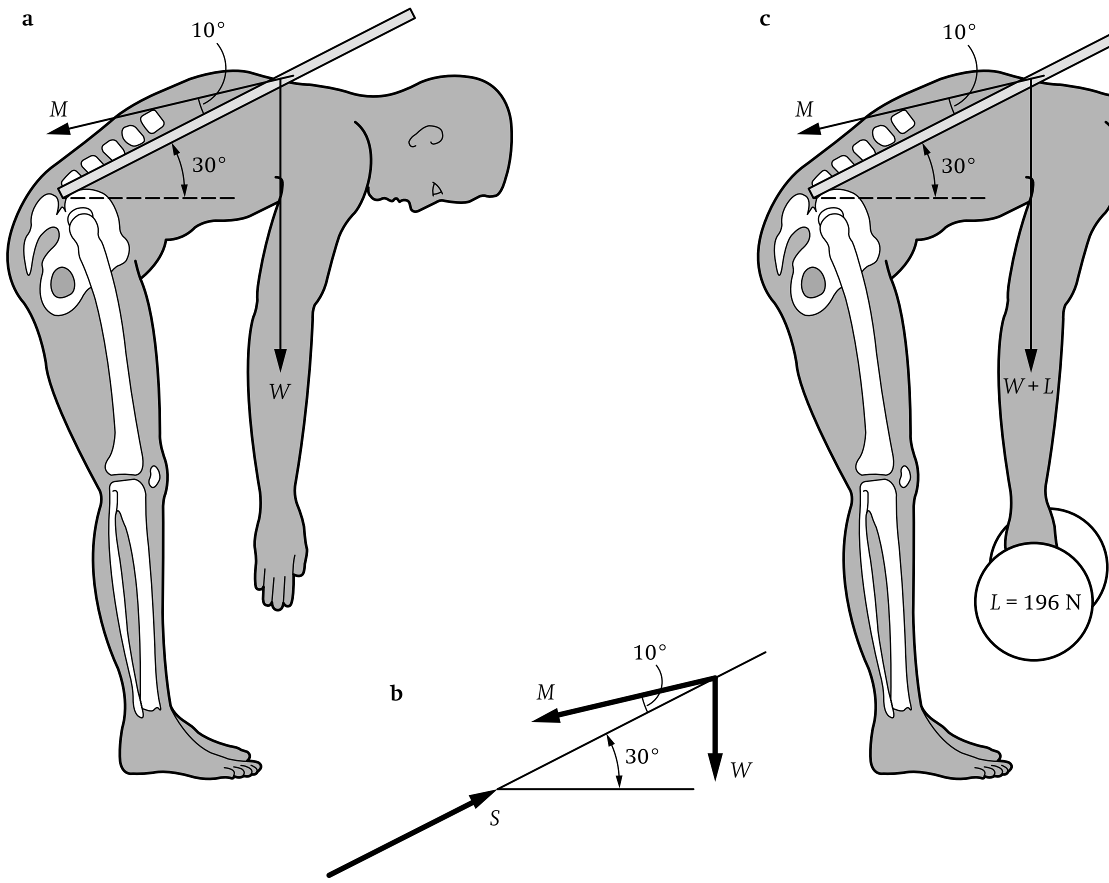
This large force causes the lumbrosacral disc to compress. As the angle of bending increases then the muscular effort and the reaction force on the lumbrosacral disc will increase. Clearly, the techniques involved in bending and lifting are important. If the legs are bent and the spine is kept almost vertical then the forces on the lumbrosacral disc and the other discs of the spine are reduced.

SAQ 1.3

A person has a mass of 75 kg for the trunk, head and arms. Calculate the muscular force M and the reaction force S on the lumbrosacral disc when the person bends to an angle of 70° to the vertical.

It is easy to adapt our calculations to describe the situation when a heavy object such as luggage is lifted. This is shown in *figure 1.12c*. Suppose that we now have a load L of, say, 196 N and the angle is still 60°. The forces acting on the spine are the upper body weight W plus load L, the muscular force M and the reaction force S on the lumbrosacral disc. Moments are again taken about the fulcrum:

$$M \times 0.67t \sin 10° = (412 + 196) \times 0.67t \sin 60°$$



● **Figure 1.12** **a** Bending at an angle of 60° to the vertical; *W* is the upper body weight and *M* is the muscular force exerted on the spine, of length *t*. **b** Force diagram for the spine; *S* is the reaction force of the pelvis on the spine. **c** Lifting a load *L*. The forces *W*, *M* and *L* all act at roughly the same point.

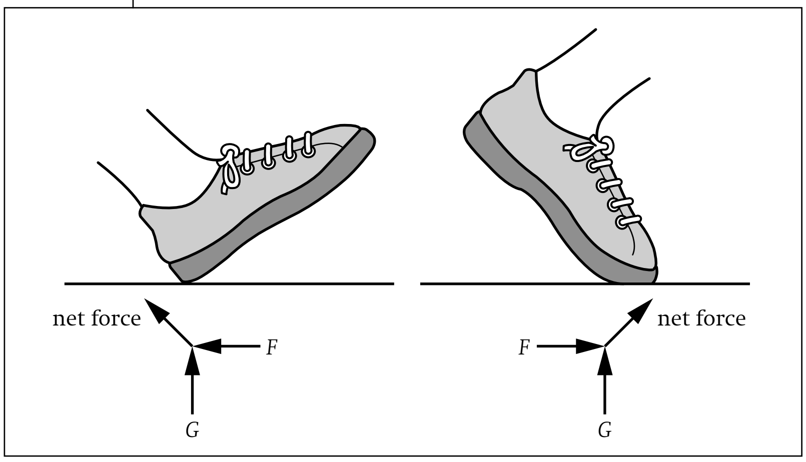
This gives *M* as 3032 N. By resolving the forces parallel to the spine, it is then possible to calculate the new value of the reaction force *S* on the lumbrosacral disc:

$$S = M \cos 10° + (L + W) \cos 60°$$
$$= 3290\,\text{N}$$

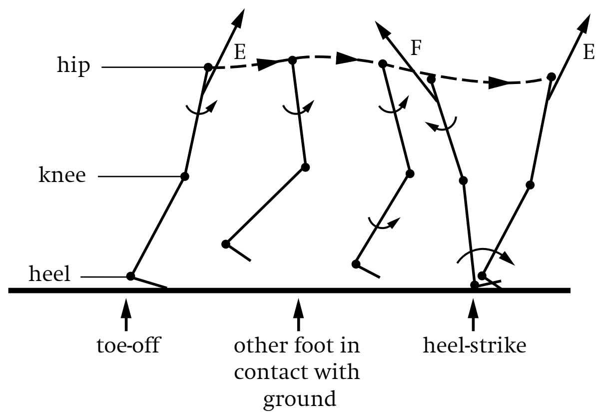
This force is eight times the upper body weight. Taking the cross-sectional area of the base of the spine to be $5\,\text{cm}^2$, this gives a pressure of 7×10^7 Pa, according to our simplified model and would create problems for one or another disc if sustained for any length of time. The likely result would be a ruptured disc.

Walking and running

When standing the body weight is balanced by the **normal reaction** force of the ground. In equilibrium, this is equal and opposite to the body weight: it acts vertically upwards. When you start to move relative to the ground this force will change. When you leave the ground an upwards accelerating force is needed and when you land on the ground there will be a decelerating force (*figure 1.13*). Thus the normal



● **Figure 1.13** In walking, when the foot strikes the ground, friction acts backwards; when it leaves the ground, friction acts forwards.



● **Figure 1.14** Action of the leg muscles in walking.

reaction is greatest just before the toe leaves the ground and when the heel strikes the ground.

The frictional force F is related to the normal reaction G by $F = \mu G$, where μ is the coefficient of static friction and has a value between 0.6 and 0.75 depending on the nature of the surface. Because F is proportional to G, it is a maximum when G is a maximum.

The resultant of F and G can be calculated using the rule for adding vectors; it will increase as you increase speed. If, however, there is a slippery surface then μ will be smaller. To avoid slipping, you need to walk with shorter strides because this requires less forward force than larger strides.

Steady walking

If you are walking at a steady speed then the force E of the hip muscle at the front of the leg swings the whole leg forward (*figure 1.14*). When this happens the leg rotates about the hip joint, with little force required. The lower leg is carried forward, rotating about the knee, by the muscles of the upper leg and the ligaments of the knee joint. The upper leg then decelerates slowly by the action F of the hip muscles, and the lower leg by the action of the muscles around the knee. As the upper leg is pulled back the heel strikes the ground. When your foot strikes the ground it rolls from heel to sole to toe in contact with the ground; the whole action is then repeated.

When we walk we all have a natural period of oscillation that depends on the mass and length of our legs. Thus to avoid tiredness it is better to shorten one's stride rather than try to lengthen the time for each pace.

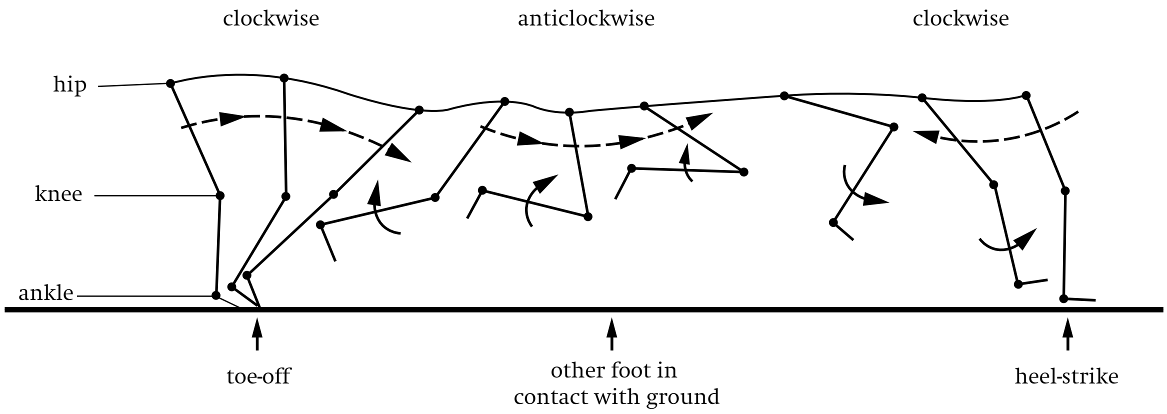
Running

However, to change from walking to running we do normally increase the number of strides we take per second. Typical speeds are:

walking, 1.5 $m\,s^{-1}$
running, 6 $m\,s^{-1}$
short sprint, 10 $m\,s^{-1}$

To increase the length of stride, we leap forward and leave the ground for a short period of time. The inertia of the body mass keeps us moving forward. The centre of gravity C rises and falls on a slight curve. Generally the angle between the direction of leaping and the ground (the angle of projection) is kept fairly low since forward momentum is lost whenever a foot hits the ground. During the time that we are in the air one leg must move beneath us.

As in walking there is a rotation of the legs about the hip and knee joints (*figure 1.15*). At toe-off, the



● **Figure 1.15** Action of the leg muscles in running. The labels 'clockwise' and 'anticlockwise' refer to the motion of the upper leg about the hip joint.

upper leg is moving clockwise, as viewed in the figure, about the hip joint. The upper leg then swings forwards anticlockwise, while the lower leg swings clockwise about the knee joint. At the extreme point (the third position from the right in the figure) the upper leg starts falling back clockwise again and the lower leg anticlockwise; the effect of the two opposite rotations brings the upper and lower leg into a nearly straight line for heel-strike. The leg now rotates clockwise about the point of contact with the ground until toe-off is reached again.

SUMMARY

- The basic mechanical structure of the human body consists of bones, ligaments, tendons, muscles and joints.
- Joints occur where the bones come together. Where a joint allows movement the bones are held by ligaments.
- Muscles are attached to bones by tendons. Muscles act in antagonistic pairs: one bends or flexes the joint, the other straightens the joint.
- The principle of moments and the concept of mechanical advantage can be applied to bones acting as levers.
- The forces on the spine involved in standing, bending and lifting can be calculated from Newton's first law (the net force on a body in equilibrium is zero) and the principle of moments.
- Correct body posture, particularly when lifting, requires the spine to be nearly vertical to avoid excess pressure on the discs of the spine.
- When standing the body weight is balanced by the normal reaction of the ground.
- In walking and running there are three external forces on the body: weight, normal reaction G and friction F. The latter two are related by $F = \mu G$.

When a runner reaches a constant speed only a small amount of energy is used in overcoming air resistance and producing the leap (*figure 1.15*). The main part of the energy expended is used in moving the legs.

The runner appears to rotate about a vertical axis if viewed from above. Moving the left arm forwards and the right arm backwards causes a clockwise rotation of the upper body. Reacting to this, the lower body rotates slightly in an anticlockwise direction and the right leg swings forward.

Questions

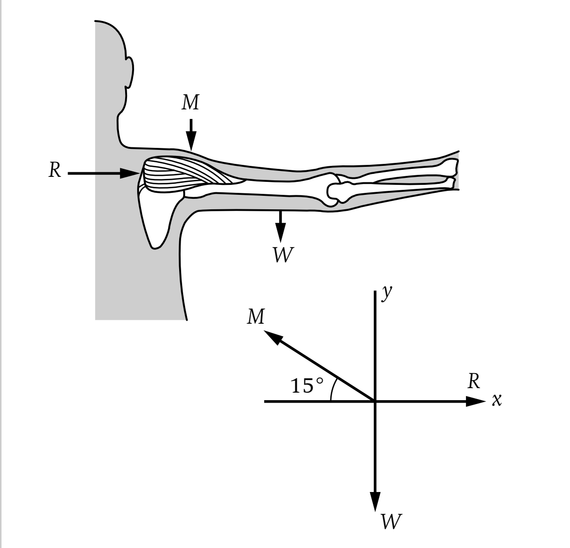
1 When you raise your arm there are three forces involved, as shown in *figure 1.16*. These are

W, the weight of the arm acting downwards

M, the force of the muscle acting at 15°

R, the force exerted by the shoulder on the humerus

The weight of the arm is 13 N. By resolving the force M of the muscle along the x and y axes, calculate M and R.



• **Figure 1.16**

2 Many injuries to the human body occur as a result of the incorrect lifting of heavy objects. Explain why the spine should be kept as vertical as possible during lifting to prevent such injuries.