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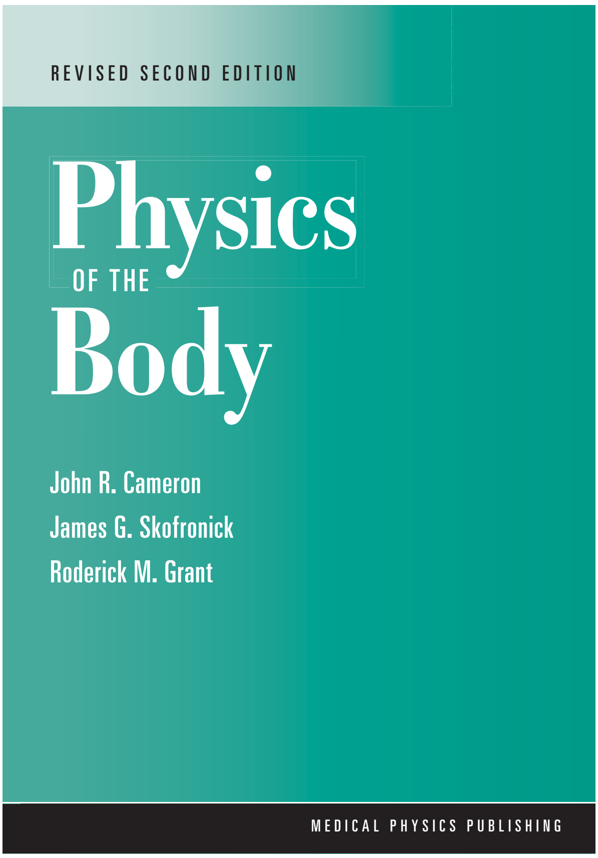

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3

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 107 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

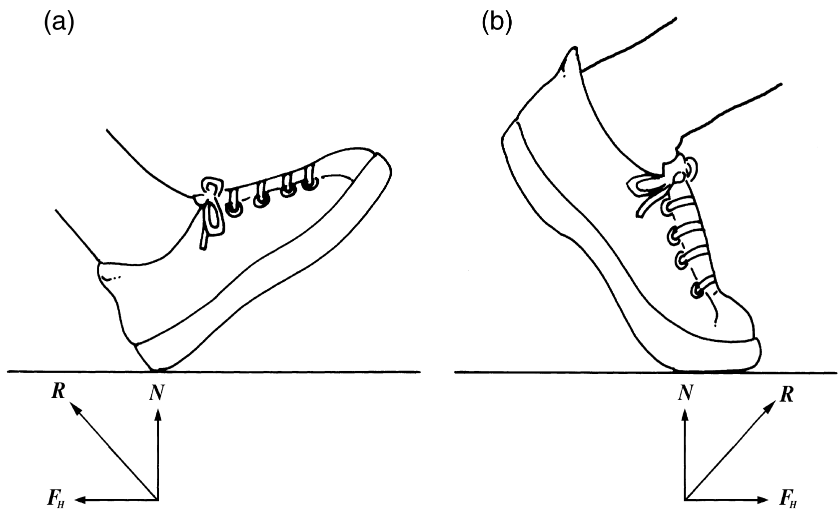


Figure 3.1 Normal walking. (a) Both a horizontal frictional component of force, F_H, and a vertical component of force N with resultant R exist on the heel as it strikes the ground, decelerating the foot and body. The friction between the heel and surface prevents the foot from slipping forward. (b) 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, by permission.)

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 (Figure 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 m is the coefficient of friction between the two surfaces. The value of m depends upon the two materials in contact, and it is essentially independent of the surface area. Table 3.1 gives values of m for a number of different materials.

The horizontal force component of the heel as it strikes the ground when a person is walking (Figure 3.1a) has been measured and found to be approximately 0.15 W, where W is the person's weight. This is how large the frictional

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 web concrete road	0.7
Steel on ice	0.03
Between tendon and sheath	0.013
Normal bone joint	0.003

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 $f = \mu W$. 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 (0.15 W). 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 (Figure 3.1b). Occasionally, a person slips on an icy, wet, or oily surface where m 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

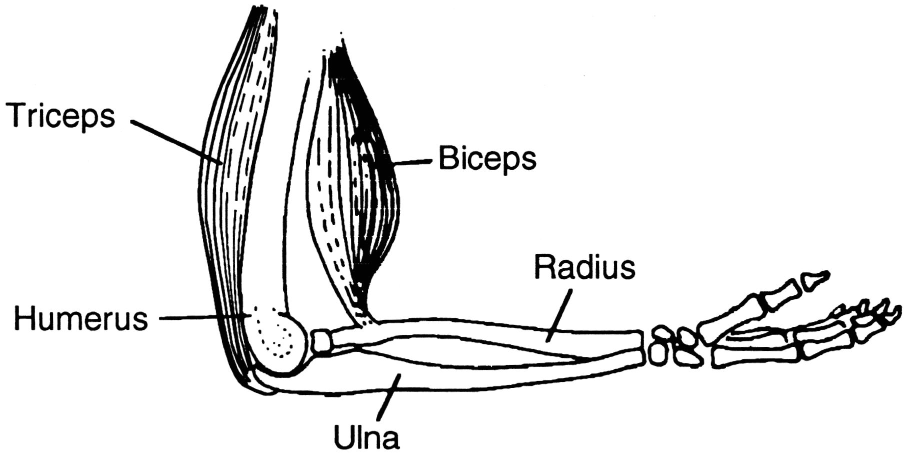


Figure 3.2 Schematic view of the muscle system used to bend the elbow. Biceps bend the elbow to lift and triceps straighten it.

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 Figure 3.2, which will be examined further later in this section. 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 Figure 3.3, the filaments

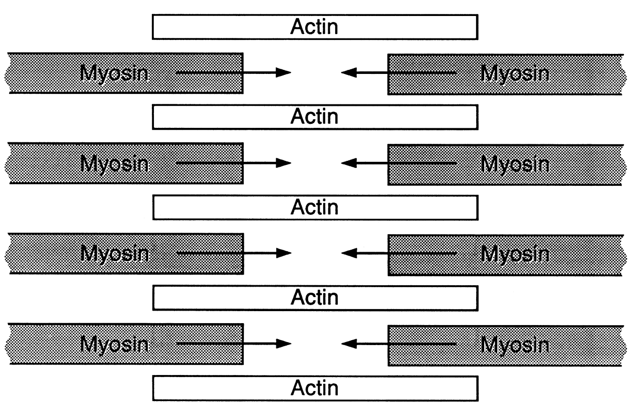


Figure 3.3 Schematic view of actin and myosin filaments with arrows showing the sliding movement between the filaments associated with muscle contraction.

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 to 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).

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 (Figure 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 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.

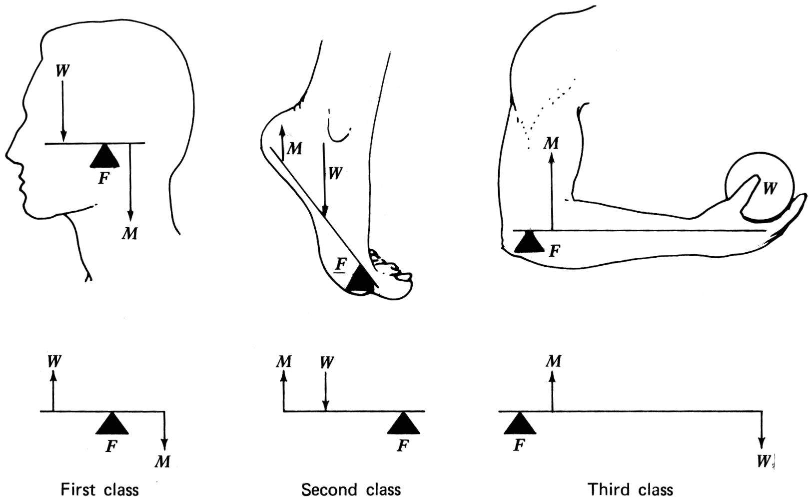


Figure 3.4 The three lever classes in the body and schematic examples of each. W is a force that is usually the weight, F is the force at the fulcrum point, and M is the muscular force. Note that the different levers depend upon different arrangement of the three forces, M, W, and F.

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.

PROBLEM 3.1

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 farther 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 (Figure 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 30 W acting clockwise) and that produced by the muscle force M (which acts counterclockwise and is of magnitude 4 M). 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).

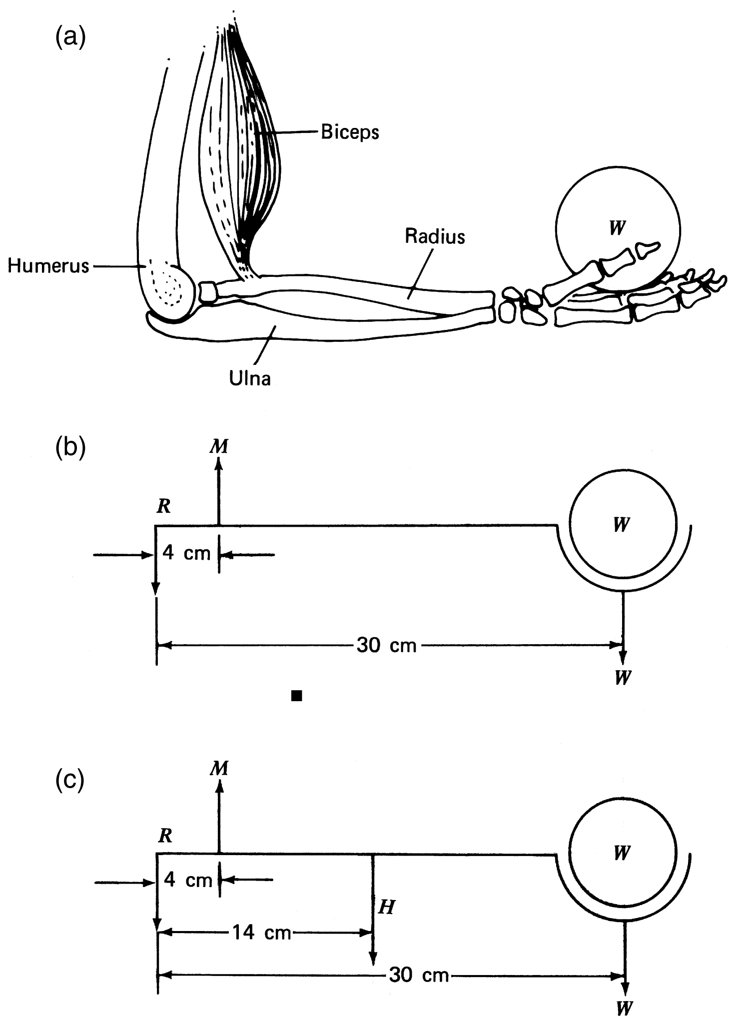


Figure 3.5 The forearm. (a) The muscle and bone system. (b) The forces and dimensions: R is the reaction force of the humerus on the ulna, M is the muscle force supplied by the biceps, and W is the weight in the hand. (c) The forces and dimensions where the weight of the tissue and bones of the hand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

For individuals building their muscles through weight lifting, the exercise of lifting a dumbbell as in Figure 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 Figure 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 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 Figure 3.6a? Figure 3.6b shows the forces we must consider for an arbitrary angle alpha, 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.

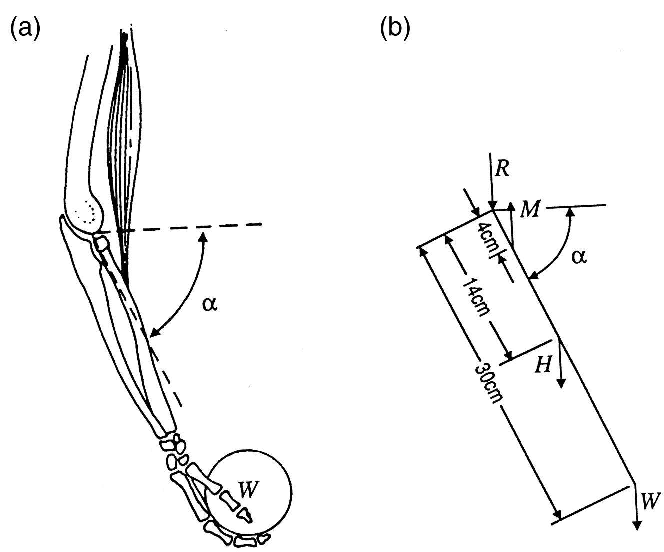


Figure 3.6 The forearm at an angle α to the horizontal. (a) The muscle and bone system. (b) The forces and dimensions.

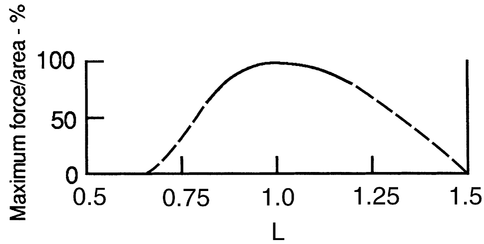


Figure 3.7 At its resting length, L, a muscle is close to its optimum length for producing force. At about 80% of this length it cannot shorten much more, and the force it can produce drops significantly. The same is true for stretching of the muscle to about 20% greater than its natural length. A very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

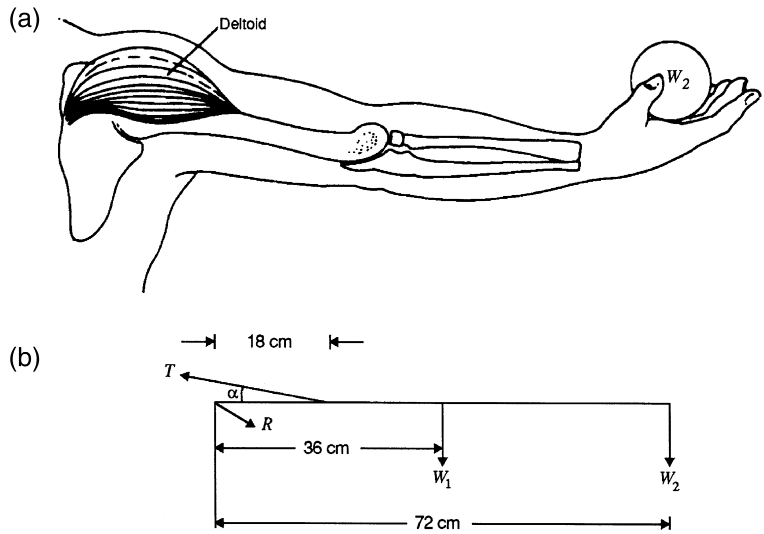


Figure 3.8 Raising the right arm. (a) The deltoid muscle and bones involved. (b) The forces on the arm. T is the tension in the deltoid muscle fixed at the angle α, R is the reaction force on the shoulder joint, W_1 is the weight of the arm located at its center of gravity, and W_2 is the weight in the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

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 Figure 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.

The arm can be raised and held out horizontally from the shoulder by the deltoid muscle (Figure 3.8a); we can show the forces schematically (Figure 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 $\alpha = 16°$, the weight of the arm $W_1 = 68$ N (~15 lb), and the weight in the hand $W_2 = 45$ N (~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 Figure 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 Figure 3.6, the muscle force is independent of the angle.

PROBLEM 3.4

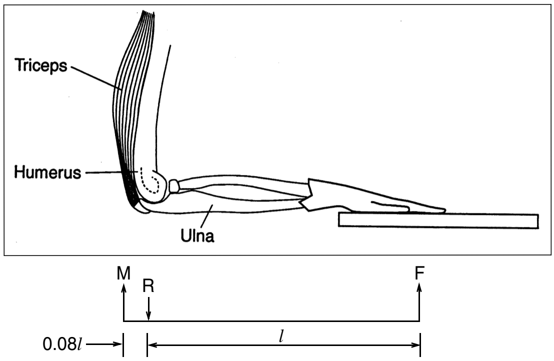
Derive Equation 3.1 for the arm and deltoid muscle system.

PROBLEM 3.5

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 that weighs 2600 N?

PROBLEM 3.6

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 of the triceps muscle 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.



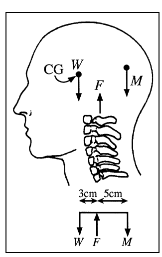
PROBLEM 3.7

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 below). The head has a mass of about 3 kg, or weight W ≅ 30 N.

(a) Find F and M.

(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.

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



3.3.3 The Spinal Column

Bones provide the main structural support for the body (see Chapter 4, Figure 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 Figure 3.9. Note that the vertebrae increase in both thick-

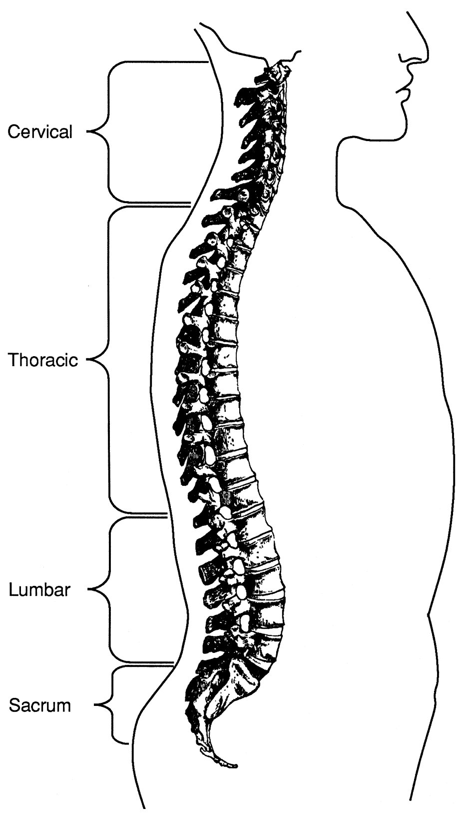


Figure 3.9 The spinal column provides the main support for the head and trunk of the body. The column has an S shape, and the vertebrae increase in cross-sectional area as the supporting load increases. The length of the column for a typical adult male is about 0.7 m.

ness 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).

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 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 Figure 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 (Figure 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 (Figure 3.10b). *Scoliosis* is a condition in which the spine curves in an "S" shape as seen from the back (Figure 3.10c). Normal posture is shown in Figure 3.10d.

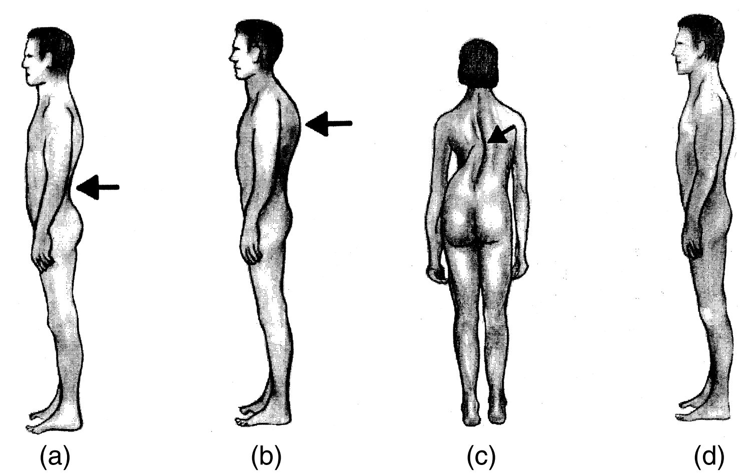


Figure 3.10 Sketches for the abnormal spinal conditions of (a) lordosis (or sway-back), (b) kyphosis (or hunch-backed), and (c) scoliosis. (d) The normal condition. (Adapted from *A Guide to Physical Examination*, B. Bates. Philadelphia: J. P. Lippincott, 1974, by permission.)

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?

(b) Estimate the stress at a disc located at the level of the center of gravity of your body when you are standing vertically.

(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 Figure 3.11. An overweight condition (or a pronounced slump) leads 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 (Figure 3.12a). If the vertical projection of your cg falls outside this area, you will tip over. When your feet are close together (Figure 3.12a) you are less stable than when they are spread apart (Figure 3.12b). Likewise, if the cg is lowered, you become more stable. A cane or crutch also improves your stability (Figure 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 10 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 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. This condition occurs when the wall of the disc weakens and tears, leading to a bulge that sometimes pushes against nerves pass-

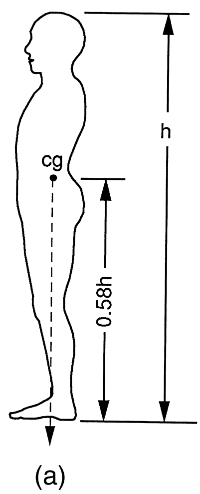


Figure 3.11 (a) The center of gravity of a normal person is located about 58% of the person's height above the soles of their feet. (b) An overweight condition can shift the cg forward so that the vertical projection of it passes underneath the balls of the feet, causing the body to compensate by assuming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

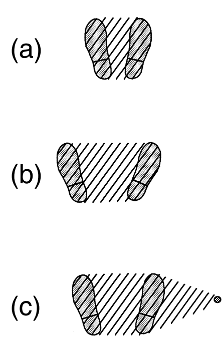


Figure 3.12 The body remains table as long as the vertical projection of the cg remains inside the cross-hatched area between the feet. (a) The stable area when the feet are close together, (b) the stable area when the feet are spread apart, and (c) the stable area when a cane or crutch is used.

ing 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 Figure 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

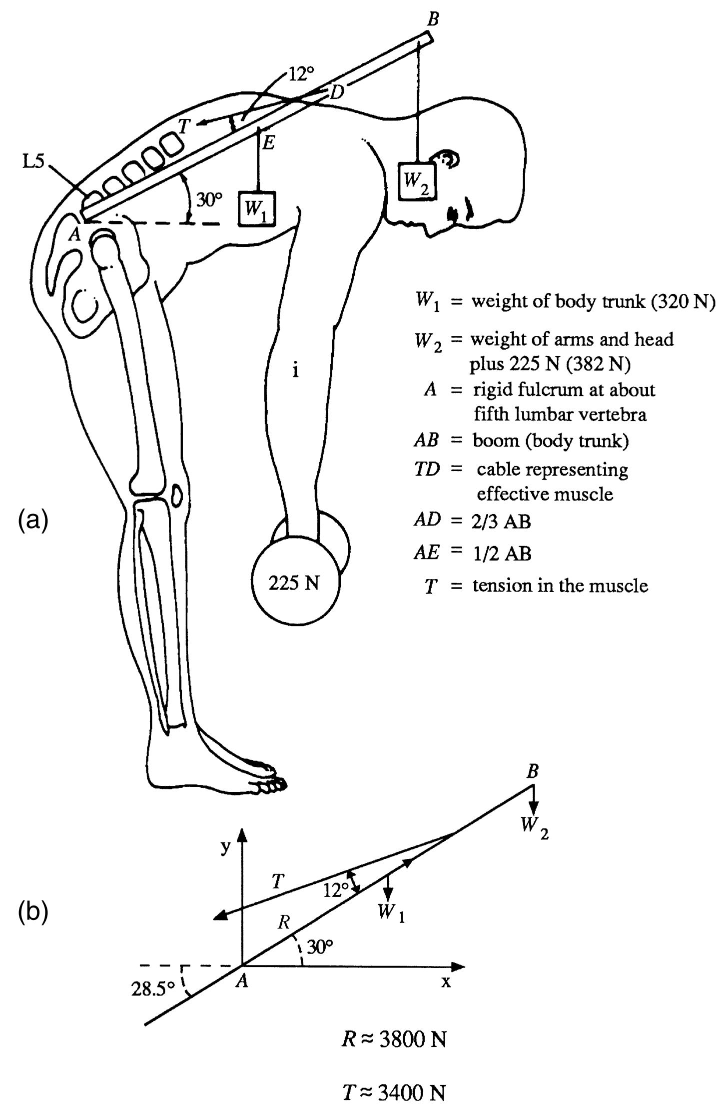


Figure 3.13 Lifting a weight. (a) Schematic of forces used. (b) The forces where T is an approximation for all of the muscle forces and R is the resultant force on the fifth lumbar vertebra (L5). Note that the reaction force R at the fifth lumbar vertebra is large. (Adapted from L. A. Strait, V. T. Inman,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

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,

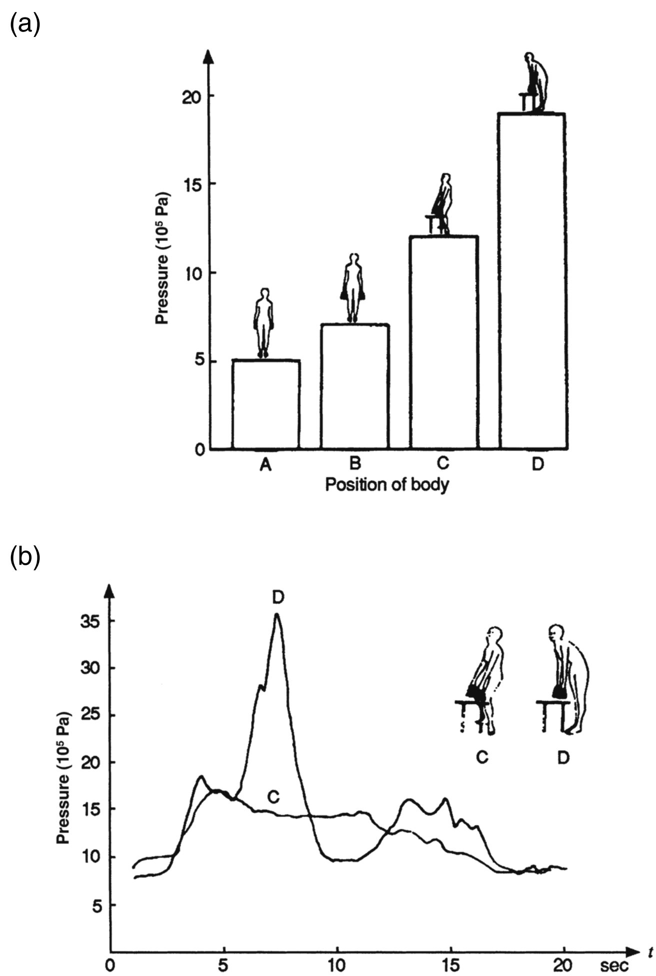


Figure 3.14 Pressure on the spinal column. (a) The pressure on the third lumbar disc for a subject (A) standing, (B) standing and holding 20 kg, (C) picking up 20 kg correctly by bending the knees, and (D) picking up 20 kg incorrectly without bending the knees. (b) The instantaneous pressure in the third 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.)

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 Figure 3.14. 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.

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 (Figure 3.15). 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 con-

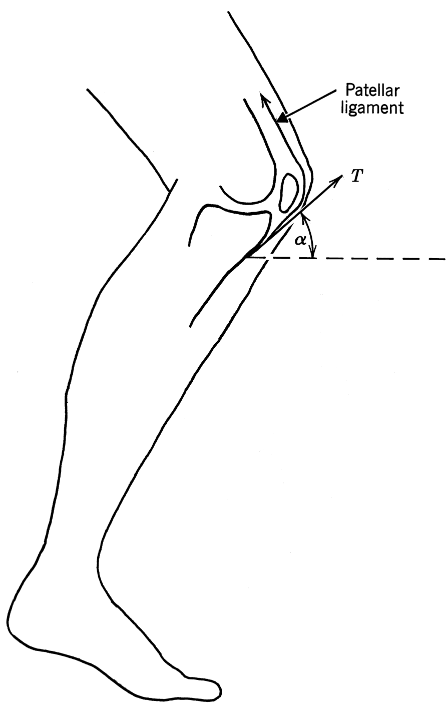


Figure 3.15 Diagram of the tensile force on the patellar ligament (tendon) during squatting. The tension T is very large when a person is in a low squat.

nected 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 Figure 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 (Figure 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. Figure 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, WL, 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 Figure 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!

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 Figure 3.16a. It does this by tipping the body so that the cg is directly over the ball of the femur and the foot (Figure 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.

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 Figure 3.16c. There are three forces acting on the body: the weight, W, the force pushing upward on the cane, F_C, and the upward force on the foot equal to W – FC. 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