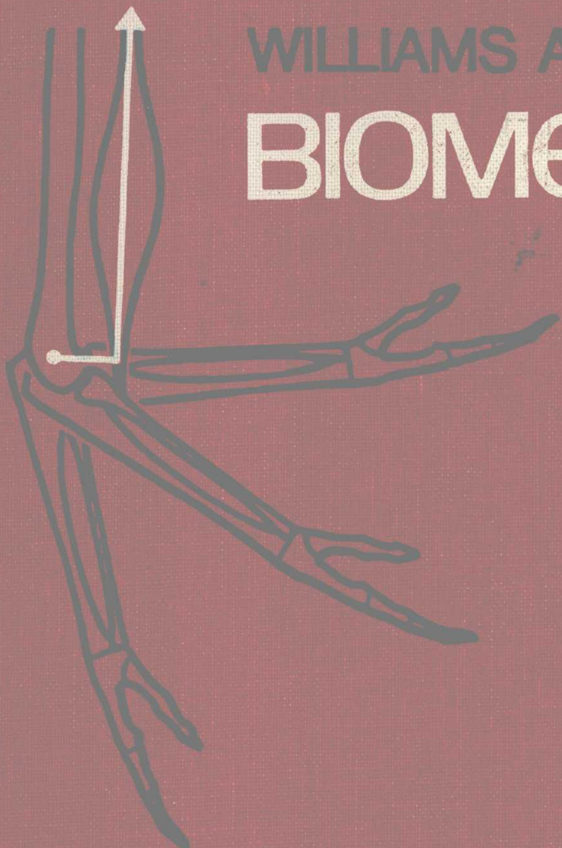
WILLIAMS AND LISSNER:

BIOMECHANICS OF HUMAN MOTION



LE VEAU

Second Edition

WILLIAMS AND LISSNER:

BIOMECHANICS OF HUMAN MOTION

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PREFACE
TO THE FIRST EDITION

This text represents an integration of material from two fields. In it the principles of engineering mechanics are applied to the activities and fundamental knowledge of the physical therapist. While many of the examples have been selected from the clinical area, the analysis of muscle and joint function and of external forces acting on the body has a broad application far beyond the scope of any single professional group. It is of importance to all students of human motion in both its normal and pathological aspects.

The science of mechanics is so basic and familiar that its existence is often overlooked. Whenever we pick up an object, push open a door, walk or stand still, our bodies are under the constant influence of various forces. When the laws of mechanics are learned and applied in theory and practice, we achieve an understanding which is impossible without recognition of this subject. As early as the fifteenth century Leonardo da Vinci, one of the world's greatest artists and a scientist years ahead of his time, recognized the significance of mechanics in his biological studies. He wrote, "Mechanical science [or the science of mechanics] is the noblest and above all others the most useful, seeing that by means of it all animated bodies which have movement perform all their actions."

Since the days of da Vinci the science of mechanics has been developed and formalized so that in the usual study the subject is treated for itself and its wide applications are not fully explored. The student of physical therapy or physical education, to whom the subject of mechanics is usually presented as a division of physics, has difficulty in carrying over the full implications of his basic coursework into actual practice later on. We have attempted to bridge this gap by developing many illustrations throughout the text and by setting up and solving a variety of problems both in functional anatomy and treatment.

The main purpose of this text is to suggest techniques for approaching problems. Systems of forces are considered with increasing levels of complexity. In setting up problems, the characteristics of external forces can often be measured or accurately estimated. However, calculation of internal forces of muscles and joints at the present time requires some degree of simplification. As more information relative to segment mass, center of gravity locations and other anthropometric data becomes available, and as instrumentation in the study of kinesiology continues to improve, estimates of internal forces will become more accurate. In the present text, the principles of statics are utilized in the analysis of problems, with emphasis on the very useful device of the free body diagram. It is hoped that as persons dealing with human motion become versed in these techniques of analysis they will see many ramifications in their own particular fields of activity. Certainly many areas for research are suggested in the material presented.

The authors are grateful to the National Foundation for making publication of this book possible. We wish also to thank Mr. Maurice Gallott, who was responsible for the illustrations, with assistance from Miss Jo Ann Crow.

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CHAPTER 1

INTRODUCTION

The application of mechanical principles to the human body is as old as man himself. Only recently, however, has man seriously studied the implications of mechanics for the human body. Contini and Drillis (1954) briefly discussed the historical development of biomechanics up to the early 1950's. Since that time the study of biomechanics has grown rapidly. Increased awareness and interest have come from the fields of physical therapy, physical education, sports medicine, orthopedics, and industry (Rasch, 1958; Contini and Drillis, 1966; Miller and Nelson, 1973).

Mechanics is the study of forces and their effects. The application of these mechanical principles to human and animal bodies in movement and at rest is biomechanics. It is an attempt to combine engineering with anatomy and physiology. Biomechanics covers a broad spectrum, from theoretical study to practical application.

A full discussion of segmental forces in body movement should include not only biomechanical but also physiological considerations of muscle length-tension relationships and controlling neuromotor mechanisms. Sensory feedback apparatus is a most important factor in adequate neuromuscular function. However, in this text we are concerned only with the mechanical aspects and will simply note in passing that these do not constitute the whole story.

Anatomical Examples

By observing the gross anatomy of the muscular system we can see that muscles have different fiber arrangements. This internal structure of the muscle determines the relationship of the force which the muscle can produce and the distance over which the muscle can contract.

The effect of muscle contraction also depends upon the muscle's attachments to the skeleton. The angle at which a muscle pulls upon the bony lever determines its rotational and stabilizing components of force. The distance of the muscle attachment from the axis of the lever system determines the moment of force which can be produced. When two or more muscles act on a bone, the final resultant depends upon the force developed by each muscle, their individual angles of pull, and their locations relative to the joint axis.

External Loads

The resistance offered to the forces of muscles, bones, and joints may come from the pull of gravity, water resistance, elasticity of materials, friction, stationary structures, or manual resistance. The angle of the line of application of the resistance, or load, and the distance of the load from the axis of the lever system determines the effectiveness of the load. *Gravity,* the most common load on the body, provides a line of force in a constant direction. Both the weight and position of the exercise resistance and of the body part are important when determining the effect of gravity.

Pulley systems are used to change the line of pull on the body. These may be set up to offer resistance, or to aid in support or movement, and may act in any direction.

The force of gravity may be reduced or neutralized by immersing the body or body part in a tank of water. In this case, the gravitational force is balanced by the force of buoyancy, since the body is buoyed up by a force equal to the weight of the volume of water it displaces. Water also offers resistance, directly opposing a body part as that body part moves through it. Another method of reducing the effect of gravity is by suspension in slings, as advocated by Guthrie-Smith (1943).

A variety of elastic materials (such as springs, rubber bands, balloons, etc.) can be used to provide resistance for muscular exercise. The line of resisting force lies along the length of the elastic material.

Many recently developed exercise devices make use of frictional resistance as load for the muscle contraction. Some devices provide a line of force which is perpendicular to the bony lever throughout the range of motion.

Stationary structures provide resistance for isometric contractions, whereas manual resistance can offer isometric resistance or can give a wide range of resisting loads.

Clinical Applications

Manual muscle testing depends upon the skill of the clinician in applying test forces of varying degrees of magnitude in order to gauge the patient's ability to resist these forces. The significance of lever arm lengths involved in the muscle test, as well as the force applied, must be considered.

The location of the center of mass of each body part affects the activity of the muscles which support that part. The clinician can evaluate the patient's posture while standing, sitting, and lifting and moving objects. Treatment procedures based on mechanical principles can be developed to overcome posture problems.

Other clinical treatments provide examples of biomechanics as well. Various traction procedures utilize force to overcome gravity, friction, and soft tissue resistance. Crutches and canes help relieve forces of gravity on an injured or weak body part. The coefficient of friction between the walking surface and the crutch tips determines the angle with which the crutches can safely contact the ground. Evaluation and treatment of gait relies upon the mechanical parameters of displacement, velocity, and acceleration. These values are also important in the adjustment of braces and prostheses. Recent research in orthotics and prosthetics has been focused upon patient examination, assessment, and design. Casts, corsets, and a variety of braces provide support for the body parts involved, and apply forces and moments to the body. Thorough knowledge of their application depends upon understanding of mechanical principles.

Knowledge of anatomy and mechanical principles also provides a better understanding of normal growth and the development of deformities. Physicians use this information to determine the extent of the problem and the method of treatment. Quite often, properly applied casts, braces, or splints supply the necessary force to correct a deformity.

Physical therapists and physical educators continually evaluate exercises, many of which may subsequently be found to be harmful. The forces involved in certain exercises may develop stress that could be damaging to the joints and soft tissues of the body. Mechanical analysis of each exercise provides information which could lead to safer and more effective exercise programs.

To evaluate an injury accurately, knowledge of the exact mechanism of the injury is essential. For example, stress fractures, bending fractures, compression fractures, sprains, and concussions are all caused by forces, but the mechanism may determine whether the injury is a fracture or a sprain. The type of fracture in turn produced depends on the characteristics of the force involved; different applications of force may cause either bending fractures, stress fractures, or compression fractures. The tissues involved are more easily located and the extent of the injury can be better evaluated when one understands how the injury was caused.

Summary

The preceding examples have shown some of the many applications of biomechanics in medical and associated areas. These same principles can also be applied in analysis of sport activities, work space and control design, tool development, and automobile design.

The practitioner may not need exact computations of many of the forces with which he works. He should recognize, however, the importance of such factors as lever action, the concept of the center of mass of the body and its component parts, and their relation to the base of support in stance and locomotion. The practitioner will function most effectively and find his job most interesting when he has a clear understanding of the principles of mechanics as they apply to his work. This is the goal of the present text.

QUESTIONS

1. Define: mechanics, biomechanics.
2. Discuss the application of biomechanics to exercise programs.
3. Cite examples of biomechanical principles related to orthopedic appliances and surgical applications.
4. Discuss in general the biomechanical factors involved in locomotion.
5. What is the value of understanding the biomechanical principles involved in growth and development?
6. Cite examples of biomechanical principles involved in rehabilitation.
7. List disciplines in which biomechanical principles are applied and cite several specific examples for each.

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CHAPTER 2

USEFUL TERMS AND CONCEPTS

The entire subject of mechanics covers two basic areas: *statics,* the study of bodies remaining at rest or in equilibrium as a result of forces acting upon them; and *dynamics,* the study of moving bodies. Dynamics, in turn, may be subdivided into *kinematics* and *kinetics*. Kinematics might be called the science of motion, since it deals with the relationships that exist between displacements, velocities, and accelerations in translational or rotational motion. It does not concern itself with the forces involved, but only with the description of the movements themselves. Kinetics deals with moving bodies and the forces that act to produce the motion. As an example, Eberhart and colleagues (1954), in their discussion of human locomotion, dealt first with the kinematics of walking and described the displacements of the body segments in the three cardinal planes, covering flexion and extension of the thigh and leg, pelvic rotation, and so on. They considered next the kinetics of walking, analyzing the forces of the muscle, as well as those of gravity and of floor reaction, all of which are necessary for propulsion of the body and control of segmental displacement. More recently, Dillman (1971) studied the kinematics and kinetics of the motion of the recovery leg during running, while Plagenhoef (1968) devised a method of studying dynamics using a computer.

Force is one of the basic concepts in mechanics and may be defined as a push or pull. To produce a force, one object or body must always act on another. This action may result in a pull or a push, and the body being pushed pushes back just as hard as the body doing the pushing. This means, for example, that if you push down on the desk with a force of 5 lb., the desk is pushing back up against you with a force of 5 lb.

Forces may also act between bodies which are not in contact with each other. Examples include the attractive force of gravity, the attraction and repulsion of electrically charged particles and magnetized materials, or the attractive forces of the nucleus which hold the atom together.

In mechanics the forces involved are both external and internal. The external forces outside the structure, called loads, are those such as the forces of gravity, air resistance, water resistance, inertia, muscle action, and ground reaction. The internal forces within a structure, reacting to these loads, are called stresses. *Stress* is the internal resistance of a material which reacts to an externally applied load.

A force, whether it is a load or the force involving reaction stress, is not completely described if we know only its *magnitude*. A 10 lb. force acting downward on a table produces an entirely different effect from that of a 10 lb. force acting on the table in a horizontal direction. Thus, in addition to its magnitude, the line of application or the *action line* of the force must be known. Since the effect will be different if we pull instead of push, the *direction,* or sense, along the action line is also of fundamental importance. Finally, the *point of application,* or the point at which the force is applied, is also of significance. The four factors which characterize a force are:

1. Magnitude
2. Action line
3. Direction
4. Point of application

All four of these characteristics must be supplied to define a force completely. If we are to describe a force applied to the forearm, for example, we must give its magnitude, point of application, action line, and direction in order to have a complete picture. Any variations in any of these characteristics will produce a different result on the forearm.

Magnitude alone is a *scalar* quantity, that is, it has no direction. Examples of scalar quantities are speed, length, temperature, and time. A *vector* is a quantity which gives direction as well as magnitude. Force is considered as a vector quantity because it has magnitude and direction, and thus can be represented by a vector, which is a directed straight line. When a vector is used to represent a force, its length should be made proportional to the magnitude of the force. If we let ½ inch represent 5 lb., a line 1 inch long would represent a force of 10 lb. Since the vector drawn to scale indicates magnitude (by the length), action line (by the location of its shaft), and the direction of the force (by its arrowhead), and it is placed on the object at the point of application of the force, the vector can be used to define the force completely. For example, in Figure 2–1, a vector is used to represent the force of the biceps brachii muscle. In mechanics we use vectors consistently since this is the easiest way to deal with forces. The student should become proficient in visualizing *force systems* (any group of 2 or more forces) as a series of vectors acting in relation to an object or to one another. Any time a vector is used to represent a force, it should be labeled with a letter or number designating its magnitude, as shown in Figure 2–2. If its magnitude in pounds is known, we of course label the vector with the actual force in pounds. If, however, the magnitude of the force is not known, we use a letter such as F or P to designate the magnitude of the force. Capital letters are generally used for this purpose. In order to evaluate the effect of forces, a line drawing of the forces and the body on which the forces are acting is made. Since the object or body may be very complicated, we can represent it by a simplified drawing called a *space diagram.* Only enough details are required on the space diagram to locate the position of the forces properly. Drawing the space diagram in some cases may be quite simple, whereas in other cases it becomes more difficult. A space diagram must contain the necessary dimensions to locate accurately the position of all forces acting on the body. Dis-

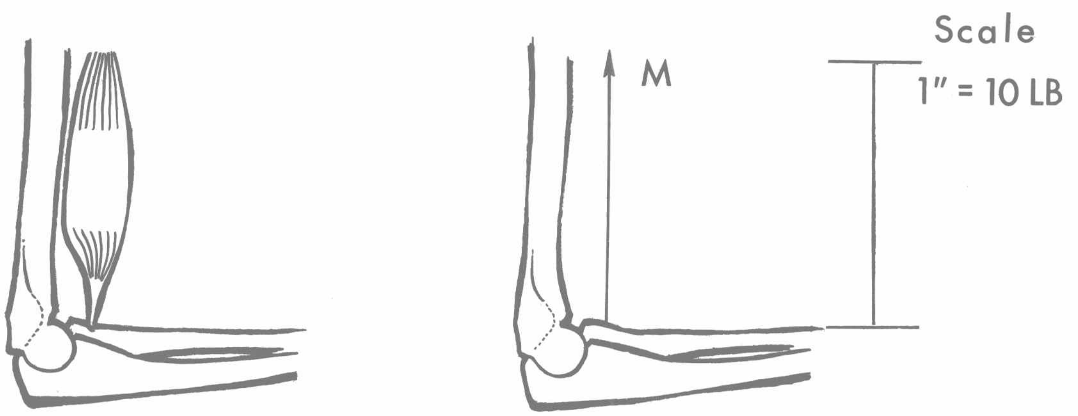

Figure 2–1 The muscle pull (M) is shown as a vector force drawn to an arbitrarily selected scale: 1 inch = 10 pounds.

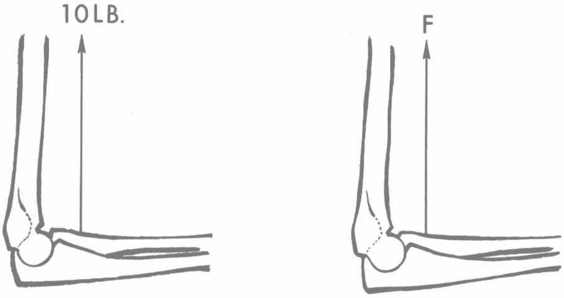

Figure 2–2 Vectors should always be identified by a label indicating magnitude.

tances may be designated in actual values, if known, or may be represented by small letters. A more accurate diagram is called the *free body diagram,* which requires that all forces be drawn in the correct proportion. Such a figure of a body shows all the forces that are acting on it, whether their values are known or unknown. The greatest difficulty with the diagram is locating all the forces acting on the body.

Space is another basic consideration in the study of mechanics. The forces that we deal with may act along a single line in a single plane or in any direction in space. Since we must have some means of locating our forces along a line, in a plane, or in space, it is necessary to provide some reference system. In the two dimensional system, we do this by dividing the plane into four quadrants by means of two perpendicular lines or axes. These axes are generally labeled X in the horizontal direction and Y in the vertical direction. The X axis is termed the abscissa; the Y axis the ordinate. The point of intersection of the two axes is known as the *origin* of the system. Measurements along the X axis to the right of the Y axis are positive. Those to the left of the Y axis are negative. Measurements along the Y axis above the X axis are positive, below are negative (Fig. 2–3). Any point on the plane can now be defined by being assigned X and Y values. These numbers, which determine the point location, are called the coordinates of the point. The point A, defined by X = 3, Y = 5, will be found three units to the right of the origin and five units above the origin. The point B, defined by X = –4, Y = 2, is found by moving 4 units to the left of the origin and up two units.

In order to locate points in three dimensions, a third axis must be introduced. This passes through the origin and is perpendicular to the X–Y plane in which the two original axes are found. The third axis is usually labeled Z. All points in front of the original X–Y plane are positive, while those behind the X–Y plane are negative. Now we have the means of locating any point in space. After the position in the X–Y plane is defined, you can locate the points either in front of the plane or behind the plane by means of a positive or negative coordinate (Fig. 2–4).

In setting up such a system of coordinates for the purpose of describing human motion, it is convenient to place the origin at the center of mass of the body, which is approximately anterior to the second sacral vertebrae. Three cardinal planes may then be visualized in relation to the X, Y, and Z coordinates (Fig. 2–5): frontal (or coronal), dividing the body into front and back portions (X–Y plane); sagittal, dividing the body into right and left halves (Y–Z plane); and transverse (or horizontal), dividing the body into upper and lower portions (X–Z plane). This system of reference coordinates and planes facilitates description of movement of the body segments and allows for an exact definition of any point in space. Fick

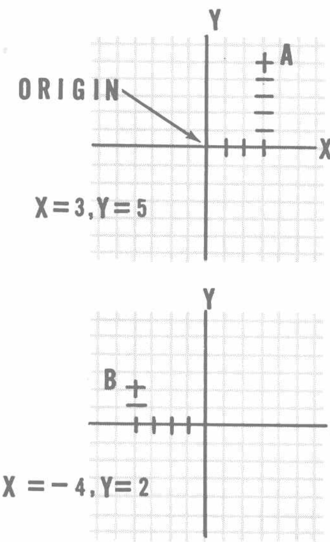

Figure 2–3 The location of points in a plane in relation to the X and Y axes.

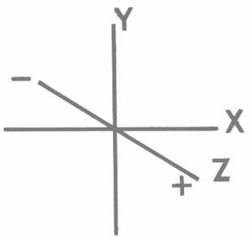

Figure 2–4 Addition of the Z axis to the X and Y coordinates permits the location of points in space.

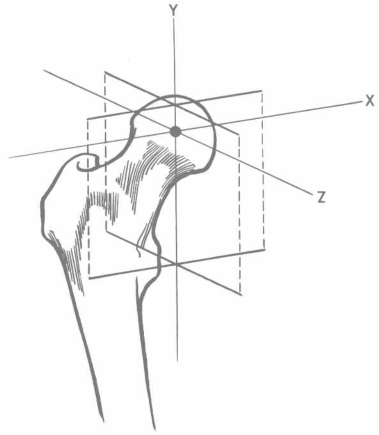

Figure 2–6 System of coordinates related to the mechanical axis of the hip joint.

(1850), who first computed the action of the thigh muscles on the hip joint a little over a hundred years ago, used such a system. Since he was interested in muscle action relative to the hip joint, he placed the origin of his coordinate system at the axis of the joint, as shown in Figure 2–6. By projecting the action lines of the individual muscles, he could determine their effect in moving the femur in each of the three cardinal planes. For example, a muscle such as the iliacus or pectineus, pulling in a direction anterior to the X–Y plane, flexes the part. The gluteus maximus, pulling posterior to this plane, extends it. The adductor and abductor muscles apply their force from points medial and lateral (respectively) to the Y–Z plane. Rotation is calculated in relation to the Y axis. (This means of computing the values of muscle forces such as these will be considered in Chapter 3.) The method employed by Fick to determine the action of muscles about the center of rotation of a joint has been in general use for many years. Elaborate globe-shaped devices have been designed to measure the position of the body segments in space and to record ranges of motion in joints which move in two or more planes (Fig. 2–7). A number of such examples are cited by Steindler (1955) and Morehouse and Miller (1971). For the purpose of kinematic analysis of movements of the upper extremity, Taylor and Blaschke (1951) have worked out a complex system of angles, axes, and centers. These authors stress that even this elaborate method is somewhat idealized and only approximates the true joint function, which is rather complicated.

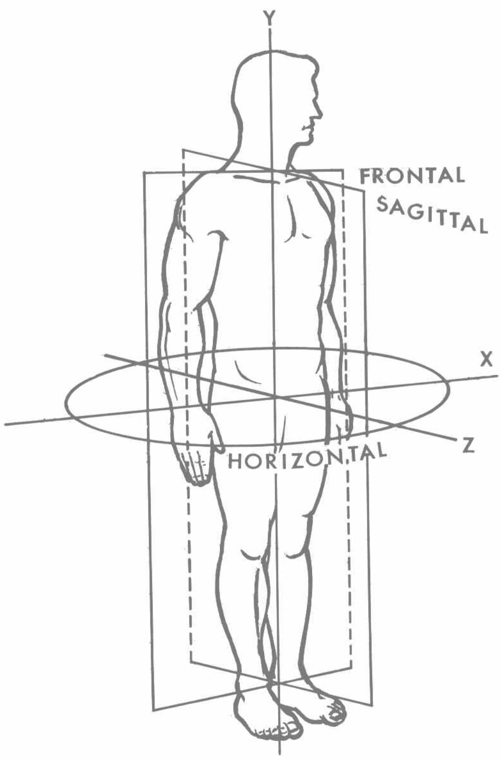

Figure 2–5 The three cardinal planes of the body related to the X, Y and Z axes.

Matter is that which occupies space. In our discussion of biomechanics we will often be dealing with the quantity of matter, or *mass,* to which the force of gravity is applied. This mass may be an object, such as an exercise

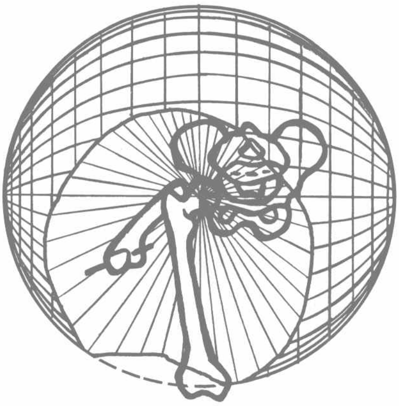

Figure 2–7 Example of "globographic" recording of range of motion (from Strasser, 1893).

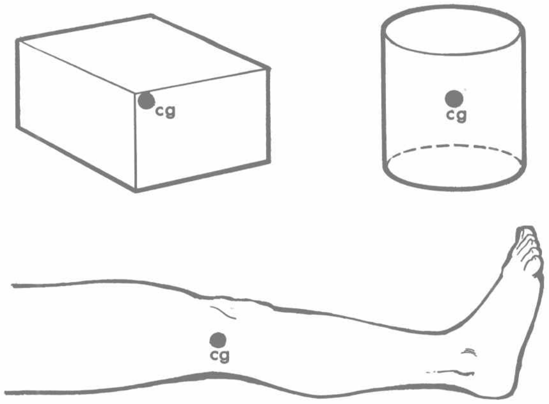

Figure 2–8 Center of mass of symmetrical and asymmetrical objects.

weight, or it may be the entire body or a segment of the body. In order to apply the principles of mechanics to human movement, the concept of *center of mass* of an object must be used constantly. The center of mass, by definition, is that point at the exact center of an object's mass. This is often called the center of gravity. In the case of a square block or a cylinder in which the mass is symmetrically distributed, this point is at the geometric center of the object (Fig. 2–8). However, if the distribution of mass is asymmetrical, as is true of the limbs of the human body, the center of mass will be nearer to the larger and heavier end. The center of mass of the entire human body when the limbs are straight as in ordinary standing lies within the pelvis (Fig. 2–9). This point may vary in position from person to person according to body build, age, and sex. It will also vary within any given person when the arrangement of the segments shifts, as in walking, running, or sitting. Since this point represents the center of the total mass, it will shift when weight is added to or subtracted from some part of the body, as with the addition of a cast or brace or following amputation of an extremity. Weights and centers of mass of the body segments have been determined by Braune and Fischer (1889), Dempster (1955), and Clauser and associates (1969). A summary of their studies is given in Appendix A and will be useful in estimating the magnitude and location of gravitational forces as accurately as possible in setting up and solving problems.

Weight is not the same as mass. The weight of a body is the pull of gravity on its mass. In the English system the unit for weight is the pound, while the unit for mass is the slug, or $\frac{\text{lb.-sec.}^2}{\text{ft.}}$. The force of gravity always acting on every object is directed vertically downward toward the center of the earth. This establishes the direction and line of action for the pull of gravity. This line of force is often referred to as the line of gravity.

The force acting on the entire mass of a

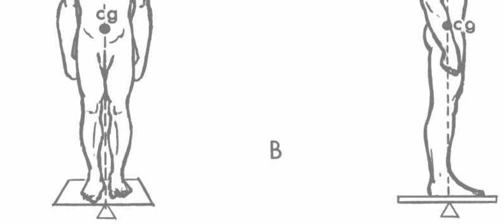

Figure 2–9 Center of mass of the entire human body.

rigid object may be considered to be acting as a single vector through its center of mass. This single vector represents the sum of many parallel forces distributed throughout the object. The use of this principle results in simplicity without the loss of accuracy.

In some instances we must deal with the many separate forces as they are in contact with other objects. *Pressure,* which is an important aspect of force, indicates how the force is distributed over an area. Pressure is defined as the total force per area of force application, as shown in the equation: $P = F/A$. This formula yields the average pressure given in units of force per unit area, for example, pounds per square inch. If a pressure pad on a back brace exerts a 4 lb. force over an area 6 in. by 8 in., the average pressure in the region beneath the pad would be 4 lb. divided by 48 square inches, or about 0.083 pound per square inch. What would be the magnitude of the force per unit area if the pad were 3 in. by 4 in. in size?

This principle of force per unit area is utilized in skiing and snowshoeing, making it possible to stand and walk on soft snow (Fig. 2-10). Without the use of skis or snowshoes a person would not be able to support his weight on the snow. Because of the small area of the

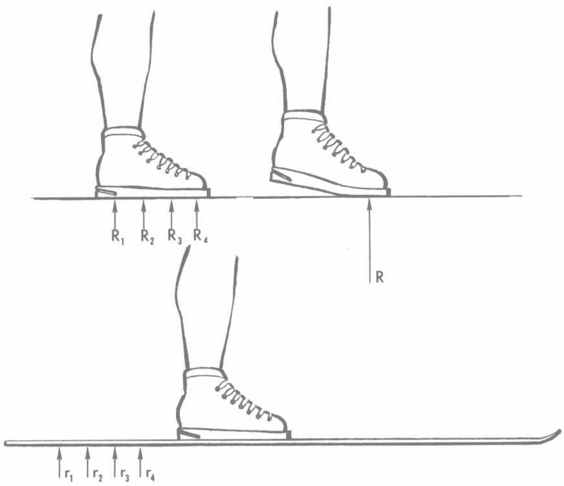

Figure 2-10 Distribution of body weight on the supporting surface varies according to the surface contact area. R = reacting force of the floor. (The pressure shown under one area actually acts over the entire length of the ski surface.)

foot, he would fall through. With the increased size or surface area of the skis or snowshoes, the body weight is distributed over a larger area and the total force per unit area is decreased, making it possible for the body weight to be supported. If you push with your fist in the palm of the opposite hand, you can withstand considerable force without discomfort. The same amount of force exerted by your thumb into the palm becomes painful as the pressure per unit area is now much greater. An equal force exerted by the point of a needle would be disastrous. In general, to avoid pain and possible injury to the skin, forces should be sustained over as large an area of body surface as possible. Skin breakdown, pressure sores, and ulcerated areas are serious clinical complications which could be easily avoided with the application of the above principle.

The position of patients in bed should be changed frequently in order to alternate the skin areas under pressure. This is particularly true in the presence of circulatory or sensory impairment. Pressure is a critical factor in the fitting of prosthetic devices for lower extremity amputees, especially those with ischial weight-bearing devices or end-bearing stumps. The socket must be designed so that the contact force is distributed over a large skin area. Padding of bony prominences is important as well in the application of braces and casts

The "give" or yield of the material contacting and supporting the body surfaces is a primary factor in avoiding dangerous effects of continuous pressure. When force is exerted against the body surface by rigid materials such as wood or metal, pressure is concentrated in the areas of bony prominences. Softer materials such as felt, padding, or sponge rubber allow for better equalization of the pressure over the entire contact area and protect the skin over bony prominences. Equalization of pressure has been attempted by inserting an air-filled chamber or water bag of some sort between the two contacting surfaces. Bremner (1959) applied this principle in scoliosis bracing by inserting a water inflated football (rugby) bladder between a plaster jacket and the thorax at the site of corrective pressure. The advantage of this hydrostatic bag was said to be "automatic pressure distribution and perfect congruity