Basic Biomechanical Factors and Concepts

Objectives

- To know and understand how knowledge of levers can help improve physical performance
- To know and understand how the musculoskeletal system functions as a series of simple machines
- To know and understand how knowledge of torque and lever arm lengths can help improve physical performance
- To know and understand how knowledge of Newton’s laws of motion can help improve physical performance
- To know and understand how knowledge of balance, equilibrium, and stability can help improve physical performance
- To know and understand how knowledge of force and momentum can help improve physical performance
- To know and understand the basic effects of mechanical loading on body tissues

In Chapter 1 we defined kinesiology, very simply, as the study of muscles, bones, and joints as they are involved in the science of movement. From this general definition we can go into greater depth in exploring the science of body movement, which primarily includes anatomy, physiology, and mechanics. For a true understanding of movement, a vast amount of knowledge is needed in all three areas. The focus of this text is primarily structural and functional anatomy. We have only very minimally touched on some physiology in the first two chapters. A much greater study of physiology as it relates to movement should be addressed in an exercise physiology course, for which there are many excellent texts and resources. Likewise, the study of mechanics as it relates to the functional and anatomical analysis of biological systems, known as biomechanics, should be addressed to a greater degree in a separate course. Human movement is quite complex. In order to make recommendations for its improvement, we need to study movements from a biomechanical perspective, both qualitatively and quantitatively. This chapter introduces some basic biomechanical factors and concepts, with the understanding that many readers will subsequently study these in more depth in a dedicated course utilizing much more thorough resources.
Many students in kinesiology classes have some knowledge, from a college or high school physics course, of the laws that affect motion. These principles and others are discussed briefly in this chapter, which should prepare you as you begin to apply them to motion in the human body. The more you can put these principles and concepts into practical application, the easier it will be to understand them.

Mechanics, the study of physical actions of forces, can be subdivided into statics and dynamics. Statics involves the study of systems that are in a constant state of motion, whether at rest with no motion or moving at a constant velocity without acceleration. In statics all forces acting on the body are in balance, resulting in the body being in equilibrium. Dynamics involves the study of systems in motion with acceleration. A system in acceleration is unbalanced due to unequal forces acting on the body. Additional components of biomechanical study include kinematics and kinetics. Kinematics is concerned with the description of motion and includes consideration of time, displacement, velocity, acceleration, and space factors of a system's motion. Kinetics is the study of forces associated with the motion of a body.

Types of machines found in the body

As discussed in Chapter 2, we utilize muscles to apply force to the bones on which they attach to cause, control, or prevent movement in the joints they cross. As is often the case, we utilize bones such as those in the hand to either hold, push, or pull on an object while using a series of bones and joints throughout the body to apply force via the muscles to affect the position of the object. In doing so we are using a series of simple machines to accomplish the tasks. Machines are used to increase or multiply the applied force in performing a task or to provide a mechanical advantage. The mechanical advantage provided by machines enables us to apply a relatively small force, or effort, to move a much greater resistance or to move one point of an object a relatively small distance to result in a relatively large amount of movement of another point of the same object. We can determine mechanical advantage by dividing the load by the effort. The mechanical aspect of each component should be considered with respect to the component's machine-like function.

Another way of thinking about machines is to note that they convert smaller amounts of force exerted over a longer distance to larger amounts of force exerted over a shorter distance. This may be turned around so that a larger amount of force exerted over a shorter distance is converted to a smaller amount of force over a greater distance. Machines function in four ways:

1. To balance multiple forces
2. To enhance force in an attempt to reduce the total force needed to overcome a resistance
3. To enhance range of motion and speed of movement so that resistance can be moved farther or faster than the applied force
4. To alter the resulting direction of the applied force

Simple machines are the lever, wheel and axle, pulley, inclined plane, screw, and wedge. The arrangement of the musculoskeletal system provides three types of machines in producing movement: levers, wheel/axles, and pulleys. Each of these involves a balancing of rotational forces about an axis. The lever is the most common form of simple machine found in the human body.

Levers

It may be difficult for a person to visualize his or her body as a system of levers, but this is actually the case. Human movement occurs through the organized use of a system of levers. While the anatomical levers of the body cannot be changed, when the system is properly understood they can be used more efficiently to maximize the muscular efforts of the body.

A lever is defined as a rigid bar that turns about an axis of rotation, or fulcrum. The axis is the point of rotation about which the lever moves. The lever rotates about the axis as a result of force (sometimes referred to as effort, E) being applied to it to cause its movement against a resistance or weight. In the body, the bones represent the bars, the joints are the axes, and the muscles contract to apply the force. The amount of resistance can vary from minimal to maximal. In fact, the bones themselves or the weight of the body segment may be the only resistance applied. All lever systems have each of these three components in one of three possible arrangements.

The arrangement or location of three points in relation to one another determines the type of lever and the application for which it is best suited. These points are the axis, the point of force application (usually the muscle insertion), and the
point of resistance application (sometimes the center of gravity of the lever and sometimes the location of an external resistance). When the axis (A) is placed anywhere between the force (F) and the resistance (R), a first-class lever is produced (Fig. 3.1). In second-class levers, the resistance is somewhere between the axis and the force (Fig. 3.2). When the force is placed somewhere between the axis and the resistance, a third-class lever is created (Fig. 3.3). Table 3.1 provides a summary of the three classes of levers and the characteristics of each.

The mechanical advantage of levers may be determined using the following equations:

\[
\text{Mechanical advantage} = \frac{\text{resistance}}{\text{force}}
\]

or

\[
\text{Mechanical advantage} = \frac{\text{length of force arm}}{\text{length of resistance arm}}
\]
FIG. 3.3 • A and B, Third-class levers. Note that the paddle and shovel function as third-class levers only when the top hand does not apply force but serves as a fixed axis of rotation. If the top hand applied force and the lower hand acted as the axis, then these would represent first-class levers.

### TABLE 3.1 • Classification of levers and characteristics of each

<table>
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<tr>
<th>Class</th>
<th>Illustration</th>
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<th>Arm movement</th>
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<td>F = A = R</td>
<td>Resistance arm and force arm move in opposite directions</td>
<td>Balanced movements</td>
<td>Axis near middle</td>
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<td>Erector spinae extending the head on cervical spine</td>
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<td>Axis between force and resistance</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Force motion</td>
<td>Axis near resistance</td>
<td>Crowbar</td>
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<tr>
<td>2nd</td>
<td>R = F</td>
<td>Resistance arm and force arm move in the same direction</td>
<td>Force motion (large resistance can be moved with relatively small force)</td>
<td>Axis near resistance</td>
<td>Wheelbarrow, nutcracker</td>
<td>Gastrocnemius and soleus in plantar flexing the foot to raise the body on the toes</td>
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<tr>
<td>3rd</td>
<td>F = R</td>
<td>Resistance arm and force arm move in the same direction</td>
<td>Speed and range of motion (requires large force to move a relatively small resistance)</td>
<td>Axis near force</td>
<td>Shoveling dirt, catapult</td>
<td>Biceps brachii and brachialis in flexing the elbow</td>
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</table>

**First-class levers**

Typical examples of a first-class lever are the crowbar, the seesaw, pliers, oars, and the triceps in overhead elbow extension. In the body an example is when the triceps applies the force to the olecranon (F) in extending the nonsupported forearm (R) at the elbow (A). Other examples are when the agonist and antagonist muscle groups
on either side of a joint axis are contracting simultaneously, with the agonist producing the force and the antagonist supplying the resistance. A first-class lever (see Fig. 3.1) is designed basically to produce balanced movements when the axis is midway between the force and the resistance (e.g., a seesaw). When the axis is close to the force, the lever produces speed and range of motion (e.g., the triceps in elbow extension). When the axis is close to the resistance, the lever produces force motion (e.g., a crowbar).

In applying the principle of levers to the body, it is important to remember that the force is applied where the muscle inserts in the bone, not in the belly of the muscle. For example, in elbow extension with the shoulder fully flexed and the arm beside the ear, the triceps applies the force to the olecranon of the ulna behind the axis of the elbow joint. As the applied force exceeds the amount of forearm resistance, the elbow extends.

The type of lever may be changed for a given joint and muscle depending on whether the body segment is in contact with a surface such as a floor or wall. For example, we have demonstrated that the triceps in elbow extension is a first-class lever with the hand free in space and the arm pushed away from the body. If the hand is placed in contact with the floor, as in performing a push-up to push the body away from the floor, the same muscle action at this joint now changes the lever to second class, because the axis is at the hand and the resistance is the body weight at the elbow joint.

Second-class levers

A second-class lever (see Fig. 3.2) is designed to produce force movements, since a large resistance can be moved by a relatively small force. Examples of second-class levers include a bottle opener, a wheelbarrow, and a nutcracker. We have just noted the example of the triceps extending the elbow in a push-up. A similar example of a second-class lever in the body is plantar flexion of the ankle to raise the body on the toes. The ball (A) of the foot serves as the axis of rotation as the ankle plantar flexors apply force to the calcaneus (F) to lift the resistance of the body at the tibiofibular articulation (R) with the talus. Opening the mouth against resistance provides another example of a second-class lever. There are relatively few other examples of second-class levers in the body.

Third-class levers

Third-class levers (see Fig. 3.3), with the force being applied between the axis and the resistance, are designed to produce speed and range of motion. Most of the levers in the human body are of this type, which requires a great deal of force to move even a small resistance. Examples include a catapult, a screen door operated by a short spring, and the application of lifting force to a shovel handle with the lower hand while the upper hand on the shovel handle serves as the axis of rotation. The biceps brachii is a typical example in the body. Using the elbow joint (A) as the axis, the biceps brachii applies force at its insertion on the radial tuberosity (F) to rotate the forearm up, with its center of gravity (R) serving as the point of resistance application.

The brachialis is an example of true third-class leverage. It pulls on the ulna just below the elbow, and, since the ulna cannot rotate, the pull is direct and true. The biceps brachii, on the other hand, supinates the forearm as it flexes, so the third-class leverage applies to flexion only.

Other examples include the hamstrings contracting to flex the leg at the knee in a standing position and the iliopsoas being used to flex the thigh at the hip.

Factors in use of anatomical levers

Our anatomical leverage system can be used to gain a mechanical advantage that will improve simple or complex physical movements. Some individuals unconsciously develop habits of using human levers properly, but frequently this is not the case.

Torque and length of lever arms

To understand the leverage system, the concept of torque must be understood. **Torque**, or moment of force, is the turning effect of an eccentric force. **Eccentric force** is a force that is applied off center or in a direction not in line with the center of rotation of an object with a fixed axis. In objects without a fixed axis, it is an applied force that is not in line with the object’s center of gravity; for rotation to occur, an eccentric force must be applied. In the human body, the contracting muscle applies an eccentric force (not to be confused with eccentric contraction) to the bone on which it attaches and causes the bone to rotate about an axis at the joint. The amount of torque can be determined by multiplying the **force magnitude** (amount of force) by the **force arm**. The perpendicular distance between the location of force application and the axis is known as the force arm, moment arm, or torque arm. The force arm may be best understood as the shortest distance from the axis of rotation to the line of action of the force. The
greater the distance of the force arm, the more torque produced by the force. A frequent practical application of torque and levers occurs when we purposely increase the force arm length in order to increase the torque so that we can more easily move a relatively large resistance. This is commonly referred to as increasing our leverage.

It is also important to note the resistance arm, which may be defined as the distance between the axis and the point of resistance application. In discussing the application of levers, it is necessary to understand the length relationship between the two lever arms. There is an inverse relationship between force and the force arm, just as there is between resistance and the resistance arm. The longer the force arm, the less force required to move the lever if the resistance and resistance arm remain constant, as shown graphically in Fig. 3.4. In addition, if the force and force arm remain constant, a greater resistance may be moved by shortening the resistance arm.

Also, there is a proportional relationship between the force components and the resistance components. That is, for movement to occur when either of the resistance components increases, there must be an increase in one or both of the force components. See Figs. 3.5, 3.6, and 3.7 to see how these relationships apply to first-, second-, and third-class levers, respectively.

![Graph](image)

**Fig. 3.4** • Relationships among forces, force arms, and resistance arms. (The graph assumes a constant resistance of 20 kilograms, and as a result the graphical representations of the resistance arm and force arm lie directly over each other.) With the resistance held constant at 20 kilograms and a resistance arm of 1 meter, the product of the (force) × (force arm) must equal 20 newtons. Thus there is an inverse relationship between the force and the force arm. As the force increases in newtons, the force arm length decreases in meters, and vice versa.

![Diagram](image)

**Fig. 3.5** • First-class levers. A, If the force arm and resistance arm are equal in length, a force equal to the resistance is required to balance it. B, As the force arm becomes longer, a decreasing amount of force is required to move a relatively larger resistance; C, As the force arm becomes shorter, an increasing amount of force is required to move a relatively smaller resistance, but the speed and range of motion that the resistance can be moved are increased. Forces (moments) are calculated to balance the lever system. The effort and resistance forces sum to zero. If any of the components are moved in relation to one another, then either a greater force or a greater resistance will be required.
FIG. 3.6  •  Second-class levers have a positive mechanical advantage due to the force arm always being longer than the resistance arm and are well suited for moving larger resistances with smaller forces. 

A, Placing the resistance halfway between the axis and the point of force application provides a mechanical advantage of 2; 

B, Moving the resistance closer to the axis increases the mechanical advantage but decreases the distance the resistance is moved; 

C, The closer the resistance is positioned to the point of force application, the less the mechanical advantage but the greater the distance the resistance is moved. Forces (moments) are calculated to balance the lever system. The effort and resistance forces sum to zero. If any of the components are moved in relation to one another, then either a greater force or a greater resistance will be required.

FIG. 3.7  •  Third-class levers. 

A, A force greater than the resistance, regardless of the point of force application, is required due to the resistance arm always being longer; 

B, Moving the point of force application closer to the axis increases the range of motion and speed but requires more force; 

C, Moving the point of force application closer to the resistance decreases the force needed but also decreases the speed and range of motion. Forces (moments) are calculated to balance the lever system. The effort and resistance forces sum to zero. If any of the components are moved in relation to one another, then either a greater force or a greater resistance will be required.
slight variations in the location of the force and the resistance are important in determining the mechanical advantage (MA) and effective force of the muscle. This point can be illustrated with the simple formula shown in Fig. 3.8, using the biceps brachii muscle in each example.

In Example A, the only way to move the insertion of the biceps brachii is with surgery, so this is not practical. In some orthopaedic conditions, the attachments of tendons are surgically relocated in an attempt to change the dynamic forces the muscles exert on the joints. In Example B, we can and often do shorten the resistance arm to enhance our ability to move an object. When attempting a maximal weight in a biceps curl exercise, we may flex our wrist to move the weight just a little closer, which shortens the resistance arm. Example C is straightforward in that we obviously can reduce the force needed by reducing the resistance.

The system of leverage in the human body is built for speed and range of motion at the expense of force. Short force arms and long resistance arms require great muscular strength to produce movement. In the forearm, the attachments of the biceps and triceps muscles clearly illustrate this point, since the force arm of the biceps is 1 to 2 inches and that of the triceps is less than 1 inch. Many similar examples are found all over the body. From a practical point of view, this means that the muscular system should be strong to supply the necessary force for body movements, especially in strenuous sports activities.

When we speak of human leverage in relation to sport skills, we are generally referring to several levers. For example, throwing a ball involves levers at the shoulder, elbow, and wrist joints as well as from the ground up through the lower extremities and the trunk. In fact, it can be said that there is one long lever from the feet to the hand.

The longer the lever, the more effective it is in imparting velocity. A tennis player can hit a tennis ball harder (deliver more force to it) with a straight-arm drive than with a bent elbow, because the lever (including the racket) is longer and moves faster.

Fig. 3.9 indicates that a longer lever (Z1) travels faster than a shorter lever (S1) in traveling the same number of degrees. In sports activities in which it is possible to increase the length of a lever with a racket or bat, the same principle applies.

In baseball, hockey, golf, field hockey, and other sports, long levers produce more linear force and thus better performance. However, to be able to fully execute the movement in as short a time as possible, it is sometimes desirable to have a short lever arm. For example, a baseball catcher attempting to throw a runner out at second base does not have to throw the ball so that it travels as fast as when the pitcher is attempting to throw a strike. In the catcher's case, it is more important to initiate and complete the throw as soon as possible than to deliver as much velocity to the ball as possible. The pitcher, when attempting to throw a ball at

FIG. 3.8 • Torque calculations with examples of modifications in the force arm, resistance arm, and resistance.
FIG. 3.9 • Length of levers. The end of a longer lever (Z1) travels faster than a shorter lever (S1) when moved over the same number of degrees in the same amount of time. The farther the resistance is from the axis, the farther it is moved and the more force is delivered to it, resulting in the resistance moving at a greater velocity. The same principle applies in sports in which it is possible to increase the lever length with a racket or bat.

90-plus miles per hour, will utilize his body as a much longer lever system throughout a greater range of motion to impart velocity to the ball.

Wheels and axles

Wheels and axles are used primarily to enhance range of motion and speed of movement in the musculoskeletal system. A wheel and an axle essentially function as a form of lever. When either the wheel or the axle turns, the other must turn as well. Both complete one turn at the same time. The centers of the wheel and the axle both correspond to the fulcrum. Both the radius of the wheel and the radius of the axle correspond to the force arms. If the radius of the wheel is greater than the radius of the axle, then the wheel has a mechanical advantage over the axle due to the longer force arm. That is, a relatively smaller force may be applied to the wheel to move a relatively greater resistance applied to the axle. Very simply, if the radius of the wheel is five times the radius of the axle, then the wheel has a 5 to 1 mechanical advantage over the axle, as shown in Fig. 3.10. The mechanical advantage of a wheel and axle for this scenario may be calculated by considering the radius of the wheel over the radius of the axle. This application enables the wheel and axle to act as a second-class lever to gain force motion.

Mechanical advantage = \( \frac{\text{radius of the wheel}}{\text{radius of the axle}} \)

In this case the mechanical advantage is always more than 1. An application of this example is using the outer portion of an automobile steering wheel to turn the steering mechanism. Before the development of power steering, steering wheels had a much larger diameter than today in order to give the driver more of a mechanical advantage. An example in the body of applying force to the wheel occurs when we attempt to manually force a person’s shoulder into internal rotation while she or he holds it in external rotation isometrically. The humerus acts as the axle, and the person’s hand and wrist are located near the outside of the wheel when the elbow is flexed approximately 90 degrees. If we unsuccessfully attempt to break the force of the contraction of the external rotators by pushing internally at the midforearm, we can increase our leverage or mechanical advantage and our likelihood of success by applying the force nearer to the hand and wrist.
If the application of force is reversed so that it is applied to the axle, then the mechanical advantage results from the wheel's turning a greater distance at greater speed. Using the same example, if the wheel radius is five times greater than the radius of the axle, the outside of the wheel will turn at a speed five times that of the axle. Additionally, the distance the outside of the wheel turns will be five times that of the outside of the axle. This application enables the wheel and axle to act as a third-class lever to gain speed and range of motion. The mechanical advantage of a wheel and axle for this scenario may be calculated by considering the radius of the axle over the radius of the wheel.

\[
\text{Mechanical advantage} = \frac{\text{radius of the axle}}{\text{radius of the wheel}}
\]

In this case the mechanical advantage is always less than 1. This is the principle utilized in the drivetrain of an automobile to turn the axle, which subsequently turns the tire one revolution for every turn of the axle. We utilize the powerful engine of the automobile to supply the force to increase the speed of the tire and subsequently carry us great distances. An example of the muscles applying force to the axle to result in greater range of motion and speed may again be seen in the upper extremity, in the case of the internal rotators attaching to the humerus. With the humerus acting as the axle and the hand and wrist located at the outside of the wheel (when the elbow is flexed approximately 90 degrees), the internal rotators apply force to the humerus. With the internal rotators concentrically internally rotating the humerus a relatively small amount, the hand and wrist travel a great distance. Using the wheel and axle in this manner enables us to significantly increase the speed at which we can throw objects.

**Pulleys**

Single pulleys have a fixed axle and function to change the effective direction of force application. Single pulleys have a mechanical advantage of 1, as shown in Fig. 3.11, A. Numerous weight machines utilize pulleys to alter the direction of the resistive force. Pulleys may be movable and can be combined to form compound pulleys to further increase the mechanical advantage. Every additional rope connected to movable pulleys increases the mechanical advantage by 1, as shown in Fig. 3.11, B.

In the human body, an excellent example is provided by the lateral malleolus, acting as a pulley around which the tendon of the peroneus longus runs. As this muscle contracts, it pulls toward its belly, which is toward the knee. Due to its use of the lateral malleolus as a pulley (Fig. 3.12), the force is transmitted to the planter aspect of the foot, resulting in downward and outward movement of the foot. Other examples in the human body include pulleys on the volar aspect of the phalanges to redirect the force of the flexor tendons.

**FIG. 3.11** • **A**, Single pulley; **B**, Compound movable pulley.

**FIG. 3.12** • Pulley. The lateral malleolus serves as a pulley for the peroneus longus tendon.
Laws of motion and physical activities

Motion is fundamental in physical education and sports activity. Body motion is generally produced, or at least started, by some action of the muscular system. Motion cannot occur without a force, and the muscular system is the source of force in the human body. Thus, development of the muscular system is indispensable to movement.

Basically, there are two types of motion: linear motion and angular motion. Linear motion, also referred to as translatory motion, is motion along a line. If the motion is along a straight line, it is rectilinear motion, whereas motion along a curved line is known as curvilinear motion. Angular motion, also known as rotary motion, involves rotation around an axis. In the human body, the axis of rotation is provided by the various joints. In a sense, these two types of motion are related, since angular motion of the joints can produce the linear motion of walking. In many sports activities, the cumulative angular motion of the joints of the body imparts linear motion to a thrown object (ball, shot) or to an object struck with an instrument (bat, racket).

Displacement is a change in the position or location of an object from its original point of reference, whereas distance, or the path of movement, is the actual sum length it is measured to have traveled. Thus an object may have traveled a distance of 10 meters along a linear path in two or more directions but be displaced from its original reference point by only 6 meters. Fig. 3.13 provides an example. Angular displacement is the change in location of a rotating body. Linear displacement is the distance a system moves in a straight line.

We are sometimes concerned about the time it takes for displacement to occur. Speed is how fast an object is moving, or the distance an object travels in a specific amount of time. Velocity, the rate at which an object changes its position, includes the direction and describes the rate of displacement.

A brief review of Newton's laws of motion will indicate the many applications of these laws to physical education activities and sports. Newton's laws explain all the characteristics of motion, and they are fundamental to understanding human movement.

Law of inertia

A body in motion tends to remain in motion at the same speed in a straight line unless acted on by a force; a body at rest tends to remain at rest unless acted on by a force.

Inertia can be described as the resistance to action or change. In terms of human movement, inertia refers to resistance to acceleration or deceleration. Inertia is the tendency for the current state of motion to be maintained, whether the body segment is moving at a particular velocity or is motionless.

Muscles produce the force necessary to start motion, stop motion, accelerate motion, decelerate motion, or change the direction of motion. Put another way, inertia is the reluctance to change status; only force can do so. The greater the mass of an object, the greater its inertia. Therefore, the greater the mass, the more force needed to significantly change an object's inertia. Numerous examples of this law are found in physical education activities. A sprinter in the starting blocks must apply considerable force to overcome resting inertia. A runner on an indoor track must apply considerable force to overcome moving inertia and stop before hitting the wall. Fig. 3.14 provides an example of how a skier in motion remains in motion even though airborne after skiing off a hill. We routinely experience inertial forces when our upper body tends to move forward if we are driving a car at the speed limit and then suddenly have to slow down. Balls and other objects that are thrown or struck require force to stop them. Starting, stopping, and changing direction—a part
of many physical activities—provide many examples of the law of inertia applied to body motion.

Because force is required to change inertia, it is obvious that any activity that is carried out at a steady pace in a consistent direction will conserve energy and that any irregularly paced or directed activity will be very costly to energy reserves. This explains in part why activities such as handball and basketball are so much more fatiguing than jogging and dancing.

**Law of acceleration**

A change in the acceleration of a body occurs in the same direction as the force that caused it. The change in acceleration is directly proportional to the force causing it and inversely proportional to the mass of the body.

**Acceleration** may be defined as the rate of change in velocity. To attain speed in moving the body, a strong muscular force is generally necessary. **Mass**, the amount of matter in a body, affects the speed and acceleration in physical movements. A much greater force is required from the muscles to accelerate an 80-kilogram man than to accelerate a 58-kilogram man to the same running speed. Also, it is possible to accelerate a baseball faster than a shot because of the difference in mass. The force required to run at half speed is less than the force required to run at top speed. To impart speed to a ball or an object, it is necessary to rapidly accelerate the part of the body holding the object. Football, basketball, track, and field hockey are a few sports that demand speed and acceleration.

**Law of reaction**

*For every action there is an opposite and equal reaction.*

As we place force on a supporting surface by walking over it, the surface provides an equal resistance back in the opposite direction to the soles of our feet. Our feet push down and back, while the surface pushes up and forward. The force of the surface reacting to the force we place on it is referred to as **ground reaction force**. We provide the action force, while the surface provides the reaction force. It is easier to run on a hard track than on a sandy beach because of the difference in the ground reaction forces of the two surfaces. The track resists the runner's propulsion force, and the reaction drives the runner ahead. The sand dissipates the runner's force, and the reaction force is correspondingly reduced, with an apparent loss in forward force and speed (Fig. 3.15). A sprinter applies a force in excess of 1355 Newtons on the starting blocks, which resist with an equal force. When a body is in flight, as in jumping, movement of one part of the body produces a reaction in another part because there is no resistive surface to supply a reaction force.

**Friction**

**Friction** is the force that results from the resistance between the surfaces of two objects moving on each other. Depending on the activity involved, we
may desire increased or decreased friction. In running, we depend on friction forces between our feet and the ground so that we may exert force against the ground and propel ourselves forward. When friction is reduced due to a slick ground or shoe surface, we are more likely to slip. In skating, we desire decreased friction so that we may slide across the ice with less resistance. Friction may be further characterized as either static or kinetic. See Fig. 3.16, A, B, and C. Static friction is the amount of friction between two objects that have not yet begun to move, whereas kinetic friction is the friction between two objects that are sliding along each other. Static friction is always greater than kinetic friction. As a result, it is always more difficult to initiate dragging an object across a surface than it is to continue dragging it. Static friction may be increased by increasing the normal or perpendicular forces pressing the two objects together, as by adding more weight to one object sitting on another object. To determine the amount of friction forces, we must consider both the forces pressing the two objects together and the coefficient of friction, which depends on the hardness and roughness of the surface textures. The coefficient of friction is the ratio of the force needed to overcome the friction to the force holding the surfaces together. Rolling friction (Fig. 3.16, D) is the resistance to an object rolling across a surface, such as a ball rolling across a court or a tire rolling across the ground. Rolling friction is always much less than static or kinetic friction.

Balance, equilibrium, and stability

Balance is the ability to control equilibrium, either static or dynamic. In relation to human move-
ment, equilibrium refers to a state of zero acceleration, where there is no change in the speed or direction of the body. Equilibrium may be either static or dynamic. If the body is at rest or completely motionless, it is in static equilibrium. Dynamic equilibrium occurs when all the applied and inertial forces acting on the moving body are in balance, resulting in movement with unchanging speed or direction. For us to control equilibrium and hence achieve balance, we need to maximize stability. Stability is the resistance to a change in the body’s acceleration or, more appropriately, the resistance to a disturbance of the body’s equilibrium. Stability may be enhanced by determining the body’s center of gravity and changing it appropriately. The center of gravity is the point at which all of the body’s mass and weight is equally balanced or equally distributed in all directions. Very generally, the center of gravity for humans is located in the vicinity of the umbilicus.

Balance is important for the resting body as well as for the moving body. Generally, balance is to be desired, but there are circumstances in which movement is improved when the body tends to be unbalanced. Following are certain general factors that apply toward enhancing equilibrium, maximizing stability, and ultimately achieving balance:

1. A person has balance when the center of gravity falls within the base of support (Fig. 3.17).
2. A person has balance in direct proportion to the size of the base. The larger the base of support, the more balance.
3. A person has balance depending on the weight (mass). The greater the weight, the more balance.
4. A person has balance depending on the height of the center of gravity. The lower the center of gravity, the more balance.
5. A person has balance depending on where the center of gravity is in relation to the base of support. The balance is less if the center of gravity is near the edge of the base. However, when anticipating an oncoming force, stability may be improved by placing the center of gravity nearer the side of the base of support expected to receive the force.
6. In anticipation of an oncoming force, stability may be increased by enlarging the size of the base of support in the direction of the anticipated force.
7. Equilibrium may be enhanced by increasing the friction between the body and the surfaces it contacts.
8. Rotation about an axis aids balance. A moving bike is easier to balance than a stationary bike.
9. Kinesthetic physiological functions contribute to balance. The semicircular canals of the inner ear, vision, touch (pressure), and kinesthetic sense all provide balance information to the performer. Balance and its components of equilibrium and stability are essential in all movements. All are affected by the constant force of gravity, as well as by inertia. Walking has been described as an activity in which a person throws the body in and out of balance with each step. In rapid running movements in which moving inertia is high, the individual has to lower the center of gravity to maintain balance when stopping or changing direction. Conversely, in jumping activities, the individual attempts to raise the center of gravity as high as possible.

**Force**

Muscles are the main source of force that produces or changes movement of a body segment, the entire body, or an object thrown, struck, or stopped. As discussed previously, a variety of factors affect the ability of a muscle to exert force. We obviously need to understand these various factors. And we must utilize this knowledge in properly managing the factors to condition our muscles appropriately to achieve the desired response in dealing with both internal and external forces. As a result, we usually desire stronger muscles in order to be able to produce more force for both maximum and sustained exertion.

**Forces** either push or pull on an object in an attempt to affect motion or shape. Without forces acting on an object, there is no motion. Force is the product of mass times acceleration. The mass of a body segment or the entire body times the speed of acceleration determines the force. Obviously, in football this is very important, yet it is just as important in other activities that use only a part of the human body. In throwing a ball, the force applied to the ball is equal to the mass of the arm times the arm's speed of acceleration. Also, as previously discussed, leverage is important.

\[
\text{Force} = \text{mass} \times \text{acceleration} = F = m \times a
\]

The quality of motion, or, more scientifically stated, the **momentum**, which is equal to mass times velocity, is important in skill activities. The greater the momentum, the greater the resistance to change in the inertia or state of motion. In other words, a larger person with greater mass moving at the same velocity as a smaller person will have more momentum. On the other hand, a person with less mass moving at a higher velocity may have more momentum than a person with greater mass moving at a lower velocity. Momentum may be altered by **impulse**, which is the product of force and time.

It is not necessary to apply maximal force and thereby increase the momentum of a ball or an object being struck in all situations. In skillful performance, regulation of the amount of force is necessary. Judgment as to the amount of force required to throw a softball a given distance, hit a golf ball 200 yards, or hit a tennis ball across the net and into the court is important.

In activities involving movement of various joints, as in throwing a ball or putting a shot, there should be a summation of forces from the beginning of movement in the lower segment of the body to the twisting of the trunk and movement at the shoulder, elbow, and wrist joints. The speed at which a golf club strikes the ball is the result of a summation of forces of the lower extremities, trunk, shoulders,
arms, and wrists. Shot-putting and discus and javelin throwing are other good examples that show that a summation of forces is essential.

Mechanical loading basics

As we utilize the musculoskeletal system to exert force on the body to move and to interact with the ground and other objects or people, significant mechanical loads are generated and absorbed by the tissues of the body. The forces causing these loads may be internal or external. Only muscles can actively generate internal force, but tension in tendons, connective tissues, ligaments, and joint capsules may passively generate internal forces. External forces are produced from outside the body and originate from gravity, inertia, or direct contact. All tissues, in varying degrees, resist changes in their shape. Obviously, tissue deformation may result from external forces, but we also have the ability to generate internal forces large enough to fracture bones, dislocate joints, and disrupt muscles and connective tissues. To prevent injury or damage from tissue deformation, we must use the body to absorb energy from both internal and external forces. Along this line, it is to our advantage to absorb such force over larger aspects of our body rather than smaller ones, and to spread the absorption rate over a longer period of time. Additionally, the stronger and healthier we are, the more likely we are to be able to withstand excessive mechanical loading and the resultant excessive tissue deformation. Tension (stretching or strain), compression, shear, bending, and torsion (twisting) are all forces that act individually or in combination to provide mechanical loading that may result in excessive tissue deformation. Fig. 3.18 illustrates the mechanical forces that act on tissues of the body.

Functional application

In the performance of various sport skills, many applications of the laws of leverage, motion, and balance may be found. A skill common to many activities is throwing. The object thrown may be some type of ball, but it is frequently an object of another size or shape, such as a rock, beanbag, Frisbee, discus, or javelin. A brief analysis of some of the basic mechanical principles involved in the skill of throwing will help indicate the importance of understanding the applications of these principles. Many activities involve these and often other mechanical principles. Motion is basic to throwing when the angular motion (Fig. 2.21) of the levers (bones) of the body (trunk, shoulder, elbow, and wrist) is used to give linear motion to the ball when it is released.

Newton's laws of motion apply in throwing because the individual's inertia and the ball's inertia (see p. 79) must be overcome by the application of force. The muscles of the body provide the force to move the body parts and the ball held in the hand. The law of acceleration (Newton's second law) comes into operation with the muscular force necessary to accelerate the arm, wrist, and hand. The greater the force (mass times acceleration) a person can produce, the faster the arm will move and, thus, the greater the speed that will be imparted to the ball. The reaction of the feet against the surface on which the person stands illustrates the application of the law of reaction.

The leverage factor is very important in throwing a ball or an object. For all practical purposes, the body from the feet to the fingers can be considered one long lever. The longer the lever, either from natural body length or from the movement of the body to the extended backward position (as in throwing a softball, with extension of the shoulder and elbow joints), the greater will be the arc through which it accelerates and thus the greater will be the speed imparted to the thrown object.

In certain circumstances, when the ball is to be thrown only a short distance, as in baseball when it is thrown by the catcher to the bases, the short lever is advantageous because it takes less total time to release the ball.

Balance, or equilibrium, is a factor in throwing when the body is rotated to the rear in the beginning of the throw. This motion moves the body nearly out of balance to the rear, and balance then
changes again in the body with the forward movement. Balance is again established with the follow-through, when the feet are spread and the knees and trunk are flexed to lower the center of gravity.

Summary

The preceding discussion has been a brief overview of some of the factors affecting motion. Analysis of human motion in light of the laws of physics poses a problem: How comprehensive is the analysis to be? It can become very complex, particularly when body motion is combined with the manipulation of an object in the hand involved in throwing, kicking, striking, or catching.

These factors become involved when we attempt an analysis of the activities common to our physical education programs—football, baseball, basketball, track and field, field hockey, and swimming, to mention a few. However, to have a complete view of which factors control human movement, we must have a working knowledge of both the physiological and the biomechanical principles of kinesiology.

It is beyond the scope of this book to make a detailed analysis of other activities. Some sources that consider these problems in detail are listed in the references and websites.

Websites

Biomechanics: The Magazine of Body Movement and Medicine
www.biomech.com

Biomechanics World Wide
www.uni-duv.de/~qpd800/WSITECOPY.html

This site enables the reader to search the biomechanics journals for recent information regarding mechanisms of injury.

Kinesiology Biomechanics Classes
www.uoregon.edu/~laurdana/biomechanics/kinesiology.htm

A listing of numerous biomechanics and kinesiology class sites on the Web, with many downloadable presentations and notes.

REVIEW AND LABORATORY EXERCISES

1. Lever component identification chart

Determine and list two practical examples of levers (in the body or in daily living) for each lever class. Do not use examples already discussed in this chapter. For each example identify the force, axis, and resistance. Also explain the advantage of using each lever—that is, whether it is to achieve balance, force, motion, speed, or range of motion.

<table>
<thead>
<tr>
<th>Lever class</th>
<th>Example</th>
<th>Force</th>
<th>Axis</th>
<th>Resistance</th>
<th>Advantage provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>2nd</td>
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<td>2nd</td>
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<td>3rd</td>
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</tr>
</tbody>
</table>

2. Anatomical levers can improve physical performance. Explain how this occurs using the information you have learned in relation to throwing.

3. If your biceps muscle inserts to your forearm 2 inches below your elbow, the distance from the elbow to the palm of your hand is 18 inches, and you lift a 20-pound weight, how much force must your muscle exert to achieve elbow flexion?

4. If the weight of an object is 50 kilograms and your mechanical advantage is 4, how much force would you need to exert to lift the object with a lever system?

5. For the lever system component calculation chart, arrange the lever components as listed for each task a. through j. Determine the lever class and calculate the values for the force arm (FA), the resistance arm (RA), the force, and the mechanical advantage (MA). You may want to draw all the various arrangements of the components on a separate sheet of paper.

![Lever System Components](image_url)
Each vertical line on the lever bar represents the points at which the components are to be arranged, with the left endpoint representing 0 and the right endpoint representing 20.

**Lever system component calculation chart**

<table>
<thead>
<tr>
<th>Lever components</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force applied at</td>
</tr>
<tr>
<td>a.</td>
<td>0</td>
</tr>
<tr>
<td>b.</td>
<td>0</td>
</tr>
<tr>
<td>c.</td>
<td>3</td>
</tr>
<tr>
<td>d.</td>
<td>8</td>
</tr>
<tr>
<td>e.</td>
<td>12</td>
</tr>
<tr>
<td>f.</td>
<td>19</td>
</tr>
<tr>
<td>g.</td>
<td>16</td>
</tr>
<tr>
<td>h.</td>
<td>13</td>
</tr>
<tr>
<td>i.</td>
<td>8</td>
</tr>
<tr>
<td>j.</td>
<td>20</td>
</tr>
</tbody>
</table>

6. What class of lever is an automobile steering wheel?

7. List two different wheel and axles in which the force is applied to the wheel. From your observation, estimate which of the two has the greater mechanical advantage.

8. List two different wheel and axles in which the force is applied to the axle. From your observation, estimate which of the two has the greater mechanical advantage.

9. When attempting to remove a screw, is it easier when using a screwdriver with a larger grip on the handle? Why?

10. If a pulley setup has five supporting ropes, what is the MA of the setup?

11. What amount of force is needed to lift an object in a pulley system if the weight of the object being lifted is 200 kg and the number of supporting ropes is four?

12. Identify a practical example of Newton's law of inertia. Explain how the example illustrates the law.

13. Identify a practical example of Newton's law of acceleration. Explain how the example illustrates the law.

14. Identify a practical example of Newton's law of reaction. Explain how the example illustrates the law.

15. If a baseball player hit a triple and ran around the bases to third base, what would be his displacement? Hint: The distance from each base to the next is 90 feet.

16. Select a sporting activity and explain how the presence of too much friction becomes a problem in the activity.

17. Select a sporting activity and explain how the presence of too little friction becomes a problem in the activity.

18. Using the mechanical loading basic forces of compression, torsion, and shear, describe each force by using examples from soccer or volleyball.

19. **Laws of motion task comparison chart**

For this chart, assume that you possess the skill, strength, etc., to be able to perform each of the paired tasks. Circle the task that would be easier to perform based on Newton's laws of motion and explain why.

<table>
<thead>
<tr>
<th>Paired tasks</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Throw a baseball 60 mph OR Throw a shot-put 60 mph.</td>
<td></td>
</tr>
<tr>
<td>b. Kick a bowling ball 40 yards OR Kick a soccer ball 40 yards.</td>
<td></td>
</tr>
<tr>
<td>c. Bat a whiffle ball over a 320-yard fence OR Bat a baseball over a 320-yard fence.</td>
<td></td>
</tr>
<tr>
<td>d. Catch a shot-put that was thrown at 60 mph OR Catch a softball that was thrown at 60 mph.</td>
<td></td>
</tr>
<tr>
<td>e. Tackle a 240-pound running back sprinting toward you full speed OR Tackle a 200-pound running back sprinting toward you full speed.</td>
<td></td>
</tr>
<tr>
<td>f. Run a 40-yard dash in 4.5 seconds on a wet field OR Run a 40-yard dash in 4.5 seconds on a dry field.</td>
<td></td>
</tr>
</tbody>
</table>
20. Develop special projects and class reports by individuals or small groups of students on the mechanical analysis of all the skills involved in the following:
   a. Basketball
   b. Baseball
   c. Dancing
   d. Diving
   e. Football
   f. Field hockey
   g. Golf
   h. Gymnastics
   i. Soccer
   j. Swimming
   k. Tennis
   l. Wrestling

21. Develop term projects and special class reports by individuals or small groups of students on the following factors in motion:
   a. Balance
   b. Force
   c. Gravity
   d. Motion
   e. Torque
   f. Leverge
   g. Projectiles
   h. Friction
   i. Buoyancy
   j. Aerodynamics
   k. Hydrodynamics
   l. Restitution
   m. Impulse
   n. Spin
   o. Rebound angle
   p. Momentum
   q. Center of gravity
   r. Equilibrium
   s. Stability
   t. Base of support
   u. Inertia
   v. Linear displacement
   w. Angular displacement
   x. Speed
   y. Velocity
   z. Work

22. Develop demonstrations, term projects, or special reports by individuals or small groups of students on the following activities:
   a. Lifting
   b. Throwing
   c. Standing
   d. Walking
   e. Running
   f. Jumping
   g. Falling
   h. Sitting
   i. Pushing and pulling
   j. Striking

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