3

Muscle and Forces

Physicists recognize four fundamental forces. In the order of their relative strength from weakest to strongest they are: gravitational, electrical, weak nuclear, and strong nuclear. Only the gravitational and electrical forces are of importance in our study of the forces affecting the human body. The electrical force is important at the molecular and cellular levels, e.g., affecting the binding together of our bones and controlling the contraction of our muscles. The gravitational force, though very much weaker than the electrical force by a factor of 10^{39}, is important as a result of the relatively large mass of the human body (at least as compared to its constituent parts, the cells).

3.1 How Forces Affect the Body

We are aware of forces on the body such as the force involved when we bump into objects. We are usually unaware of important forces inside the body, for example, the muscular forces that cause the blood to circulate and the lungs to take in air. A more subtle example is the force that determines if a particular atom or molecule will stay at a given place in the body. For example, in the bones there are many crystals of bone mineral (calcium hydroxyapatite) that require calcium. A calcium atom will become part of the crystal if it gets close to a natural place for calcium and the electrical forces are great enough to trap it. It will stay in that place until local conditions have changed and the electrical forces can no longer hold it in place. This might happen if the bone crystal is destroyed by cancer. We do not attempt to consider all the various forces in the body in this chapter; it would be an impossible task.

Medical specialists who deal with forces are (a) physiatrists (specialists in physical medicine) who use physical methods to diagnose and treat disease, (b) orthopedic specialists who treat and diagnose diseases and abnormalities of the musculoskeletal system, (c) physical therapists, (d) chiropractors who treat the spinal column and nerves, (e) rehabilitation specialists, and (f) orthodontists who deal with prevention and treatment of irregular teeth.

3.1.1 Some Effects of Gravity on the Body

One of the important medical effects of gravity is the formation of varicose veins in the legs as the venous blood travels against the force of gravity on its way to the heart. We discuss varicose veins in Chapter 8, *Physics of the Cardiovascular System*. Yet gravitational force on the skeleton also contributes in some way to healthy bones. When a person becomes "weightless," such as in an orbiting satellite, he or she loses some bone mineral. This may be a serious problem on very long space journeys. Long-term bed rest is similar in that it removes much of the force of body weight from the bones which can lead to serious bone loss.

3.1. 2 Electrical Forces in the Body

Control and action of our muscles is primarily electrical. The forces produced by muscles are caused by electrical charges attracting opposite electrical charges. Each of the trillions of living cells in the body has an electrical potential difference across the cell membrane. This is a result of an imbalance of the positively and negatively charged ions on the inside and outside of the cell wall (see Chapter 9, *Electrical Signals from the Body*). The resultant potential difference is about 0.1 V, but because of the very thin cell wall it may produce an electric field as large as 10^7 V/m, an electric field that is much larger than the electric field near a high voltage power line.

Electric eels and some other marine animals are able to add the electrical potential from many cells to produce a stunning voltage of several hundred volts. This special “cell battery” occupies up to 80% of an eel’s body length! Since the eel is essentially weightless in the water, it can afford this luxury. Land animals have not developed biological electrical weapons for defense or attack.

In Chapter 9 we discuss the way we get information about body function by observing the electrical potentials generated by the various organs and tissues.

3.2 Frictional Forces

Friction and the energy loss resulting from friction appear everywhere in our everyday life. Friction limits the efficiency of machines such as electrical generators and automobiles. On the other hand, we make use of friction when our hands grip a rope, when we walk or run, and in devices such as automobile brakes.

Some diseases of the body, such as arthritis, increase the friction in bone joints. Friction plays an important role when a person is walking. A force is transmitted from the foot to the ground as the heel touches the ground (Fig. 3.1a). This force can be resolved into vertical and horizontal components. The vertical reaction force, supplied by the surface, is labeled N (a force perpendicular to the surface). The horizontal reaction component, F_H, must be supplied by frictional forces. The maximum force of friction F_f is usually described by:

$$F_f = \mu N$$

where N is a normal force and μ is the coefficient of friction between the two surfaces. The value of μ depends upon the two materials in contact, and it is essentially independent of the surface area. Table 3.1 gives values of μ for a number of different materials.

The horizontal force component of the heel as it strikes the ground when a person is walking (Fig. 3.1a) has been measured, and found to be approximately 0.15W, where W is the person’s weight. This is how large the frictional force must be in order to prevent the heel from slipping. If we let $N \approx W$, we can apply a frictional force as large as $f = \mu W$.

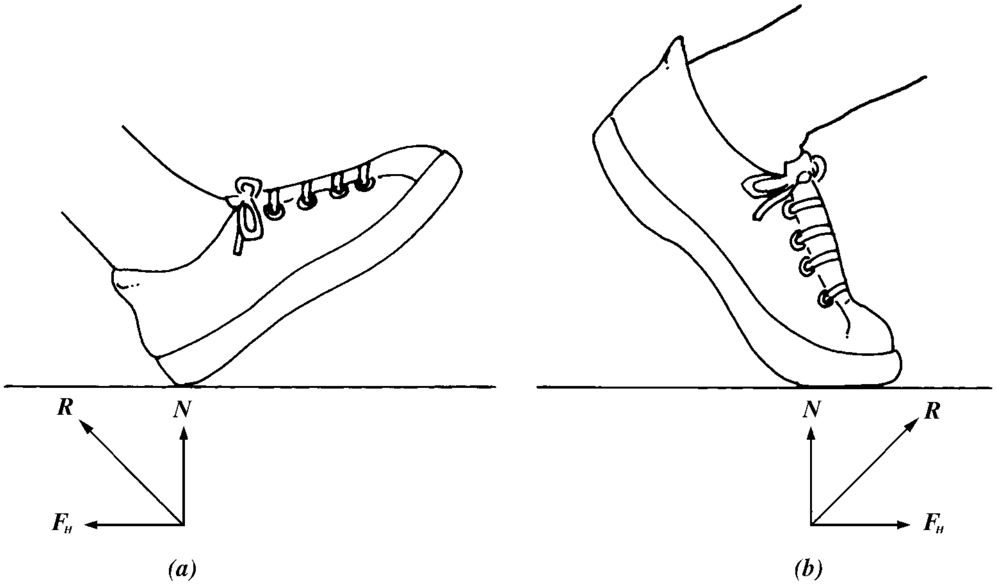


Figure 3.1. Normal walking. (a) Both a horizontal frictional component of force, F_H, and a vertical component of force N with resultant R exist on the heel as it strikes the ground, decelerating the foot and body. The friction between the heel and surface prevents the foot from slipping forward. (b) When the foot leaves the ground, the frictional component of force, F_H, prevents the foot from slipping backward and provides the force to accelerate the body forward. (Adapted from M. Williams and H. R. Lissner, *Biomechanics of Human Motion*, Philadelphia, W. B. Saunders Company, 1962, p. 122, by permission.)

Table 3.1. Examples of Values of Coefficients of Friction

Material	μ (Static Friction)
Steel on steel	0.15
Rubber tire on dry concrete road	1.00
Rubber tire on wet concrete road	0.7
Steel on ice	0.03
Between tendon and sheath	0.013
Normal bone joint	0.003

For a rubber heel on a dry concrete surface, the maximum frictional force can be as large as $f \cong W$, which is much larger than the needed horizontal force component (0.15W). In general, the frictional force is large enough both when the heel touches down and when the toe leaves the surface to prevent a person from slipping (Fig. 3.1b). Occasionally, a person slips on an icy, wet, or oily surface where μ is less than 0.15. This is not only embarrassing; it may result in broken bones. Slipping can be minimized by taking very small steps.

Friction must be overcome when joints move, but for normal joints it is very small. The coefficient of friction in bone joints is usually much lower than in engineering-type materials (Table 3.1). If a disease of the joint exists, the friction may become significant. Synovial fluid in the joint is involved in lubrication, but controversy still exists as to its exact behavior. Joint lubrication is considered further in Chapter 4.

The saliva we add when we chew food acts as a lubricant. If you swallow a piece of dry toast you become painfully aware of this lack of lubricant. Most of the large internal organs in the body are in more or less constant motion and require lubrication. Each time the heart beats, it moves. The lungs move inside the chest with each breath, and the intestines have a slow rhythmic motion (peristalsis) as they move food toward its final destination. All of these organs are lubricated by a slippery mucus covering to minimize friction.

3.3 Forces, Muscles, and Joints

In this section we discuss forces in the body and forces at selected joints and give some examples of muscle connections to tendons and bones of the skeleton. Since movement and life itself depends critically on muscle contraction, we start by examining muscles.

3.3.1 Muscles and Their Classification

Several schemes exist to classify muscles. One widely used approach is to describe how the muscles appear under a light microscope. Skeletal muscles have small fibers with alternating dark and light bands, called *striations*—hence the name *striated muscle*. The fibers are smaller in diameter than a human hair and can be several centimeters long. The other muscle form, which does not exhibit striations, is called *smooth muscle*.

The fibers in the striated muscles connect to tendons and form bundles. Good examples are the biceps and triceps muscles depicted in Fig. 3.2, which will be examined further later in this section.

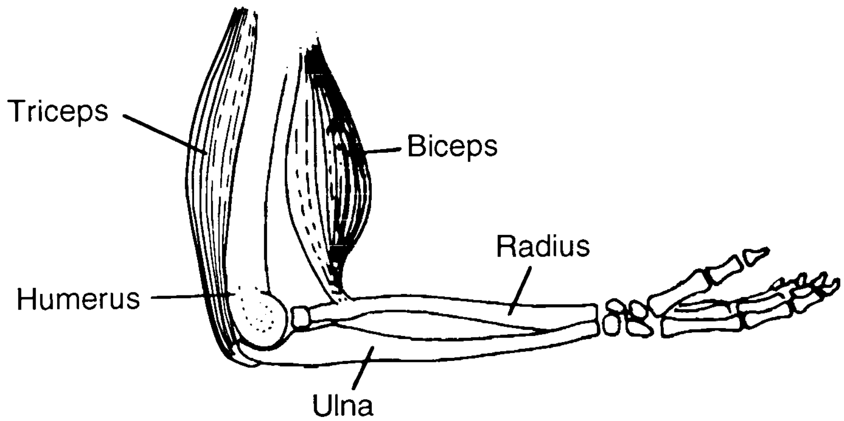


Figure 3.2. Schematic view of the muscle system used to bend the elbow. Biceps bend the elbow to lift, triceps straighten it.

Closer examination of the fibers show still smaller strands called *myofibrils* that, when examined by an electron microscope, consist of even smaller structures called *filaments*. The latter are composed of proteins. As shown schematically in Fig. 3.3, the filaments appear in two forms: (1) thick filaments that are composed of the protein myosin and are about 10 nm in diameter and 2000 nm (2×10^{-6} m or 2 micrometers) long, and (2) thin filaments that are composed of the protein actin and are about 5 nm in diameter and 1500 nm long. During contraction, an electrostatic force of attraction between the bands causes them to slide together, thus shortening the overall length of the bundle. A contraction of 15–20% of their resting length can be achieved in this way. The contraction mechanism at this level is not completely understood. It is evident that electrical forces are involved, as they are the only known force available. It should be emphasized that muscles produce a force only in contraction, that is, during a shortening of the muscle bundle.

Smooth muscles do not form fibers and, in general, are much shorter than striated muscles. Their contraction mechanism is different, and in some cases they may contract more than the resting length of an individual muscle cell. This effect is believed to be caused by the slipping of muscle cells over each other. Examples of smooth muscles in the body are circular muscles around the anus, bladder, and intestines, and in the walls of arteries and arterioles (where they control the flow).

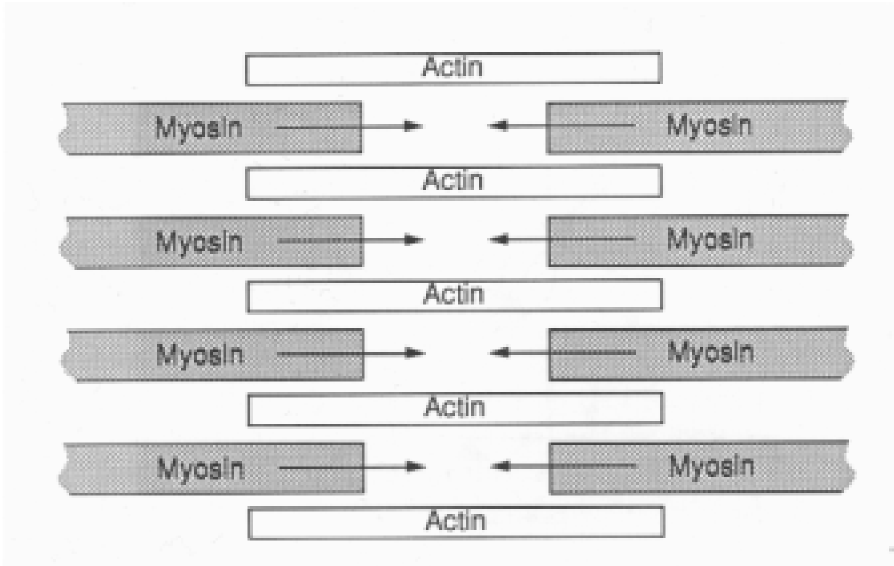


Figure 3.3. Schematic view of actin and myosin filaments with arrows showing the sliding movement between the filaments associated with muscle contraction.

Sometimes muscles are classified as to whether their control is voluntary (generally, the striated muscles) or involuntary (generally, the smooth muscles). This classification breaks down, however; the bladder has smooth muscle around it, yet is (usually) under voluntary control.

A third method of classifying muscles is based on the speed of the muscle's response to a stimulus. Striated muscles usually contract in times around 0.1 s (for example, the time to bend an arm), while smooth muscles may take several seconds to contract (control of the bladder).

3.3.2 Muscle Forces Involving Levers

For the body to be at rest and in equilibrium (static), the sum of the forces acting on it in any direction and the sum of the torques about any axis must both equal zero.

Many of the muscle and bone systems of the body act as levers. Levers are classified as first-, second-, and third-class systems (Fig. 3.4). Third-class levers are most common in the body, while first-class levers are least common.

Third-class levers, however, are not very common in engineering. To illustrate why this is so, suppose you were to open a door whose

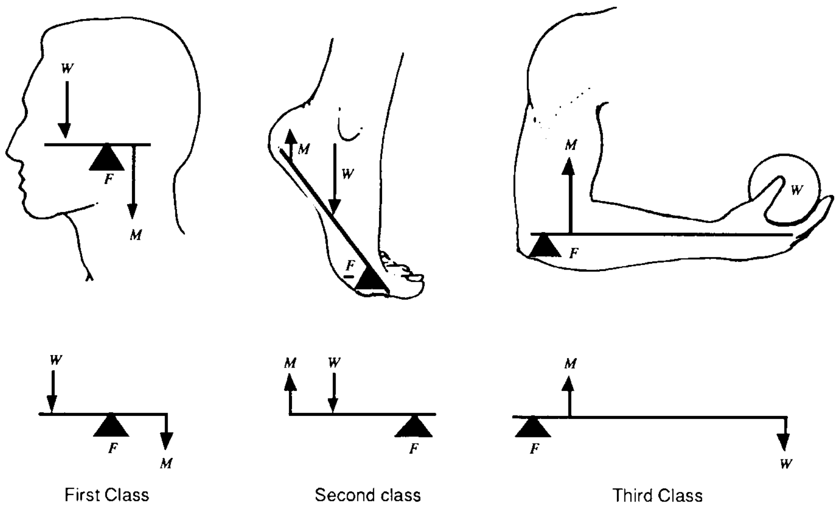


Figure 3.4. The three lever classes in the body and schematic examples of each. W is a force that is usually the weight, F is the force at the fulcrum point, and M is the muscular force. Note that the different levers depend upon different arrangement of the three forces, M, W, and F.

doorknob was located close to the hinge side of the door. It requires a certain amount of torque to open the door. Recall that torque is the product of the applied force and a lever arm that describes the effect this force will have to produce rotation about the hinge. Since the lever arm in this example is small, it follows that it will require a great deal of force to open the door. Finally, note that the applied force in this example must move the door near the hinge only a short distance to open the door. In the case of humans, this type of lever system amplifies the motion of our limited muscle contraction and thus allows for larger (and faster!) movement of the extremities. We give an example of movement of the forearm later in this section.

Muscles taper on both ends where tendons are formed. Tendons connect the muscles to the bones. Muscles with two tendons on one end are called biceps; those with three tendons on one end are called triceps. Because muscles can only contract, muscle groups occur in pairs; one group serves to produce motion in one direction about a hinged joint, and the opposing group produces motion in the opposite direction. The rotation of the forearm about the elbow is an excellent example of this principle. The biceps act to raise the forearm toward the upper arm, while the triceps (on the back of the upper arm) pull the forearm away from the upper arm. Try this yourself a few times, feeling the action of these upper arm muscles with your other hand.

3.1 PROBLEM

Try the following to experience the advantages and disadvantages of a third-class lever system. Place a large plastic bucket on a table and load it with two 5 kg masses (weight, 98 N or 22 lb). Wrap the handle of the bucket with a cloth to provide a softer suspension point. Lift the bucket with one hand, keeping the angle between your forearm and upper arm about 90°. Now repeat the experiment of lifting the bucket with the handle further up your forearm, say halfway to the elbow. Can you feel the difference in the force required in your biceps? By how much has it changed—by sense and by calculation (see below)? Repeat this experiment with varying angles between the two parts of your arm.

Let's consider further the case of the biceps muscle and the radius bone acting to support a weight W in the hand (Fig. 3.5a). Figure 3.5b shows the forces and dimensions of a typical arm. We can find the force supplied by the biceps if we sum the torques (force times distance—moment arm) about the pivot point at the joint. There are only two torques: that due to the weight W (which is equal to 30W acting clockwise) and that produced by the muscle force M (which acts counterclockwise and of magnitude 4M). With the arm in equilibrium 4 M must equal 30 W, or 4 M – 30 W = 0 and M = 7.5 W. Thus, a muscle force 7.5 times the weight is needed. For a 100 N (~22 lb) weight, the muscle force is 750 N (~165 lb).

For individuals building their muscles through weight lifting, the exercise of lifting a dumbbell as in Fig. 3.5 is called a dumbbell curl. A trained individual could probably curl about 200 N (~44 lb) requiring the biceps to provide 1500 N (~330 lb) force.

In our simplification of the example in Fig. 3.5b, we neglected the weight of the forearm and hand. This weight is not present at a particular point but is nonuniformly distributed over the whole forearm and hand. We can imagine this contribution as broken up into small segments and include the torque from each of the segments. A better method is to find the center of gravity for the weight of the forearm and hand and assume all the weight is at that point. Figure 3.5c shows a more correct representation of the problem with the weight of the forearm and hand, H, included. A typical value of H is 15 N (~3.3 lb). By summing the

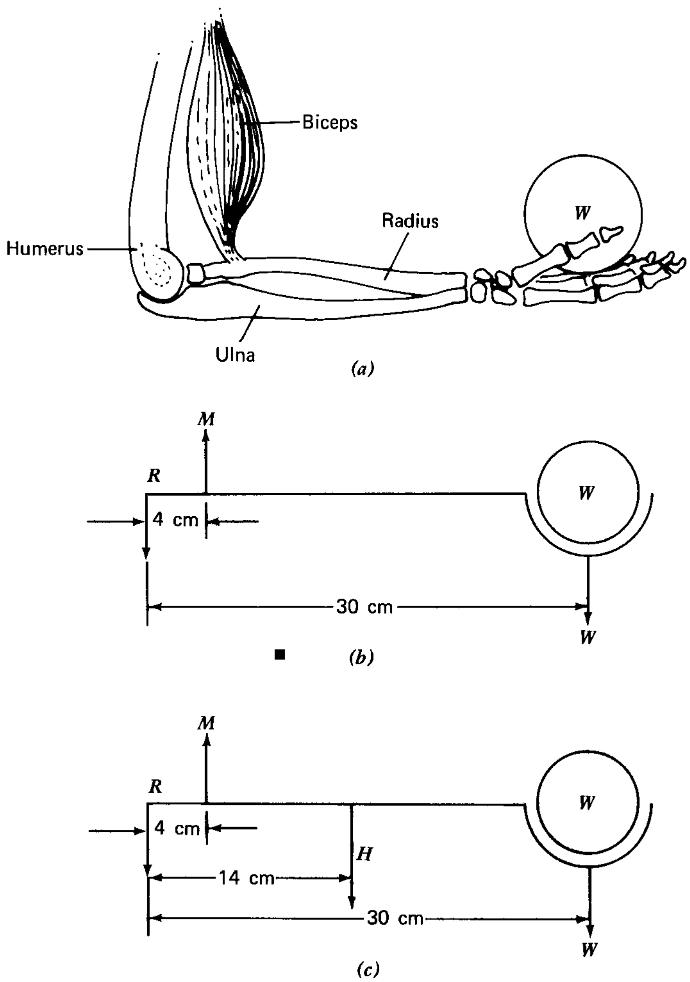


Figure 3.5. The forearm. (a) The muscle and bone system. (b) The forces and dimensions: R is the reaction force of the humerus on the ulna, M is the muscle force supplied by the biceps, and W is the weight in the hand. (c) The forces and dimensions where the weight of the tissue and bones of the hand and forearm H is included. These forces are located at their center of gravity.

torques about the joint we obtain 4 M = 14 H + 30 W, which simplifies to M = 3.5 H + 7.5 W. This simply means that the force supplied by the biceps muscle must be larger than that indicated by our first calculation by an amount 3.5 H = (3.5)(15) = 52.5 N (~12 lb).

What muscle force is needed if the angle of the arm changes from the 90° (between forearm and upper arm) that we have been considering so far, as illustrated in Fig. 3.6a? Figure 3.6b shows the forces we must consider for an arbitrary angle α. If we take the torques about the joint we find that M remains constant as alpha changes! (As you will see if you perform the calculation, this is because the same trigonometric function of α appears in each term of the torque equation.) However, the length of the biceps muscle changes with the angle. Muscle has a minimum length to which it can be contracted and a maximum length to which it can be stretched and still function. At these two extremes, the force the muscle can exert is much smaller. At some point in between, the muscle produces its maximum force (see Fig. 3.7). If the biceps pulls vertically (which is an approximation), the angle of the forearm does not affect the force required; but it does affect the length of the biceps muscle, which in turn affects the ability of the muscle to provide the needed force. Most of us become aware of the limitations of the biceps if we try to chin ourselves. With our arms fully extended we have difficulty, and as the chin approaches the bar the shortened muscle loses its ability to shorten further.

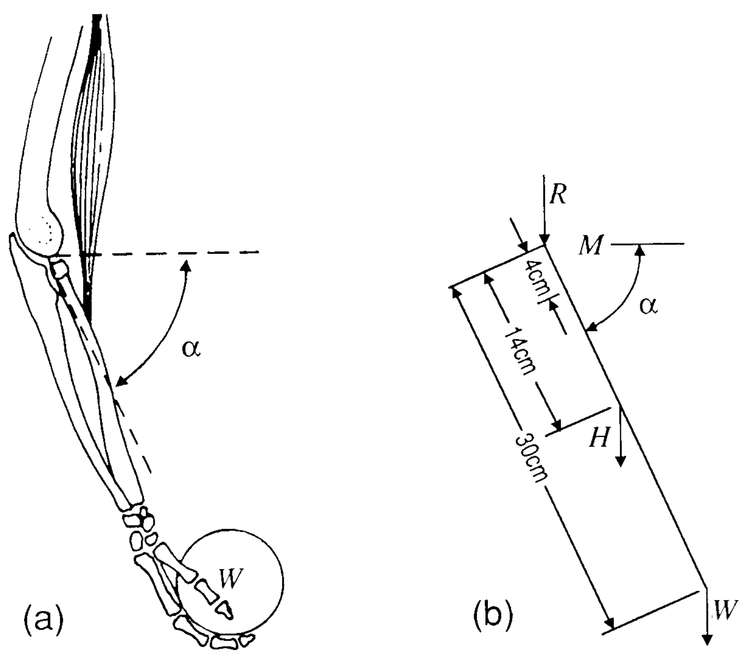


Figure 3.6. The forearm at an angle α to the horizontal. (a) The muscle and bone system. (b) The forces and dimensions.

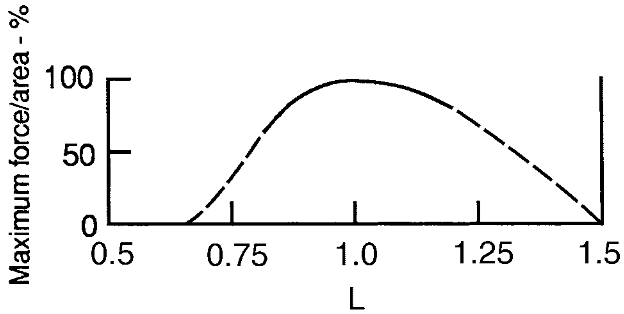


Figure 3.7. At its resting length L a muscle is close to its optimum length for producing force. At about 80% of this length it cannot shorten much more and the force it can produce drops significantly. The same is true for stretching of the muscle to about 20% greater than its natural length. A very large stretch of about 2L produces irreversible tearing of the muscle.

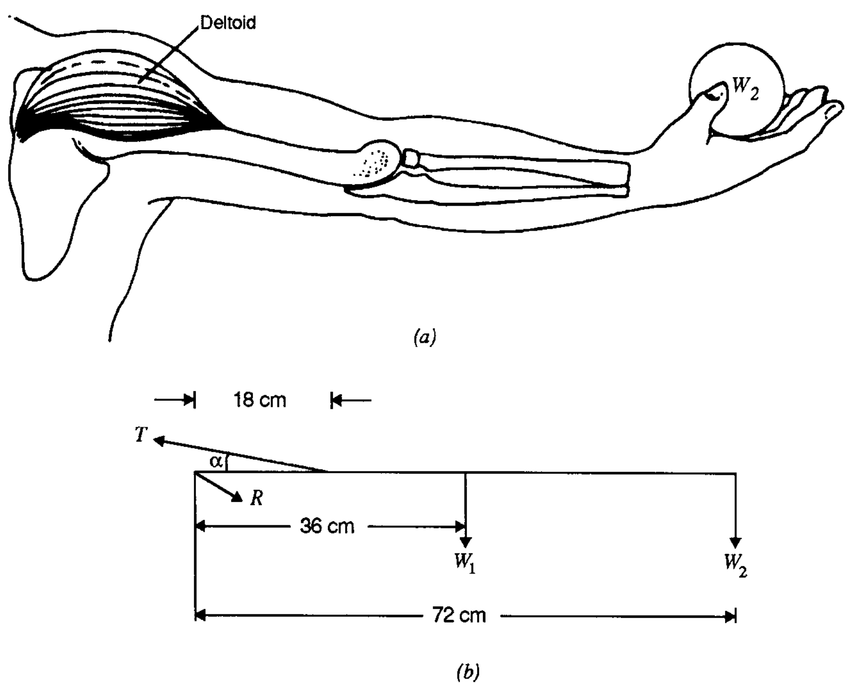


Figure 3.8. Raising the right arm. (a) The deltoid muscle and bones involved. (b) The forces on the arm. T is the tension in the deltoid muscle fixed at the angle α, R is the reaction force on the shoulder joint, W_1 is the weight of the arm located at its center of gravity, and W_2 is the weight in the hand. (Adapted from L. A. Strait, V. T. Inman, and H. J. Ralston, *Amer. J. Phys.*, 15, 1947, p. 379.)

The arm can be raised and held out horizontally from the shoulder by the deltoid muscle (Fig. 3.8a); we can show the forces schematically (Fig. 3.8b). By taking the sum of the torques about the shoulder joint, the tension T can be calculated from:

$$T = (2\,W_1 + 4\,W_2)/\sin\alpha \qquad (3.1)$$

If α = l6°, the weight of the arm W_1 = 68 N (~15 lb), and the weight in the hand W_2 = 45N (~10 lb), then T = 1145 N (~250 lb). The force needed to hold up the arm is surprisingly large.

PROBLEM 3.2

In the lever of the foot shown in Fig. 3.4, is M greater or smaller than the weight on the foot? (Hint: The muscle that produces M is attached to the tibia, a bone in the lower leg.)

PROBLEM 3.3

Show that for Fig. 3.6, the muscle force is independent of the angle.

PROBLEM 3.4

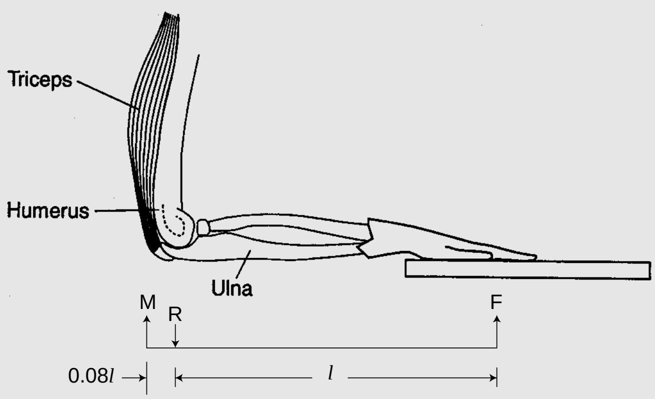
Derive Equation 3.1 for the arm and deltoid muscle system.

3.5 PROBLEM

It is known that the human biceps can produce a force of approximately 2600 N. Why can't you pick up an object with your hand which weighs 2600 N?

3.6 PROBLEM

If you turn your hand over and press it against a table, you have a first class lever system (see sketch). In this case, the biceps muscle group is relaxed and is ignored. The force of the hand F on the table is balanced by the force supplied by the triceps M pulling on the ulna and the fulcrum force R located where the humerus makes contact with the ulna. For the parameters shown below and for a force F = 100 N (22 lb), find the force needed from the triceps. Ignore the mass of the arm and hand.



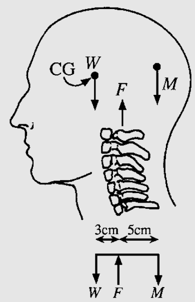
3.7 PROBLEM

One first-class lever system involves the extensor muscle, which exerts a force M to hold the head erect; the force W of the weight of the head, acting at its center of gravity (cg), lies forward of the force F exerted by the first cervical vertebra (see sketch on the next page). The head has a mass of about 3 kg, or weight W≅ 30 N.

(a) Find F and M. [Answer: F = 48 N; M = 18 N]

(b) If the area of the first cervical vertebra, on which the head rests, is 5×10^{-4} m^2, find the stress (force per unit area: N/m^2) on it. [Answer: 9.6×10^4 N/m^2]

(c) How does this stress compare with the rupture compression strength for vertebral disks (1.1×10^7 N/m^2)? [Answer: 1.3×10^6 N/m^2]



3. 3. 3 The Spinal Column

Bones provide the main structural support for the body (see Chapter 4, Fig. 4.1). Examination of that figure shows that the cross-sectional area of the supporting bones generally increases from head to toe. These bones provide the support for the additional weight of muscle and tissue as one moves downward to the soles of the feet. The body follows the same engineering principles as used in the design of a building where the major support strength is in the base. (Note, however, that there are exceptions; the femur is larger than the tibia and fibula, the supporting bones in the legs.)

Load-bearing bones are optimized for their supporting tasks. The outside or compact dense bone is designed to carry compressive loads. The inner spongy or cancellous bone, at the ends of long bones and in the vertebrae, has thread-like filaments of bone (trabeculae) which provide strength yet are light in weight. Engineering examples of such construction would be honeycomb structures used to strengthen aircraft wings, the use of lightweight graphite fibers in composite materials, and the framework used to support and strengthen buildings.

The vertebrae are examples of load-bearing bones. The spinal column of a skeleton is shown in Fig. 3.9. Note that the vertebrae increase in both thickness and cross-sectional area as you go from the neck (cervical) region to the lower back (lumbar) region. A larger surface area is needed to support the additional body mass above each succeeding vertebra. There are fibrous discs between the vertebrae that cushion the downward forces and other impacts on the spinal column. However, the pressure (force/area) remains approximately constant for all discs. The discs rupture at a stress (pressure) of about 10^7 N/m^2 (10^7 Pa; 100 atmospheres).

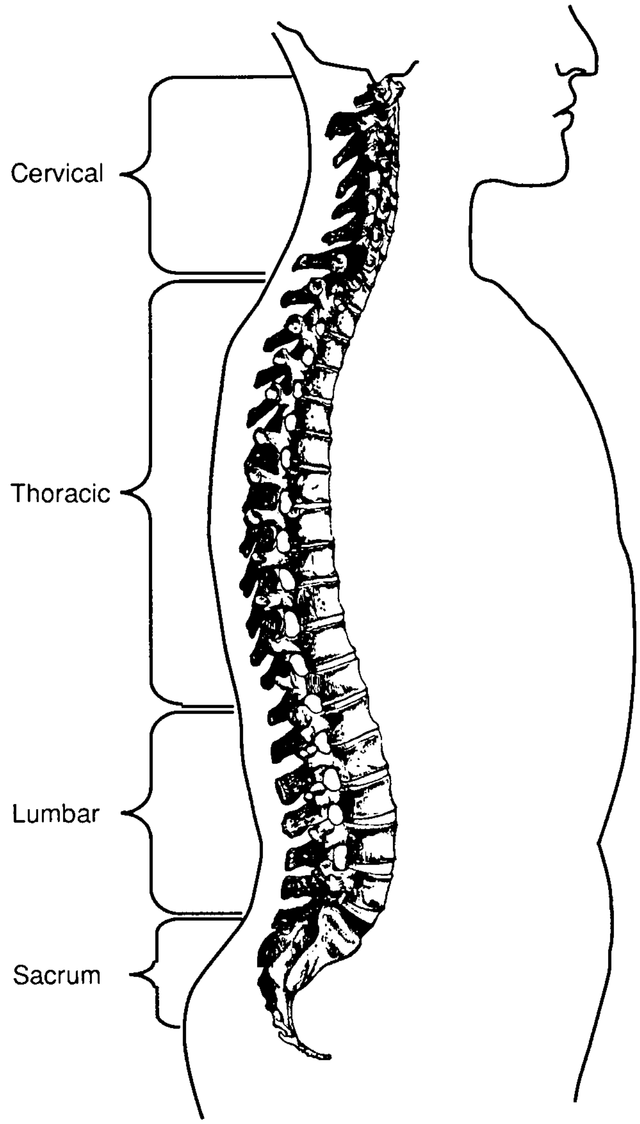


Figure 3.9. The spinal column provides the main support for the head and trunk of the body. The column has an "S" shape, and the vertebrae increase in cross-sectional area as the supporting load increases. The length of the column for a typical adult male is about 0.7 m.

The length of the spinal column shortens slightly from its normal length of about 0.7 m (male) by as much as 0.015 m (1.5 cm = 0.6 in) after arising from sleep. The original length is restored after a night's sleep. However, the spinal column does shorten permanently with age most often as the result of osteoporosis and compression of the discs, which is particularly common in elderly women. Osteoporosis causes bone to weaken and eventually to collapse. This is discussed further in the next chapter.

The spinal column has a normal curvature for stability. Viewed from the right side the lower portion of the spine is shaped like a letter "S" as shown in Fig. 3.9. Lordosis, kyphosis, and scoliosis are deviations in the shape of the spine. *Lordosis*, too much curvature, often occurs in the lumbar region. A person with this condition is sometimes called sway-backed (Fig. 3.10a). *Kyphosis* is an irregular curvature of the spinal column as seen from the side; frequently it leads to a hump in the back. A person with this condition is often referred to as hunch-backed (Fig. 3.10b). *Scoliosis* is a condition in which the spine curves in an "S" shape as seen from the back (Fig. 3.10c). Normal posture is shown in Fig. 3.10d.

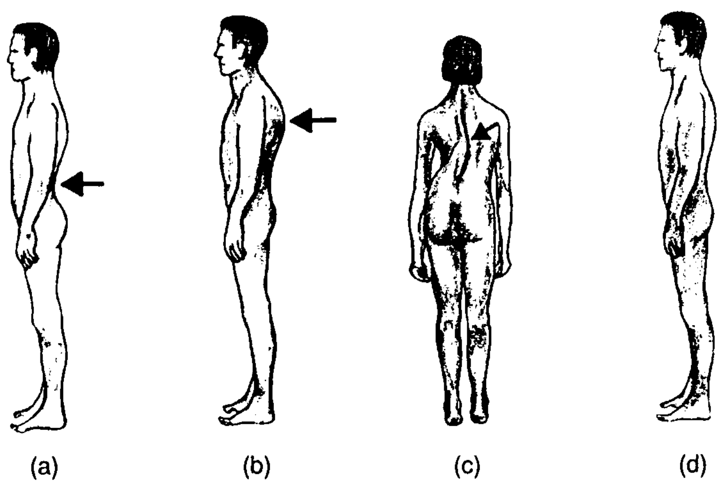


Figure 3.10. Sketches for the abnormal spinal conditions of (a) lordosis (or sway-back), (b) kyphosis (or hunch-backed), and (c) scoliosis. (d) The normal condition. (Adapted from *A Guide to Physical Examination*, B. Bates, J. P. Lippincott, Philadelphia, PA, pp. 261–261, (1974) by permission.)

PROBLEM 3.8

The discs in the spinal column can withstand a stress (force per unit area) of 1.1×10^7 N/m^2 before they rupture.

(a) If the cross-sectional area of your discs is 10 cm^2, what is the maximum force that can be applied before rupture takes place? [Answer: 1.1×10^4 N]

(b) Estimate the stress at a disc located at the level of the center of gravity of your body when you are standing vertically. [Answer: 3.5×10^5 N/m^2]

(c) What types of situations might the body experience where the stress on this vertebra would be much larger than in (b) above?

3.3.4 Stability While Standing

In an erect human viewed from the back, the center of gravity (cg) is located in the pelvis in front of the upper part of the sacrum at about 58% of the person's height above the floor. A vertical line from the cg passes between the feet. Poor muscle control, accidents, disease, pregnancies, overweight conditions, or poor posture change the position of the cg to an unnatural location in the body as illustrated in Fig. 3.11. An overweight condition (or a pronounced slump) lead to a forward shift of the cg, moving the vertical projection of it under the balls of the feet where the balance is less stable. The person may compensate by tipping slightly backward.

To retain stability while standing, you have to keep the vertical projection of your cg inside the area covered by your feet (Fig. 3.12a). If the vertical projection of your cg falls outside this area, you will tip over. When your feet are close together (Fig 3.12a) you are less stable than when they are spread apart (Fig 3.12b). Likewise, if the cg is lowered, you become more stable. A cane or crutch also improves your stability (Fig. 3.12c). Comparing the stability of a human with a four-legged animal, it is clear that the animal is more stable because the area between its four feet is larger than for two-legged humans. Thus it is understandable that a human baby takes about ten months before it is able to stand while a newborn four-legged animal achieves this in less than two days (in the wild, less than one hour), a useful condition for survival.

The body compensates its stance when lifting a heavy suitcase with one arm. The opposite arm moves out and the body tips away from the object to keep the cg properly placed for balance. (Try lifting the bucket used in Problem 3.1 out to the side to see how this works.) People who

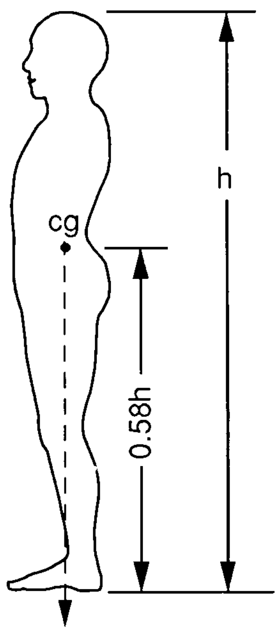


Figure 3.11. (a) The center of gravity of a normal person is located about 58% of the person's height above the soles of their feet. (b) An overweight condition can shift the cg forward so that the vertical projection of it passes underneath the balls of the feet, causing the body to compensate by assuming an unnatural position leading to possible muscle strain. (After C. R. Nave and B. C. Nave, *Physics for the Health Sciences*, W. B. Saunders Company, 1975, p. 24 by permission.)

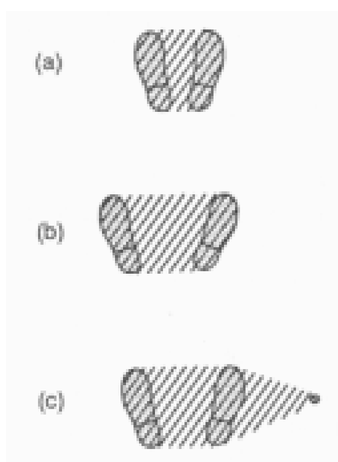


Figure 3.12. The body remains stable as long as the vertical projection of the cg remains inside the cross-hatched area between the feet. (a) The stable area when the feet are close together, (b) the stable area when the feet are spread apart, and (c) the stable area when a cane or crutch is used.

have had an arm amputated are in a situation similar to a person carrying a suitcase. They compensate for the weight of the remaining arm by bending the torso; however, continued bending of the torso leads to spine curvature. A common prosthesis is an artificial arm with a mass equal to the missing arm. Even though the false arm may not function, it helps to prevent distortion of the spine.

3.3.5 Lifting and Squatting

The spinal cord is enclosed and protected by the spinal column. The spinal cord provides the main pathway for the transmission of nerve signals to and from the brain. The discs separating the vertebrae can be damaged; one common back ailment is called a slipped disc. The condition occurs when the wall of the disc weakens and tears, leading to a bulge that sometimes pushes against nerves passing through the special holes (foramina) on the sides of each vertebra. Extended bed rest, traction, physical therapies, and surgery are all used to alleviate this condition.

An often abused part of the body is the lumbar (lower back) region, shown schematically in Fig. 3.13. Lumbar vertebrae are subject to very large forces—those resulting from the weight of the body and also the forces you create in the lumbar region by lifting. The figure illustrates the large compressive force (labeled R) on the fifth lumbar vertebra (labeled L5). When the body is bent forward at 60° to the vertical and there is a weight of 225 N (~50 lb) in the hands, the compressive force R can approach 3800 N (~850 lb, or about six times an average body weight).

It is not surprising that lifting heavy objects incorrectly is a primary cause of low back pain. Since low back pain can be serious and is not well understood, physiologists are interested in finding out exactly how large the forces are in the lumbar region. Measurements of pressure in the discs have been made by inserting a hollow needle connected to a calibrated pressure transducer into the gelatinous center of an intervertebral disc. This device measures the pressure within the disc. The pressures in the third lumbar disc for an adult in different positions are shown in Fig. 3.14a and 3.14b. Even when standing erect there is a relatively large pressure in the disc as a result of the combined effects of weight and muscular tension. If the disc is overloaded as might occur in improper lifting, it can rupture (or slip), causing pain either from the rupture or by allowing irritating materials from inside the disc to leak out.

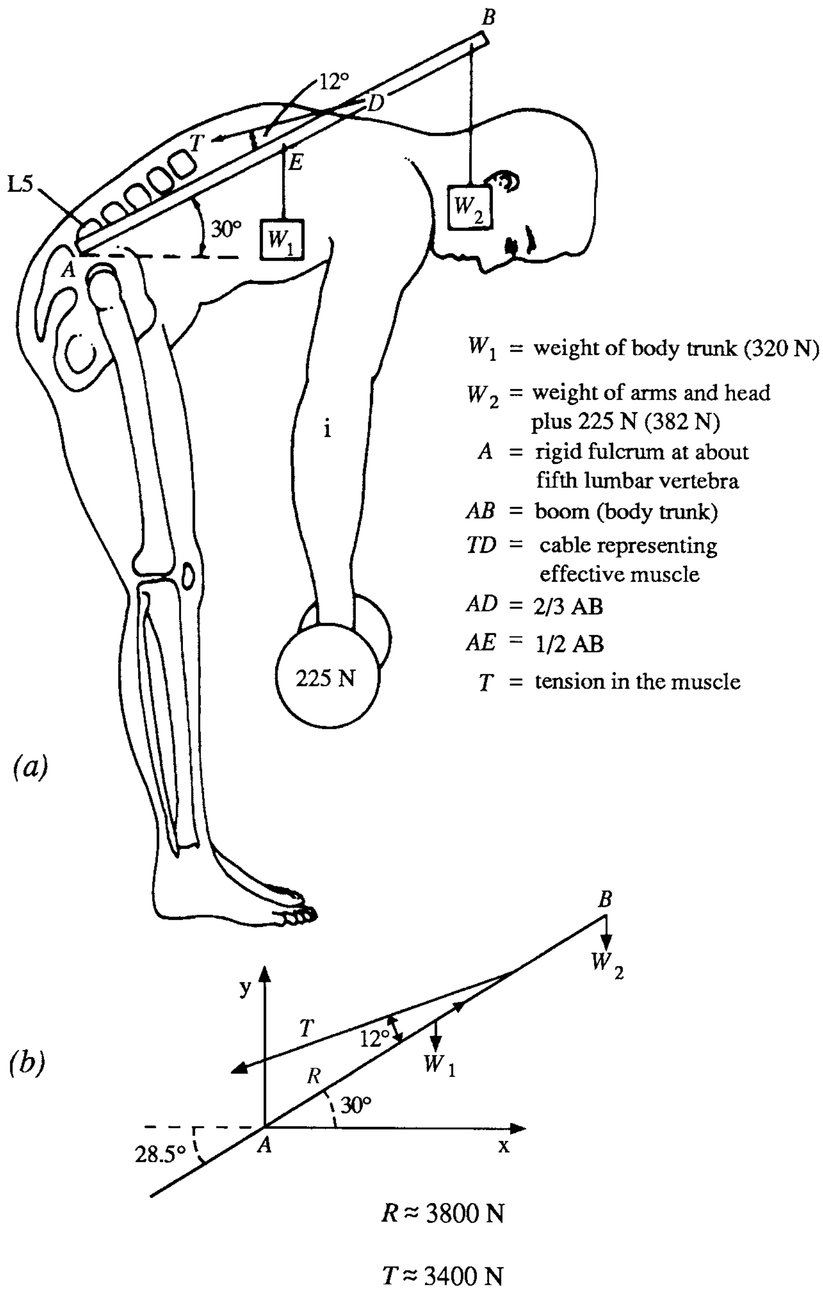


Figure 3.13. Lifting a weight. (a) Schematic of forces used. (b) The forces where T is an approximation for all of the muscle forces and R is the resultant force on the fifth lumbar vertebra (L5). Note that the reaction force R at the fifth lumbar vertebra is large. (Adapted from L. A. Strait, V. T. Inman, and H. J. Ralston, *Amer. J. Phys.*, 15, 1947, pp. 377–378.)

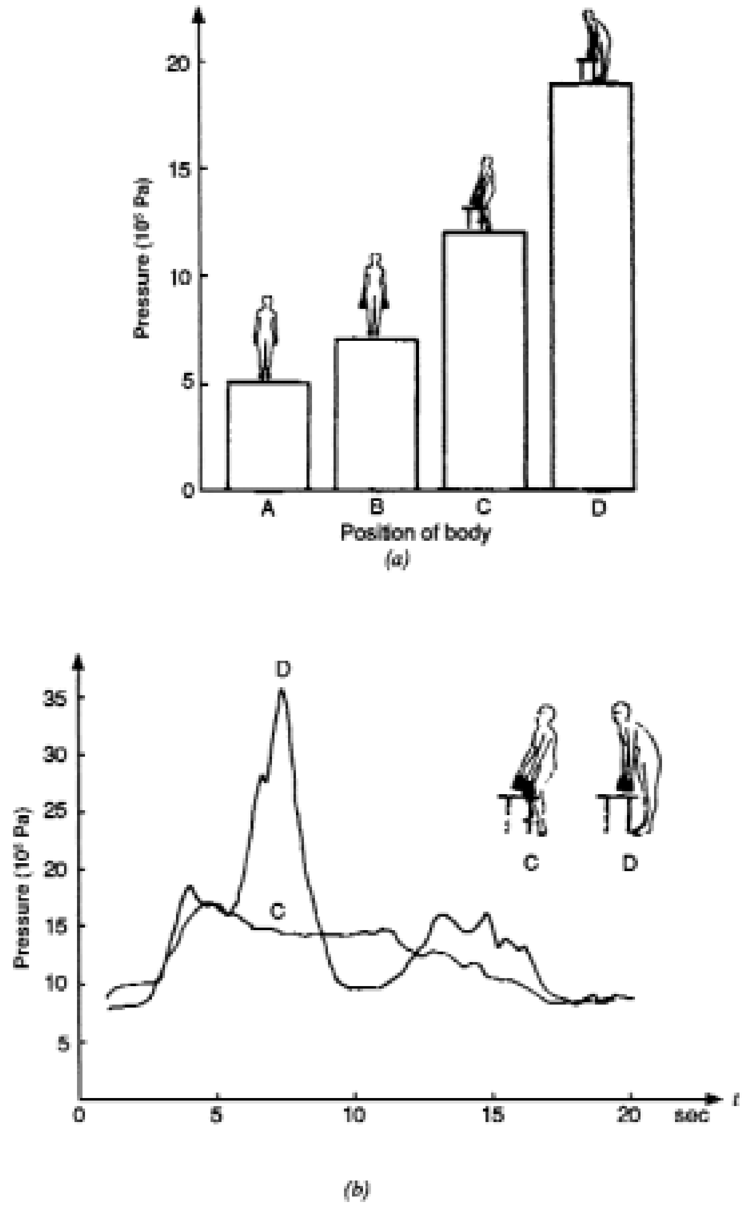


Figure 3.14. Pressure on the spinal column. (a) The pressure on the third lumbar disc for a subject (A) standing, (B) standing and holding 20 kg, (C) picking up 20 kg correctly by bending the knees, and (D) picking up 20 kg incorrectly without bending the knees. (b) The instantaneous pressure in the third lumbar disc while picking up and replacing 20 kg correctly and incorrectly. Note the much larger peak pressure during incorrect lifting. (Adapted from A. Nachemson and G. Elfstrom, *Scand. J. Rehab. Med.*, Suppl. 1, 1970, pp. 21–22.)

It has been argued that low back pain is the price that humans pay for being erect; however, disc degeneration also occurs in four-legged animals (in particular, in dachshunds). Disc failures for both animals and humans occur in regions under the greatest stress.

Just as forces can be transmitted over distances and around corners by cable and pulley systems, the forces of muscles in the body are transmitted by tendons. Tendons, the fibrous cords which connect the muscle end to a bone, minimize the bulk present at a joint. For example, the muscles that move the fingers to grip objects are located in the forearm, and long tendons are connected to appropriate places on the finger bones. Of course, the tendons have to remain in their proper locations to function properly. Arthritis in the hands often prevents the tendons from fully opening and closing the hands.

In the leg, a tendon passes over a groove in the kneecap (patella) and connects to the shin bone (tibia). With your leg extended you can move the patella with your hand but with your knee flexed you cannot; the patella is held rigidly in place by the force from the tendon as shown in Fig. 3.15. The patella also serves as a pulley for changing the direction of the force. This also acts to increase the mechanical advantage of the muscles that straighten the leg. Some of the largest forces in the body occur at the patella. When you are in a deep squatting position, the tension in the tendons that pass over the patella may be more than two times your weight (Fig. 3.15).

3.3.6 Forces on the Hip and Thigh

When you are walking, there is an instant when only one foot is on the ground and the cg of your body is directly over that foot. Fig. 3.16a shows the forces acting on that leg. These forces are (1) the upward vertical force on the foot, equal to the weight of the body, W; (2) the weight of the leg, W_L, which is approximately equal to W/7; (3) R, the reaction force acting between the hip and the femur; and (4) the tension, T, in the muscle group between the hip and the greater trochanter on the femur. The latter provides the force to keep the body in balance.

The various dimensions and the angle shown in Fig. 3.16 have been taken from cadaver measurements. Solving the equations for equilibrium in this example, it is found that T = 1.6 W and R = 2.4 W at the hip joint. Thus for a 70 kg individual, the head of the femur experiences a force of over 1600 N (≈350 lb) or 2.4 times the body weight!

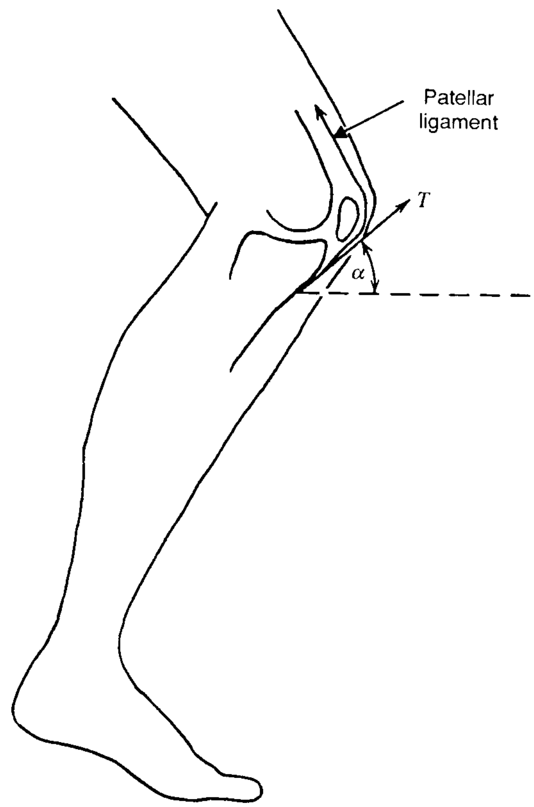


Figure 3.15. Diagram of the tensile force on the patellar ligament during squatting. The tension T is very large when a person is in a low squat.

When there is injury to the muscle group at the hip, or damage to the hip joint, the body reacts by trying to reduce the forces that cause pain—T and R in Fig. 3.16a. It does this by tipping the body so that the cg is directly over the ball of the femur and the foot (Fig. 3.16b). This reduces the muscle force, T, to nearly zero, and the reaction force, R, becomes approximately the body weight W minus one leg, or (6/7) W. R is now pointing directly downward. This reduces the forces T and R by a large amount and helps the healing process. However, the downward reaction force causes the head of the femur to grow upward, while the ball of the femur on the other leg does not change. Eventually this leads to uneven growth at the hip joints and possible permanent curvature of the spine.

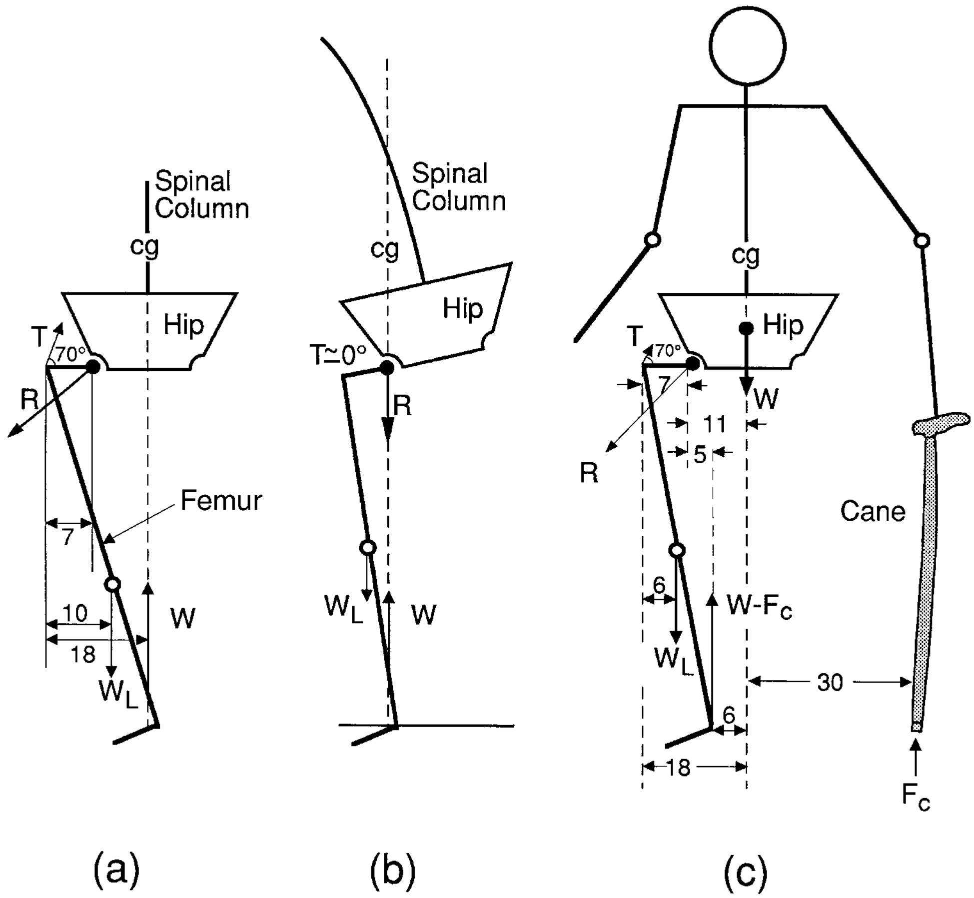


Figure 3.16. A diagram that shows approximately the forces and dimensions (in cm) for the hip-leg under different conditions. (a) When the person is standing on one foot. The vertical upward force on the foot is the person's weight, W. The weight of the leg, W_L, is taken to be W/7 and the angle of the hip abductor muscles indicated by T is taken to be 70°. R is the reaction force between the hip and the head of the femur (hip joint). (b) When either the hip joint or abductor muscle is injured, the body is bent to place the cg directly over the ball of the femur and the center of the foot, thus reducing the reaction force, R, and the force of the abductor muscle, T. (c) When a cane is used, the abductor force, T, and the reaction force, R, at the head of the femur are greatly reduced. The upward force of F_C = W/6 gives T ≈ 0.65W and R ≈ 1.3W, a substantial reduction from that of part (a). (Adapted from M. Williams and H. R. Lissner, *Biomechanics of Human Motion*, Philadelphia, W. B. Saunders Company, 1962, p.110 and from G. B. Benedek and F. M. H. Vilars, *Physics with Illustrative Examples from Medicine and Biology, Vol. 1, Mechanics*, Addison-Wesley, 1973.)

The use of crutches or a cane reduces the force on the hip joint. The physics of the use of a cane is shown schematically in Fig. 3.16c. There are three forces acting on the body: the weight, W, the force, F_C, pushing upward on the cane, and the upward force on the foot equal to $W - F_C$. Note that the cane is in the hand opposite to the injured hip. Without the cane, we found T = 1.6 W and R = 2.4 W. The use of the cane reduces these forces by allowing the foot to move from the position under the centerline of the body, as in Fig. 3.16a, to a new location closer to being under the head of the femur. The spine is not twisted as it is in Fig. 3.16b. The cane is located 0.3 m from the vertical projection line of the cg. We assume that the cane supports about 1/6 of the body's weight. For the conditions given in Fig. 3.16c, we find T = 0.65 W and R = 1.3 W. Although human nature leads us to hide our handicaps, the use of a cane can considerably aid in the healing process for hip joints.

PROBLEM 3.9

Use the equations of static equilibrium to calculate the forces T and R for the case shown in Fig. 3.16a. [Answer: T = 1.6 W; R = 2.4 W]

3.4 Forces During Collisions

When a portion of the body (or the whole body) bumps into a solid object, it rapidly decelerates, resulting in large forces. If we consider the deceleration to be constant and limit ourselves to one-dimensional motion, we can use the original form of Newton's second law. Force equals the rate of change of momentum. The more common form, mass times acceleration, can be written as:

$$F = ma = m(\Delta v/\Delta t) = \Delta(mv)/\Delta t$$

or F = the rate of change of momentum.

Newton originally wrote his second law in this form.

3.4.1 Examples of Forces during Collisions

The following example illustrates how this form of Newton's second law can be used to estimate the forces on the body when it collides with something:

Example: A person walking at 1 m/s accidentally bumps her or his head against an overhanging steel beam (ouch!). Assume that the head stops in about $\Delta t = 0.01$ s while traveling an additional distance of 0.005 m (5 mm). The mass of the head is 3 kg. What is the force which caused this deceleration?

> **Answer:** The change of momentum is $\Delta(mv) = (3\text{ kg})(0\text{ m/s}) - (3\text{ kg})(1\text{ m/s}) = -3$ kg m/s (the minus sign means that the momentum of the head has decreased; the force is in the opposite direction from the motion). Thus $F = (-3\text{ kg m/s})/(0.01\text{ s}) = -300$ N (about 67 lb force).

Example: If we repeat this accident, with a steel beam with 0.02 m (2 cm) of padding, the time of deceleration is increased to $\Delta t = 0.04$ s. What force acts to decelerate the head under these conditions?

> **Answer:** $F = \Delta(mv)/\Delta t = (3\text{ kg m/s})/(0.04\text{ s}) = 75$ N (about 15 lb), a considerable reduction from the first case.

An example of a dynamic force in the body is the apparent increase of weight when the heart beats (systole). About 0.06 kg of blood is given a velocity of about 1 m/s upward in a time of t = 0.1s. The upward momentum given to the mass of blood is (0.06 kg) (1 m/s) = 0.06 kg m/s; thus the reaction force to this movement of the blood is (0.06 kg m/sec)/(0.1 s) or 0.6 N (~0.125 lb, or 2 oz). This is enough to produce a noticeable jiggle on a sensitive spring-type scale (as noted in Chapter 1, *Terminology, Modeling, and Measurement*).

If you jump from a height of 1 m and land stiff-legged, you are in for a shock. Under these conditions, the deceleration of the body takes place mostly through compression of the padding of the feet. We can calculate that the body is traveling at 4.5 m/s (16 km/hr) just prior to hitting; and if the padding collapses by 1 cm, the body stops in about 0.005 s (5 ms). Under these conditions, the force in your legs is almost 100 times your weight (that is, 100 g; see Fig. 3.17). If you land on a

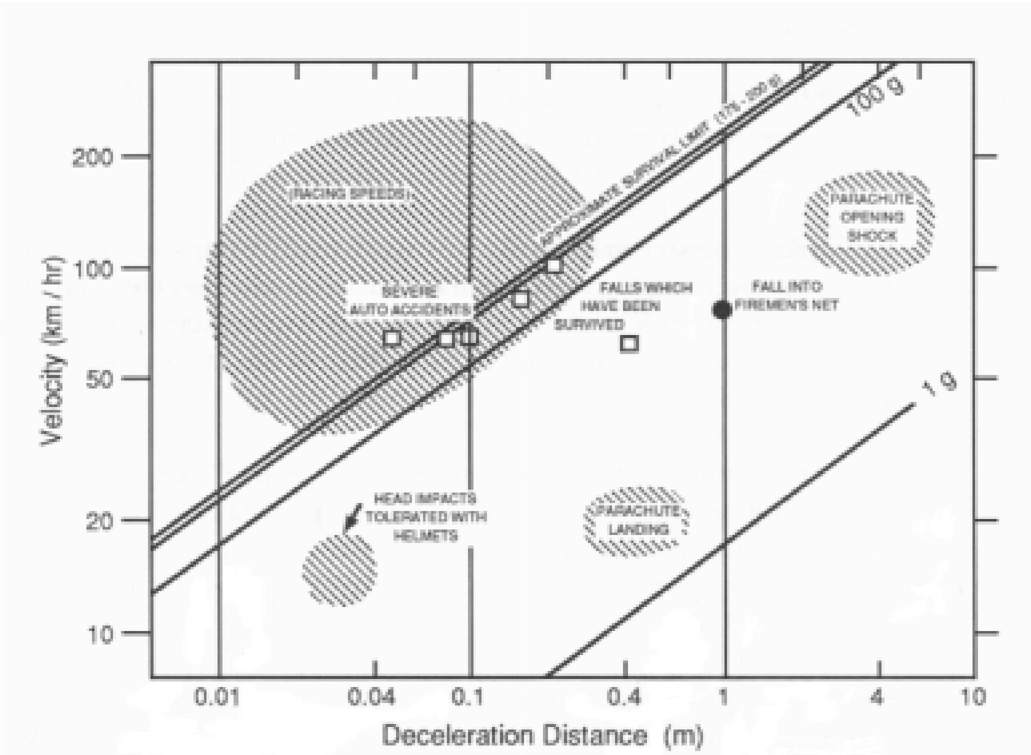


Figure 3.17. A compilation of documented cases of impact results on humans shown as a log-log plot of the velocity on impact versus the deceleration distance during impact. The diagonal lines show the deceleration in terms of acceleration of gravity, g. (One g times your body's mass is equal to your body weight.) The hollow squares represent data from documented free-fall survivors. The shaded areas represent guestimates for the other situations. (After R. G. Snyder, *Bioastronautics Data Book*, Second ed., 1973, p. 228.)

gym mat, the deceleration time would be longer; and if you follow the normal body reaction, you will land on your toes first and bend your knees to decelerate over a much longer time, thus decreasing the landing force.

A current popular form of entertainment is bungee jumping, in which a person is attached to a very stretchable bungee cord and jumps from a considerable height. The bungee cord decelerates the person over a long distance. The thrill comes from the freefall and deceleration. In terms used in Fig. 3.17, the deceleration distances would usually be more than 10 m and the velocities below 100 km/hr. This puts the conditions beyond the upper right region of the figure.

3.10 PROBLEM

A 50 kg person jumping from a height of 1 m is traveling at 4.4 m/s just prior to landing. Suppose the person lands on a pad and stops in 0.2 s. What maximum decelerating force will be experienced? [Answer: F_{max} = 1100 N]

3.4. 2 Surviving Falls from Great Heights

You might think that if you jump or fall from a great height your chance of surviving is zero, unless of course you land on something like a giant airbag. In real life, your chances are very small, but not zero. People have survived falls from great heights. It all depends on where and how you land! If you fall on bushes, tree branches, deep snow, or land on the side of a hill, the deceleration forces you experience may be small enough that you could survive. A summary of the hazardous ranges for impact collisions is shown in Fig. 3.17 along with some documented cases. This figure shows the velocity at the time of impact plotted versus the distance needed to stop. One could equally well plot the velocity versus the time needed to stop, but usually the distance is more easily measured. The heavy diagonal lines in the figure indicate the decelerations in terms of the units of gravity, g = 9.8 m/s^{-2}. For example, a deceleration of 10 g corresponds to a decelerative force equal to ten times the weight of the object. The double line in the figure represents an estimate of the limit of survivability.

3.4. 3 Collisions Involving Vehicles

Collisions of high velocity, modern cars subject occupants to very large accelerative or decelerative forces. The results of these forces on the driver and passengers can be broken bones, internal injuries, and death.

In the 1960s a federally mandated safety program for the automobile was begun. Even earlier, the military, NASA, and scientific groups were studying the forces that the body could withstand. For small controlled forces, this study was conducted using human volunteers. For more extreme limits, cadavers, dummies, or animals were used to determine the tolerance ranges.

Consider a head-on collision with a solid barrier, one of the most serious types of automobile accident. What happens to the automobile and its occupants in the collision? The front of the automobile is designed NOT to be rigid; it is built to collapse in sections, starting at the bumper, thus extending the collision distance (or time) as shown in Fig. 3.18a. The prolonged collapse reduces the deceleration force. The front of the car experiences severe damage, but the interior may be essentially undamaged with the consequence that its occupants may be bruised and shaken, but not seriously hurt. The amount of injury depends on additional safety features of the automobile, including seat belt systems and airbags which serve to protect the head and torso during a collision (Fig. 3.18b). Statistics indicate that these systems have been effective in reducing injury and death, but improper use of seatbelts and improper positioning of car seats for infants can produce the opposite result.

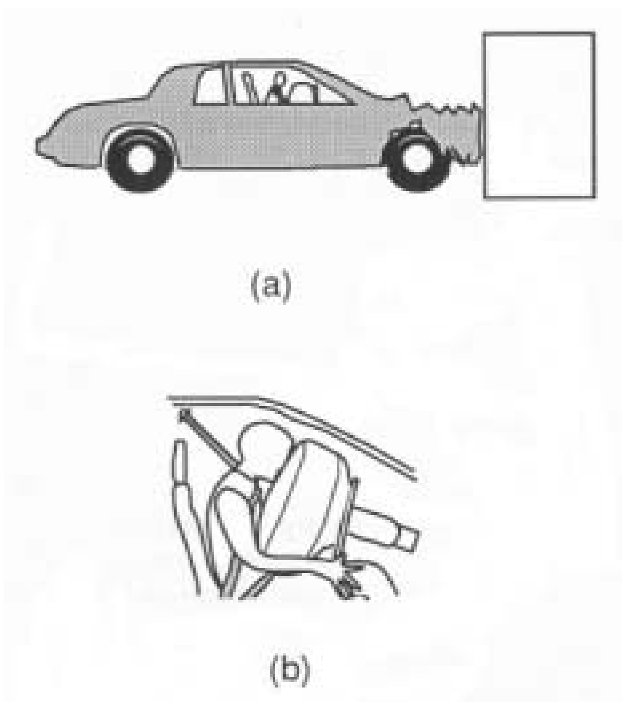


Figure 3.18. (a) An automobile is involved in a head-on collision and stops in a short distance. The deceleration distance can be about 1 m if the automobile is designed to collapse in the front end first. (b) The driver, who is wearing a harness seat belt, is rotated forward. An airbag inflates to cushion the driver's head and torso from collision with the steering wheel or dash.

Because of the hazards of uncontrolled automobile collisions, federal law requires a number of safety devices in automobiles. These include headrests, seat and shoulder belts (a three-point harness to prevent the person from being thrown from the automobile), energy-absorbing steering columns, penetration-resistant windshields, and side door beams to provide protection to the occupants during a side collision.

Information such as that given in Fig. 3.17 is used in the design of emergency escape methods from high-performance aircraft and in safety designs for commercial aircraft as well as for automobiles. For example, if a pilot is to be shot upward through an escape hatch, it is necessary to know the effects of acceleration in the seat-to-head direction. By knowing the limitations of the body, the accelerative force and its duration can be adjusted to minimize the probability of injury during emergency procedures.

A more familiar example of the use of the information in Fig. 3.17 is in the design of helmets for bicyclists, motorcycle riders, and for various sports such as baseball, football, hockey, and lacrosse. Each helmet is designed to reduce deceleration by crushing during impact. One criterion for bicycle helmets is the ability of the rider's head to withstand a 24 km/hr (15 mph) impact onto a rigid, flat surface as might happen if you fall when traveling at that speed. The helmet material must have the appropriate stiffness to compression so that the collapse of the helmet padding prolongs the deceleration and thus reduces the forces on the head. One must remember, however, that safety devices do not provide absolute protection.

3.11 PROBLEM

Estimate the force on the forehead in Fig. 3.18 if the mass of the head is 3 kg, its velocity is 15 m/s, and a padded dash is used instead of the air bag to stop the head in 0.02 s. [Answer: $F_{max} = 2.3 \times 10^3$ N]

3.4.4 Effects of Acceleration on Humans

Acceleration of the body produces a number of effects such as (1) an apparent increase or decrease in body weight, (2) changes in internal hydrostatic pressure, (3) distortion of the elastic tissues of the body, and

(4) the tendency of solids with different densities suspended in a liquid to separate. If the acceleration is sufficiently large, the body loses control because it does not have adequate muscle force to work against the large acceleration forces. Under certain conditions the blood may pool in various regions of the body; the location of the pooling depends upon the direction of acceleration. If a person is accelerated head first, the lack of blood flow to the brain can cause blackout and unconsciousness (see Chapter 8, *Physics of the Cardiovascular System*).

Astronauts in an orbiting satellite are in a condition of free fall or apparent weightlessness. Prior to man's first space flights, there were concerns about the physiological effects of weightlessness. Many of the effects predicted were based on changes observed in the body during extended periods of bed rest. We now have information about the effects on the body of extended time in space. Some physiological changes do take place; however, they have not been incapacitating or permanent.

Tissue can be distorted by acceleration and, if the forces are sufficiently large, tearing or rupture can take place. Laboratory information is sparse, but some experiments in huge centrifuges have shown that tissue can be stretched by accelerative forces until it tears. In some auto accidents, the aorta tears loose from the abdominal membrane leading to serious consequences if not death.

3.4.5 Oscillatory Motion

When walking, the legs (and arms) undergo a repetitive motion similar to that of a pendulum. Using this observation, we can estimate the speed of walking at a natural pace. We model the motion of the leg as a simple pendulum (ball at end of a string of length L) as illustrated in Fig. 3.19. The leg differs from the simple pendulum in that the mass of the leg is distributed nonuniformly, whereas the mass of the simple pendulum is concentrated at one point. To correct for this difference, we define the effective length of the leg, L_{eff}, as that length of a simple pendulum that would have the same period of oscillation as the complex shaped leg. (You might try to find this length by cutting out a model leg from heavy cardboard or other material and comparing its oscillation period with that of a simple pendulum whose length you can adjust so as to match periods.) For small oscillation amplitudes, the period of a simple pendulum is $T = 2\pi(L/g)^{1/2}$, where g is the acceleration of gravity. For a typical leg of a 2 m tall person, $L_{eff} = 0.2$ m and thus $T = 0.9$ s. (How does this agree with your natural walking pace? Remember, this is the time for one leg to return to the ground for the next step.) Since most of us have two legs, the time per step is T/2 = 0.45 s. If we assume that each step covers a distance of 0.9 m (about 3 ft) in 0.45 s, then our walking speed is

$$v = (0.9\ \text{m})/(0.45\ \text{s}) = 2\ \text{m/s}\ (7.2\ \text{km/hr or } 4.5\ \text{miles/hr})$$

Walking at a pace determined by the natural period of your leg uses the least amount of energy. Walking either faster or slower than this natural pace consumes more energy! Notice how much faster the step is for children and pets with their shorter legs.

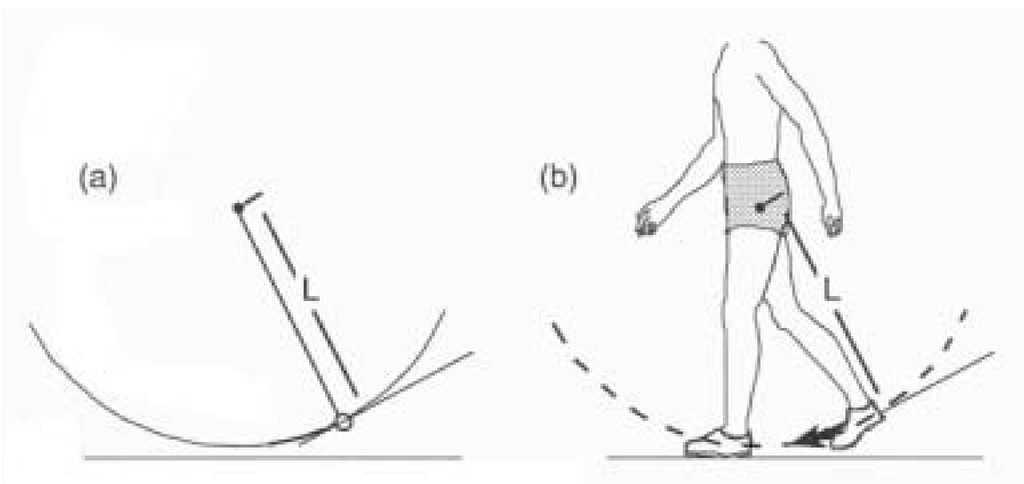


Figure 3.19. (a) A simple pendulum of length L undergoing small amplitude vibrations has a period $T = 2\pi(L/g)^{1/2}$. The quantity g is the acceleration of gravity. (b) The leg during walking also behaves like a pendulum. (After P. Davidovits, *Physics in Biology and Medicine*, Prentice-Hall, 1975, p. 47.)

Except for our bones, the organ systems in our body are composed mostly of water. Our organs are not securely fixed; they have flexible attachments to the skeleton. Each of our major organs has its own resonant frequency (or natural period) which depends on its mass and the elastic forces that act on it. Pain or discomfort occurs if a particular organ is vibrated vigorously at its resonant frequency (Fig. 3.20). Shock absorbers are devices to reduce or to dampen unwanted vibrational effects. Female athletes often use special bras to dampen the motion of their breasts

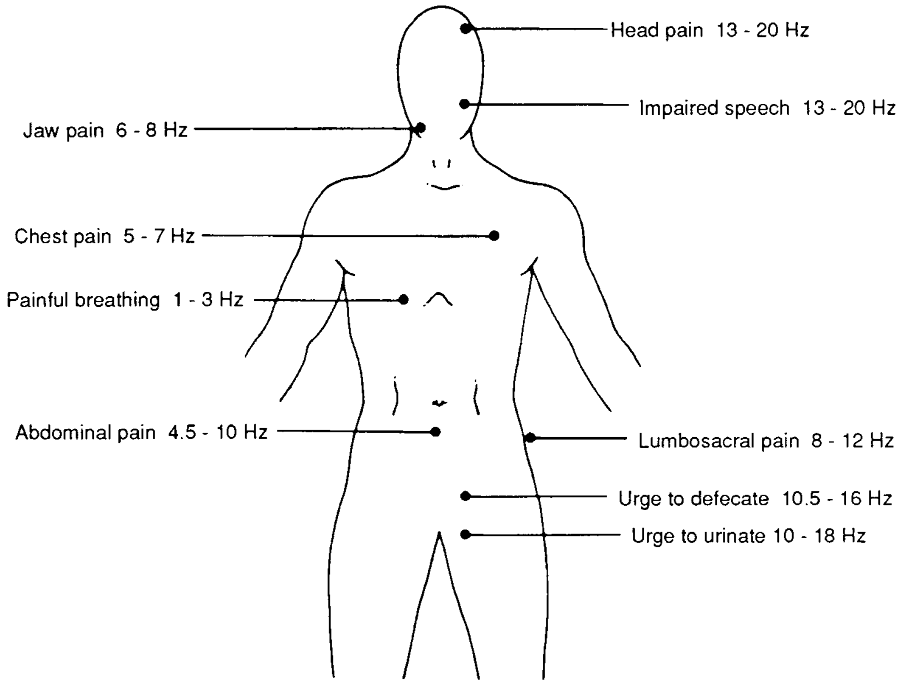


Figure 3.20. Pain symptoms of humans subjected to vibrations from 1 to 20 Hz. (Adapted from E. B. Magid, R. R. Coermann, and G. H. Ziegenruecker, "Human Tolerance to Whole Body Sinusoidal Vibration," *Aerospace Med.*, 31, 1960, p. 921.)

because they commonly jog at or near the natural frequency of the breast, which is about 2 Hz (1 Hz = 1 vibration/s), a period T = 0.5 s.

Excessive vibration often occurs in motor trucks and in some passenger aircraft. This results in fatigue and discomfort to the occupants, and may cause visual disturbances. The vibratory frequency of motorized vehicles, and of such subtle environmental systems as large fans used to distribute air in enclosed buildings, can be around 8 Hz or less, while those in aircraft are usually higher.

3.5 Physics in Teeth

As we grow into adults, our teeth undergo changes that usually do not concern us unless there is pain or expense. Toothaches and trips to the dentist cause concern, but most of the time our teeth play passive roles in our lives.

There are many applications of physics in our teeth and jaws—such as forces involved with biting, chewing, and erosion of teeth. In addition, *prosthetic* (replacement) devices such as bridges and crowns have to be biocompatible as well as have sufficient strength to function properly. Sometimes we inherit less than perfectly arranged teeth. We usually see an orthodontist who uses a variety of procedures applying force to reposition and straighten the teeth.

We consider first the physics of normal teeth, the forces involved in biting, and the force of the bite limited by the jaw (masseter) muscles. Next, we give simple examples of straightening and moving permanent teeth (*orthodontics*) and an example where the jaw is reshaped. Finally, we discuss a few prosthetic crowns and bridges.

3.5.1 Forces in Normal Teeth

Most of us wish we had teeth that were perfect. Figure 3.21 depicts the normal 32 permanent adult teeth and a cross section of a typical permanent molar tooth. It is obvious that different teeth have different functions. The *incisors* and *cuspids* (sometimes called eye teeth or canine teeth) have single cutting or biting edges. They have single roots; the roots for the cuspids located in the upper jaw are the longest. Behind the cuspids are the first and second *bicuspids*, followed by three molars, which usually have two or three roots. They are used for chewing or grinding food on the surface between the teeth (called the *occlusal surface*). Figure 3.22 shows a schematic view of the skull. The pivot for the jaw (*mandible*) is called the temporal-mandible joint (TMJ)—often a source of problems. The *masseter muscle* provides the main force for biting and chewing.

Scientists have measured the stress-strain behavior of the enamel and dentin components of teeth (see Chapter 4, *Physics of the Skeleton*, for definitions of stress-strain). A stress-strain curve for dentin is shown in Fig. 3.23. The maximum force than one can exert, measured at the first molar occlusal surface (1st biscuspid), is about 650 N. If the area of

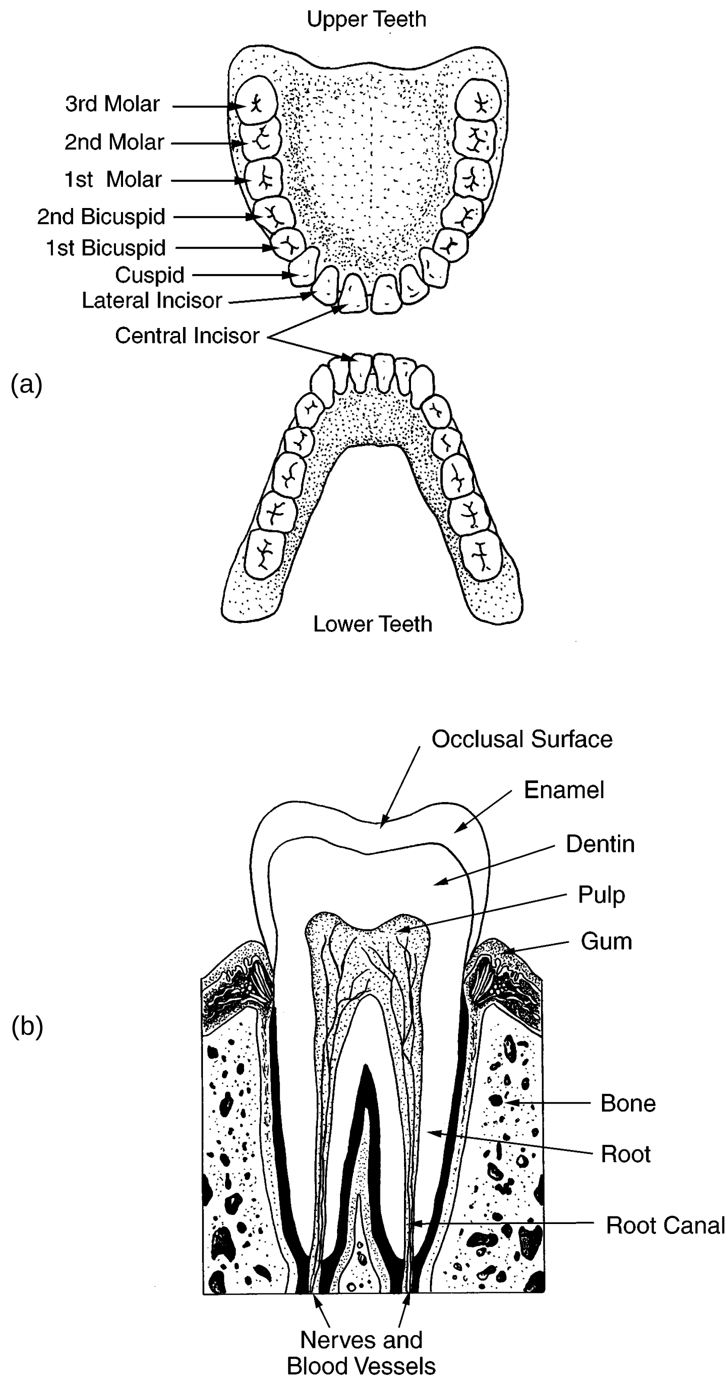


Figure 3.21. (a) The 32 normal permanent teeth of an adult. (b) Cross-section view of an adult molar tooth. (Images modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

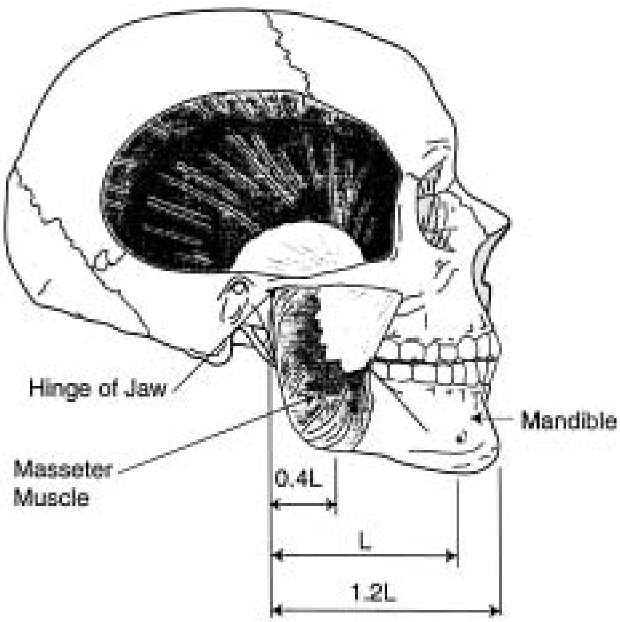


Figure 3.22. Schematic view of an adult skull showing some of the teeth and the masseter muscle that provides the closing and chewing action of the lower jaw (mandible). The dimensions are in units of L which is the distance of the first bicuspid from the hinge of the jaw. 0.4L is the approximate location of the masseter muscle from the hinge and 1.2L is the distance of the central incisor from the hinge. The value of L is typically about 6.5 cm for women and 8 cm for men. (Image modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

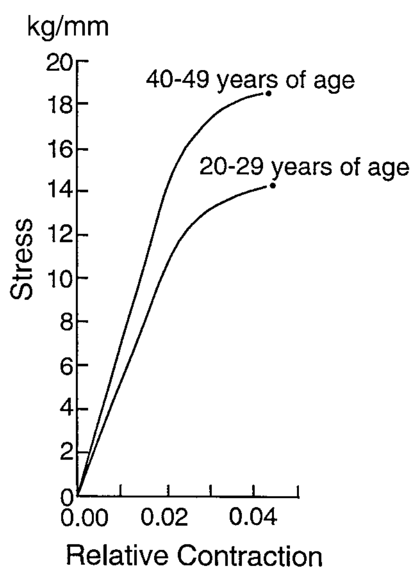


Figure 3.23. The stress-strain curve for wet dentin under compression for the premolar (bicuspids) teeth for adults in two different age groups. Young's modulus initially increases with age, but later it drops slightly. The enamel surface has a Young's modulus about five times greater than that for dentin. Note the stress scale is a factor of 10 larger if given in N/mm.[2] [After H. Yamada, *Strength of Biological Materials*, F. H. Evans (ed.), Baltimore, Williams and Wilkins, 1970, p. 150 by permission.]

contact is about 10 mm^2, the force per unit area is then nearly 65 N/mm^2 (6.5×10^7 N/m^2 or kg/mm^2). The Hooke's law portion of the stress-strain curve in Fig. 3.23 in kg/mm^2 for dentin shows about a 0.01 (1%) fractional compression of the tooth. Considering that enamel is stronger than dentin by a factor of five, the biting force is well below that where failure of the tooth would occur.

If we accidentally bite into a hard cherry stone or kernel of popcorn, the area of contact may be as small as 1 mm^2; then the compressive stress is about 650 N/mm^2 (65 kg/mm^2). Under these conditions, the tooth would fail. Many of us have learned this fact experimentally. A tooth that has been weakened by fillings or decay might be broken when you bite a hard, small object.

The 650 N biting force is supplied by the masseter muscles. Going back to Fig. 3.4 we see that biting is a third class lever with the muscle close to the fulcrum of the jaw as shown in Fig. 3.22.

3.12 PROBLEM

From the dimensions of Fig. 3.22 and the force on the first bicuspid of 650 N, show that masseter force is 1625 N and the force on the central incisors is 540 N.

Because the molars are used for grinding food, they have large surface areas compared to the incisors, which act more like knives in the biting process. If the force from the masseter muscles were acting only on the central incisors and not on the molars, the net force would be less than 650 N by the ratio of L/1.2L or 540 N. This force is about equal to the weight of a small adult. You can imagine how effective the incisors would be when you visualize using a dull knife on an apple with a force about the same as the weight of a human.

Consider biting into an apple (see Fig. 3.24). The teeth behave like the knife shown in (a). When the incisors first make contact with the apple, the stress (force/area) is very large because of the large applied force (assume 200 N) and the small area of the edge of the incisor teeth (perhaps 1 mm^2). This applied force leads to a stress of 200 N/mm^2 (20×10^7 N/m^2), which is sufficiently large to rupture the apple (b) (and most other foods as well!). Once the apple's skin has been ruptured, then the front and back surfaces of the teeth make contact with the interior of the apple. The angle of the front incisors is about 60° as shown in (c) and (d) where the force of 200 N is still applied by the jaw on the front teeth. In the simplest approximation (d), the downward force is balanced by the two components of force F normal to the front and back surfaces of the incisors. These two forces can be large and push apart the two sides of the apple being bitten, causing the crack to spread.

PROBLEM 3.13

From the force diagram of biting in Fig. 3.24(d), estimate the forces normal to the two surfaces of the incisors.

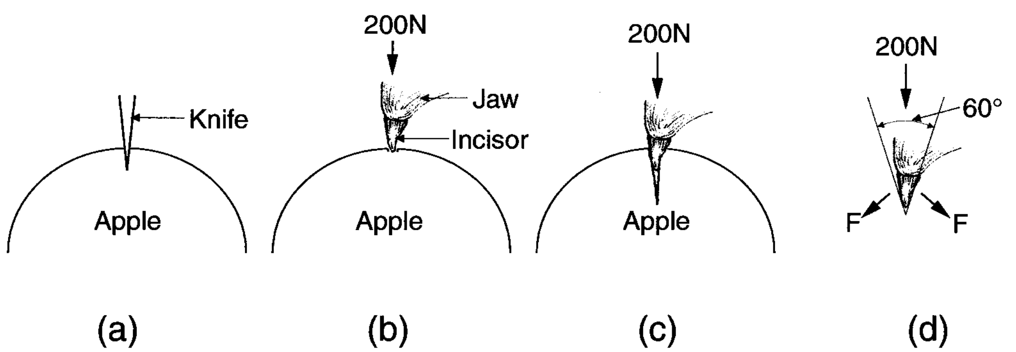


Figure 3.24. Schematic of the action of the biting behavior of an incisor tooth on an apple. (a) A knife cutting into an apple. (b) The incisor making contact with the apple and having sufficient force to cause the skin to rupture. (c) The incisor has penetrated the apple causing a crack to propagate. (d) The schematic behavior of the forces on the incisors.

Have you noticed that the permanent teeth of young adults appear very prominent in their jaws? This is particularly true of the front incisors. After 20 or 30 years this no longer seems to be the case. What has taken place is that the teeth wear; in some cases their length erodes as much as 0.1 mm/yr.

3.5.2 Some Simple Cases of the Physics in Orthodontics

Everyone has seen a child with its thumb in its mouth. It is part of growing up and nearly all children do this and eventually the thumb sucking ends. Excessive thumb sucking can change the shape of the mouth as it can move front teeth. Most often, the two central incisors are pushed out and spread apart, which can lead to a large overbite as shown in Fig. 3.25a.

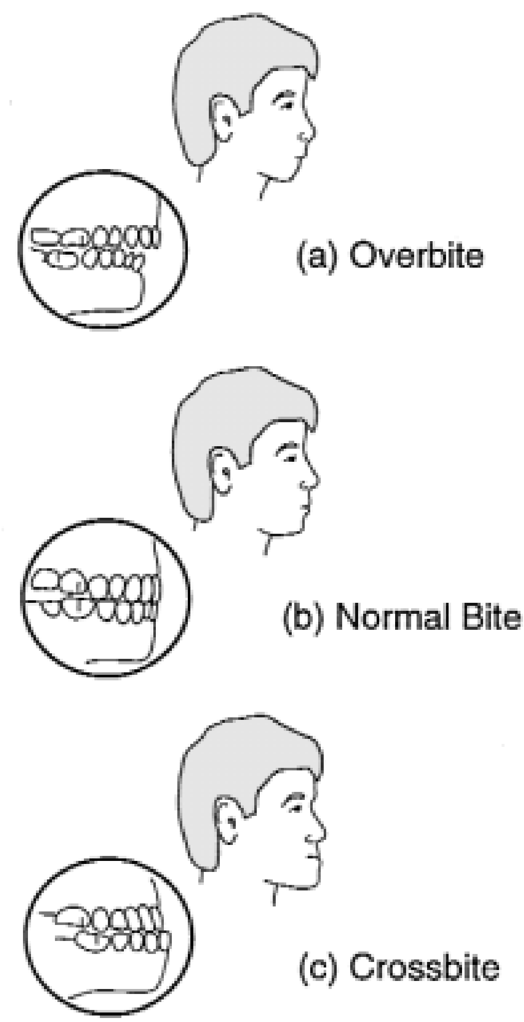


Figure 3.25. The location of the teeth in the upper jaw with respect to frontal teeth in the lower jaw leads to several conditions: (a) overbite, (b) normal bite, and (c) crossbite. (Image modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

How can those teeth be brought back to the desired location? One way is shown in Fig. 3.26a where a mechanical connection is made to the teeth that need to be moved and force is supplied by the external head-gear. Depending upon the initial conditions of the teeth, other methods such as adding a rubber band to provide tension between the teeth (shown in Fig. 3.26b) may be all that is needed to move the teeth together. Sometimes a tooth needs to be moved a small amount; this can often be accomplished by appropriate spring wires as shown in Fig. 3.26c. It is surprising how small the force needs to be, in this case only about 1 N. However, we should remember that in the early years, the erupting teeth are guided by their surroundings: the jaw and the neighboring teeth.

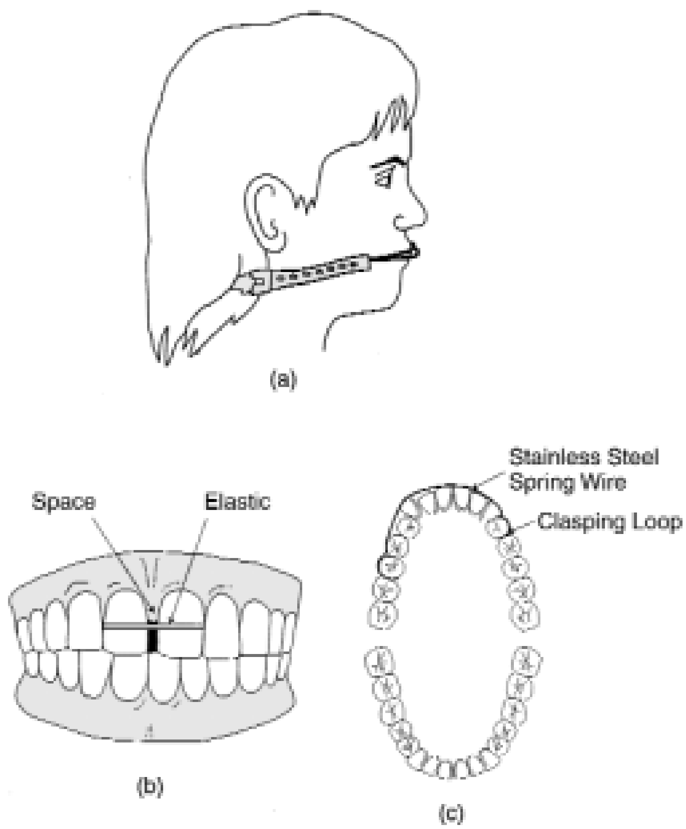


Figure 3.26. (a) Sometimes in orthodontic work the teeth are moved by an external headgear which supplies the force on the teeth. (b) For some teeth with too large a gap between them, the force of a rubber band is sufficient. (c) A simple brace (stainless spring steel) arrangement used to provide a small force (1–2 N) on a cuspid that needs to be moved into better alignment with the upper jaw. (Images modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

There are many orthodontic appliances and, to a large degree, they depend on the skill of the orthodontist. Figure 3.27 shows different methods to apply forces to move teeth. Figure 3.27a represents a fixed orthodontic apparatus. It has several features common to straightening and moving teeth, e.g., the banding and brackets are often used along with the arch wire to form the main support for other attachments to move teeth. Clever arrangements of the attachment bands, arch wire, and elastic bands can accomplish complicated movements of the teeth. Figure 3.27b depicts an adjustable, removable appliance designed to widen the jaws and straighten the front teeth. The adjustment moves about 0.8 mm per turn where each day one quarter of a turn is made. The total movement may be as much as one cm.

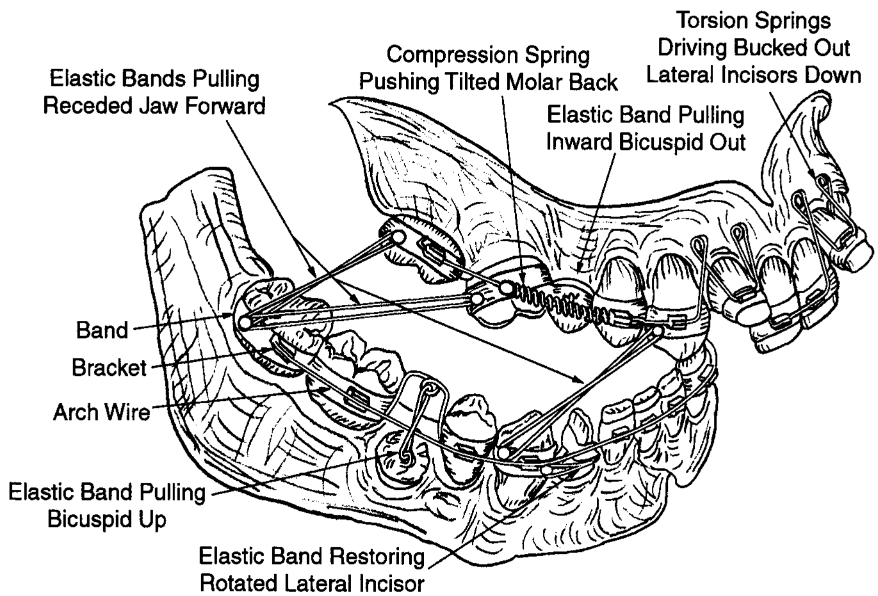
PROBLEM 3.14

Using Fig. 3.27a, give a descriptive discussion of the force directions and the desired changes for the teeth being moved or straightened.

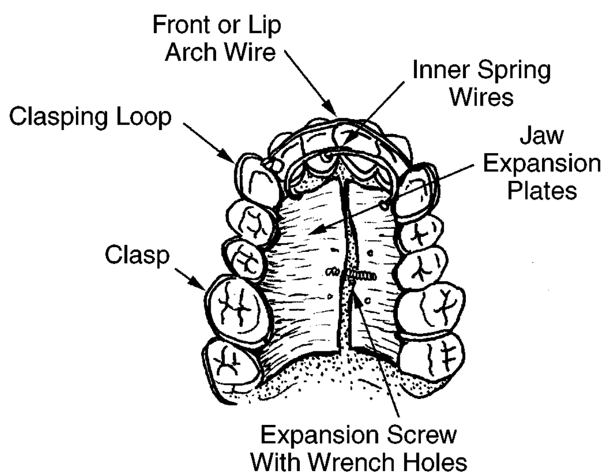
Figure 3.28 shows two examples of moving teeth: (a) A spring under compression is used to widen the space for the middle tooth. (b) A spring under tension moves a tooth to close a gap. These springs supply a variable force for compression or expansion. Typically, the force will be about 1 N, which reduces as the tooth moves. Note that the springs are connected to the brackets attached to the teeth. The bracket on the tooth to be moved can slide guided by the arch wire; the other bracket is fixed to the arch wire.

3.5. 3 Crowns, Bridges, and Implants

Despite our efforts to preserve our teeth, an accident can lead to broken teeth, or one or more teeth have decayed. We may be unfortunate and inherit genes that do not favor long-lasting teeth. Many people need

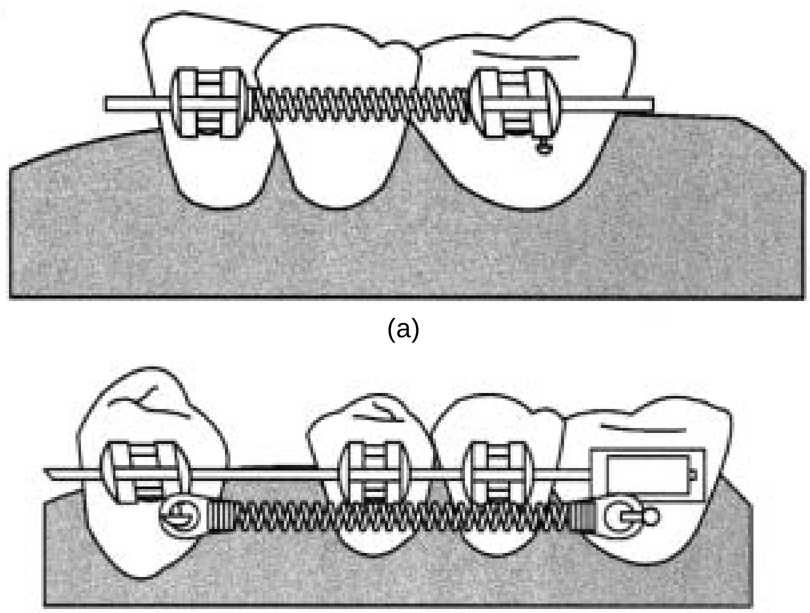


(a)



(b)

Figure 3.27. Two schematic orthodontic arrangements. (a) An exaggerated case of a fixed orthodontic apparatus used to move and control teeth in the upper and lower right jaw (left side not shown). (b) An adjustable movable appliance used to widen the upper jaw while at the same time straightening the front teeth. This arrangement, when modified, can also be used to reduce the size of the jaw. (Adapted from S. Garfield, *Teeth, Teeth, Teeth*, New York, Simon & Schuster, 1969, p. 217 by permission.)



(a)

(b)

Figure 3.28. (a) A compressed spring arrangement is used to move an improperly aligned tooth to a different position. (b) A spring under tension supplies a force to move a tooth to fill a gap.

dental repair for damaged or missing teeth. The simplest repair is a simple filling. In many cases the filling does not significantly reduce the strength of the tooth; the repair may last a lifetime if properly done and given proper care.

Let us consider a more drastic case where the tooth has had extensive fillings and now is not structurally sound. How can one preserve the tooth and the function it provides? One approach is to *crown* the tooth, as shown in Fig. 3.29. This is a *prosthesis* and involves grinding away the damaged area of the tooth and replacing it with an artificial tooth. The shape of the crown is determined from molds made of the patient's mouth, ensuring a custom fit. The crown is often made of a strong gold alloy with a porcelain face, in a color matching the permanent teeth and cemented in place. The use of gold is not a new idea—the Etruscans, over 3000 years ago, made simple crowns. We now know that gold is inert chemically; it has a strength greater than the original teeth and can easily be cast in a mold. These repairs are attractive, functional, easy to keep clean, and long lasting.

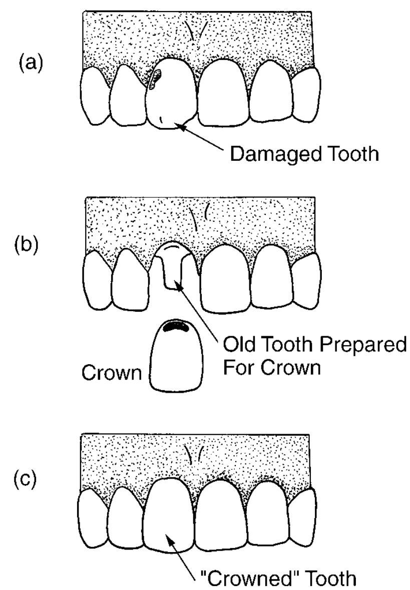


Figure 3.29. (a) A tooth damaged by decay. (b) The damaged tooth is prepared for a crown. An impression of the natural teeth is used to prepare the crown replacement. (c) Shows the crown cemented in place. (Image modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

Suppose that the tooth has been damaged so much that it needs to be removed. You might be faced with the prospect of a "bridge" prosthesis. For this to work, there have to be teeth on both sides of the missing tooth for attaching the bridge. Figure 3.30 shows an example of a bridge which uses the adjacent teeth.

A bridge may fail when the material properties of the gold alloy are improperly used, such as an improper design with insufficient strength between the replacement tooth and its attachment to the neighboring teeth. If the cross-sectional area on both sides of the replacement tooth is insufficient, then the use of the bridge in chewing could cause the replacement tooth to flex eventually breaking the connections. Engineers call this a shearing force, which is another way of classifying the strength of materials.

What happens if a nearby tooth cannot be used for a support? Fig. 3.31 shows an implanted peg screwed directly into the jaw. The prosthetic tooth is then cemented to the peg. This type of prosthesis is more difficult to keep clean, but acceptable in many situations.

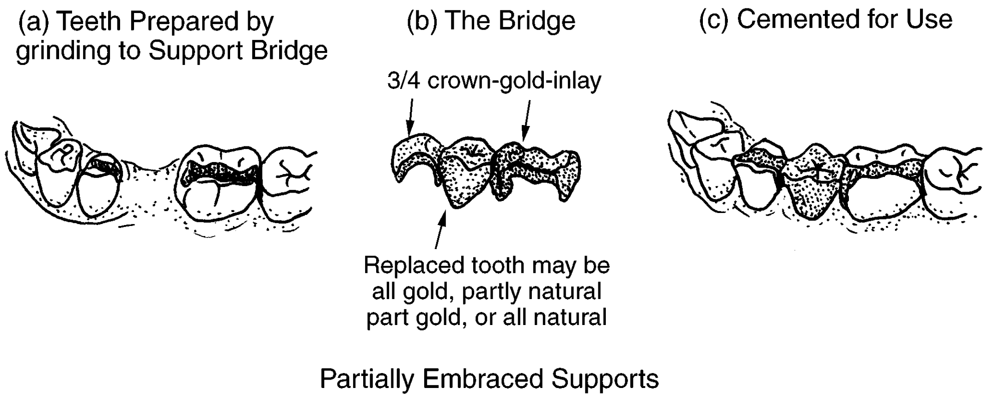


Figure 3.30. A simple bridge prosthesis. (a) The missing tooth and the teeth on either side prepared by grinding to support the bridge. (b) The bridge replacement and the supporting structures for either side of the missing tooth. A mold of the region of the missing tooth and of the teeth in the upper and lower jaw is needed to ensure the correct fit as shown in (c) for the bridge cemented into place. (Adapted from S. Garfield, *Teeth, Teeth, Teeth*, New York, Simon & Schuster, 1969, p. 257 by permission.)

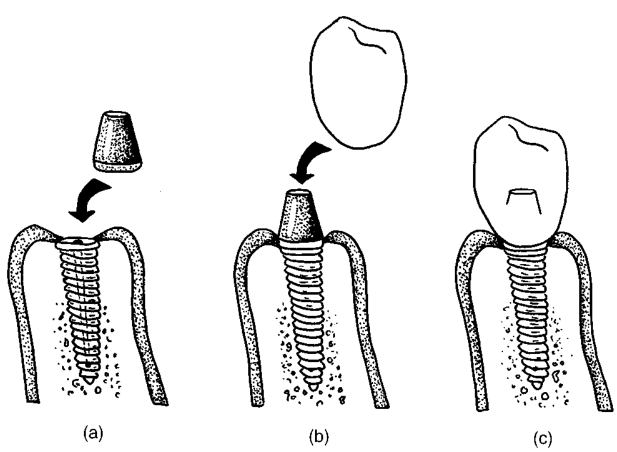


Figure 3.31. In a situation where there are no adjacent teeth to use for a bridge, sometimes an implant is used instead. (a) The implant is screwed into the jaw and the tissue and jaw are allowed to heal. (b) Later, the peg to hold the tooth is installed. (c) The finished tooth cemented in place. (Image modified by Ken Ford, original image Copyright © 1994, TechPool Studios Corp. USA.)

Of course, the materials for tooth repair need to be biocompatible. That is not a problem. Metals are often used to strengthen a body part (e.g., the hip transplant). The forces on prosthetic teeth go directly to the jaw like natural teeth. An implanted tooth is a very successful prosthesis.