CHAPTER 7

Angular Kinetics

Angular kinetics explains the causes of rotary motion and employs many variables similar to the ones discussed in the previous chapter on linear kinetics. In fact, Newton's laws have angular analogues that explain how torques create rotation. The net torque acting on an object creates an angular acceleration inversely proportional to the angular inertia called the moment of inertia. Angular kinetics is quite useful because it explains the causes of joint rotations and provides a quantitative way to determine the center of gravity of the human body. The application of angular kinetics is illustrated with the principles of **Inertia** and **Balance**.

TORQUE

The rotating effect of a force is called a **torque** or **moment of force**. Recall that a moment of force or torque is a vector quantity, and the usual two-dimensional convention is that counterclockwise rotations are positive. Torque is calculated as the product of force (**F**) and the **moment arm**. The moment arm or leverage is the perpendicular displacement ($\mathbf{d}_\perp$) from the line of action of the force and the axis of rotation (Figure 7.1). The biceps femoris pictured in Figure 7.1 has moment arms that create hip extension and knee flexion torques. An important point is that the moment arm is always the shortest displacement between the force line of action and axis of rotation. This text will use the term torque synonymously with moment of force, even though there is a more specific mechanics-of-materials meaning for torque.

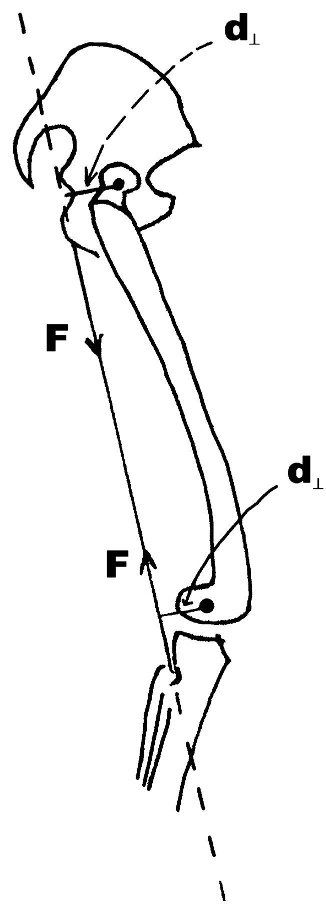

Figure 7.1. The moment arms ($\mathbf{d}_\perp$) for the biceps femoris muscle. A moment arm is the right-angle distance from the line of action of the force to the axis of rotation.

In algebraic terms, the formula for torque is $\mathbf{T} = \mathbf{F} \cdot \mathbf{d}_{\perp}$, so that typical units of torque are N·m and lb·ft. Like angular kinematics, the usual convention is to call counterclockwise (ccw) torques positive and clockwise ones negative. Note that the size of the force and the moment arm are *equally* important in determining the size of the torque created. This has important implications for maximizing performance in many activities. A person wanting to create more torque can increase the applied force or increase their effective moment arm. Increasing the moment arm is often easier and faster than months of conditioning! Figure 7.2 illustrates two positions where a therapist can provide resistance with a hand dynamometer to manually test the isometric strength of the elbow extensors. By positioning their arm more distal (position 2), the therapist increases the moment arm and decreases the force they must create to balance the torque created by the patient and gravity ($\mathbf{T}_p$).

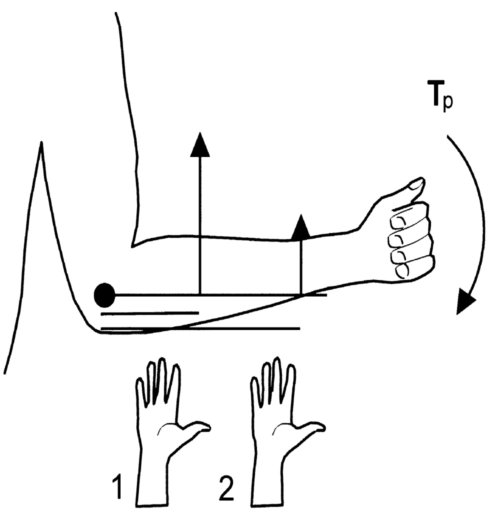

Figure 7.2. Increasing the moment arm for the therapist's (position 2) manual resistance makes it easier to perform a manual muscle test that balances the extensor torque created by the patient ($\mathbf{T}_p$).

Activity: Torque and Levers

Take a desk ruler (≈12-inch) and balance it on a sturdy small cylinder like a highlighter. Place a dime at the 11-inch position and note the behavior of the ruler. Tap the 1-inch position on the ruler with your index finger and note the motion of the dime. Which torque was larger: the torque created by the dime or your finger? Why? Tap the ruler with the same effort on different positions on the ruler with the dime at 11 inches and note the motion of the dime. Modify the position (axis of rotation) of the highlighter to maximize the moment arm for the dime and note how much force your finger must exert to balance the lever in a horizontal position. How much motion in the dime can you create if you tap the ruler? In these activities you have built a simple machine called a *lever*. A lever is a nearly rigid object rotated about an axis. Levers can be built to magnify speed or force. Most human body segment levers magnify speed because the moment arm for the effort is less than the moment arm for the resistance being moved. A biceps brachii must make a large force to make a torque larger than the torque created by a dumbbell, but a small amount of shortening of the muscle creates greater rotation and speed at the hand. Early biomechanical research was interested in using anatomical leverage principles for a theory of high-speed movements, but this turned out to be a dead end because of the discovery of sequential coordination of these movements (Roberts, 1991).

Let's look at another example of applying forces in an optimal direction to maximize torque output. A biomechanics student takes a break from her studies to bring a niece to the playground. Let's calculate the torque the student creates on the merry-go-round by the force $\mathbf{F}_1$ illustrated in Figure 7.3. Thirty pounds of force times the moment arm of 4 feet is equal to 120 lb·ft of torque. This torque can be considered positive because it acts counterclockwise. If on the second spin the student pushes with the same magnitude of force ($\mathbf{F}_2$) in a different direction, the torque and angular motion created would be smaller because of the smaller moment arm ($\mathbf{d}_B$). Use the conversion factor in Appendix B to see how many N·m are equal to 120 lb·ft of torque.

Good examples of torque measurements in exercise science are the joint torques measured by isokinetic dynamometers. The typical maximum isometric torques of several muscle groups for males are listed in Table 7.1. These torques should give you a good idea of some "ballpark" maximal values for many major joints. Peak torques from inverse dynamics in sporting movements can be larger than those seen in isokinetic testing because of antagonist activity in isokinetics testing, segment interaction in dynamic movements, the stretch-shortening cycle, and eccentric muscle actions. Most isokinetic norms are normalized to bodyweight (e.g., lb·ft/lb) and categorized by gender and age. Recall

TABLE 7.1

Typical Isometric Joint Torques Measured by Isokinetic Dynamometers

	Peak torques N·m	Peak torques lb·ft
Trunk extension	258	190
Trunk flexion	177	130
Knee extension	204	150
Knee flexion	109	80
Hip extension	150	204
Ankle plantar flexion	74	102
Elbow flexion	20	44.6
Wrist flexion	8	11
Wrist extension	4	5

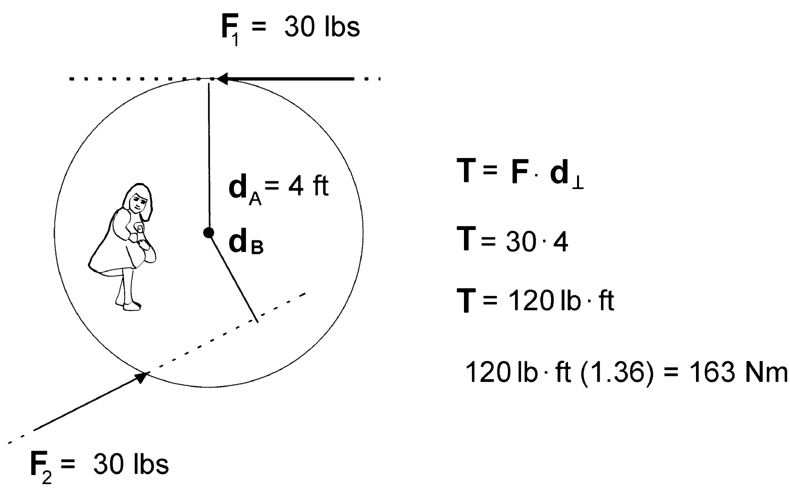

Figure 7.3. Calculating the torque created by a person pushing on a merry-go-round involves multiplying the force times its moment arm. This torque can be converted to other units of torque with conversion factors (Appendix B).

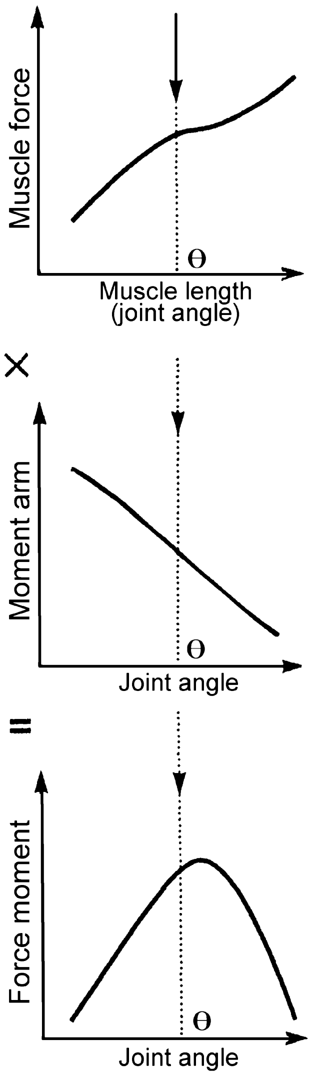

Figure 7.4. Joint torque–angle diagrams represent the strength curves of muscle groups. The shapes of joints vary based primarily upon the combined effect of changes in muscle length properties and muscle moment arms. Reprinted by permission from Zatsiorsky (1995).

that the shape of the torque-angle graphs from isokinetic testing reflects the integration of many muscle mechanical variables. The angle of the joints affects the torque that the muscle group is capable of producing because of variations in moment arm, muscle angle of pull, and the force–length relationship of the muscle. There are several shapes of torque-angle diagrams, but they most often look like an inverted "U" because of the combined effect of changes in muscle moment arm and force–length relationship (Figure 7.4).

Torque is a good variable to use for expressing muscular strength because it is not dependent on the point of application of force on the limb. The torque an isokinetic machine (**T**) measures will be the same for either of the two resistance pad locations illustrated in Figure 7.5 if the subject's effort is the same. Sliding the pad toward the subject's knee will decrease the moment arm for the force applied by the subject, increasing the force on the leg ($\mathbf{F}_2$) at that point to create the same torque. Using torque instead of force created by the subject allows for easier comparison of measurements between different dynamometers.

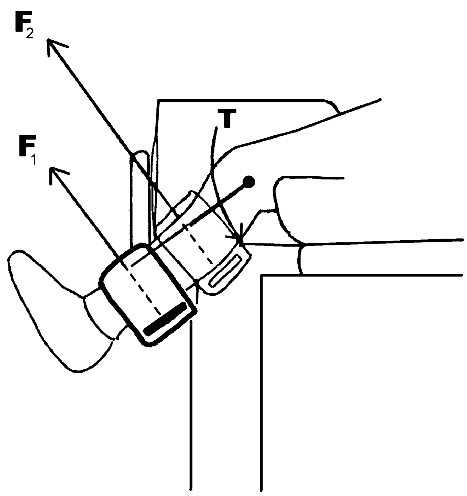

Figure 7.5. Isokinetic dynamometers usually measure torque because torque does not vary with variation in pad placement. Positioning the pad distally decreases the force the leg applies to the pad for a given torque because the moment arm for the leg is larger.

Application: Muscle-Balance and Strength Curves

Recall that testing with an isokinetic dynamometer documents the strength curves (joint torque–angle graphs) of muscle groups. Normative torques from isokinetic testing also provide valuable information on the ratio of strength between opposing muscle groups. Many dynamometers have computerized reports that list test data normalized to bodyweight and expressed as a ratio of the peak torque of opposing muscle groups. For example, peak torques created by the hip flexors tend to be 60 to 75% of peak hip extensor torques (Perrin, 1993). Another common strength ratio of interest is the ratio of the quadriceps to the hamstrings. This ratio depends on the speed and muscle action tested, but peak concentric hamstring torque is typically between 40 and 50% of peak concentric quadriceps torque (Perrin, 1993), which is close to the physiological cross-sectional area difference between these muscle groups. Greater emphasis has more recently been placed on more functional ratios (see Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998), like hamstring eccentric to quadriceps concentric strength (H_{ecc}:Q_{con}), because hamstrings are often injured ("pulled" in common parlance) when they slow the vigorous knee extension and hip flexion before foot strike in sprinting. In conditioning and rehabilitation, opposing muscle group strength ratios are often referred to as muscle balance. Isokinetic (see Perrin, 1993) and hand dynamometer (see Phillips, Lo, & Mastaglia, 2000) testing are the usual clinical measures of strength, while strength and conditioning professionals usually use one-repetition maxima (1RM) for various lifts. These forms of strength testing to evaluate muscle balance are believed to provide important sources of information on the training status, performance, and potential for injury of athletes. In rehabilitation and conditioning settings, isokinetic and other forms of strength testing are useful in monitoring progress during recovery. Athletes are cleared to return to practice when measurements return to some criterion/standard, a percentage of pre-injury levels, or a percentage of the uninvolved side of their body. It is important for kinesiology professionals to remember that the strength (torque capability) of a muscle group is strongly dependent on many factors: testing equipment, protocol, and body position, among others, affect the results of strength testing (Schlumberger *et al.*, 2006). If standards in testing are being used to qualify people for jobs or athletic participation, there needs to be clear evidence correlating the criterion test and standard with safe job performance.

SUMMING TORQUES

The state of an object's rotation depends on the balance of torques created by the forces acting on the object. Remember that summing or adding torques acting on an object must take into account the vector nature of torques. All the muscles of a muscle group sum together to create a joint torque in a particular direction. These muscle group torques must also be summed with torques from antagonist muscles, ligaments, and external forces to determine the net torque at a joint. Figure 7.6 illustrates the forces of the anterior deltoid and long head of the biceps in flexing the shoulder in the sagittal plane. If ccw torques are positive, the torques created by these muscles would be positive. The net torque of these two muscles is the sum of their individual torques, or 6.3 N·m ($60 \cdot 0.06 + 90 \cdot 0.03 = 6.3$ N·m). If the weight of this person's arm multiplied by its moment arm created a gravitational torque of –16 N·m, what is the net torque acting at the shoulder? Assuming there are no other shoulder flexors or exten-

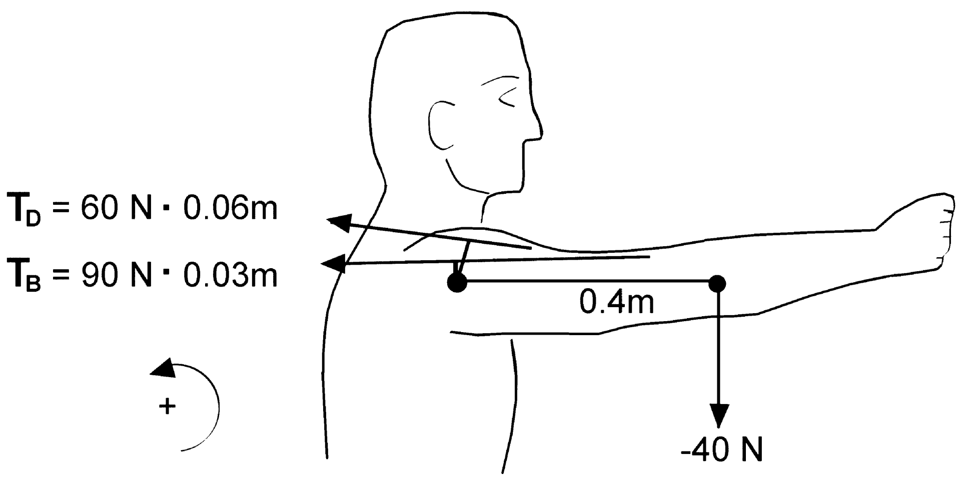

Figure 7.6. The shoulder flexion torques of anterior deltoid and long head of the biceps can be summed to obtain the resultant flexion torque acting to oppose the gravitational torque from the weight of the arm.

sors active to make forces, we can sum the gravitational torque (–16 N·m) and the net muscle torque (6.3 N·m) to find the resultant torque of –9.7 N·m. This means that there is a resultant turning effect acting at the shoulder that is an extension torque, where the shoulder flexors are acting eccentrically to lower the arm. Torques can be summed about any axis, but be sure to multiply the force by the moment arm and then assign the correct sign to represent the direction of rotation before they are summed.

Recall the isometric joint torques reported in Table 7.1. Peak joint torques during vigorous movement calculated from inverse dynamics are often larger than those measured on isokinetic dynamometers (Veloso & Abrantes, 2000). There are several reasons for this phenomenon, including transfer of energy from biarticular muscles, differences in muscle action, and coactivation. Coactivation of antagonist muscles is a good example of summing opposing torques. EMG research has shown that isokinetic joint torques underestimate net agonist muscle torque because of coactivation of antagonist muscles (Aagaard, Simonsen, Andersen, Magnusson, Bojsen-Moller, & Dyhre-Poulsen, 2000: Kellis & Baltzopoulos, 1997, 1998).

ANGULAR INERTIA (MOMENT OF INERTIA)

A *moment of force* or *torque* is the mechanical effect that creates rotation, but what is the resistance to angular motion? In linear kinetics we learned that mass was the mechanical measure of inertia. In angular kinetics, inertia is measured by the **moment of inertia**, a term pretty easy to remember because it uses the terms *inertia* and *moment* from moment of force. Like the mass (linear inertia), **moment of inertia** is the resistance to angular acceleration. While an object's mass is constant, the object has an infinite number of moments of inertia! This is because the object can be rotated about an infinite number of axes. We will see that rotating the human body is even more interesting because the links allow the configuration of the body to change along with the axes of rotation.

The symbol for the moment of inertia is I. Subscripts are often used to denote the axis of rotation associated with a moment of inertia. The smallest moment of inertia of an object in a particular plane of motion is about its center of gravity (I_0). Biomechanical studies also use moments of inertia about the proximal (I_P) and distal (I_D) ends of body segments. The formula for a rigid-body moment of inertia about an axis (A) is $I_A = \Sigma m\mathbf{r}^2$. To determine the moment of inertia of a ski in the transverse plane about an anatomically longitudinal axis (Figure 7.7), the ski is cut into eight small masses (m) of know radial distances (**r**) from the axis. The sum of the product of these masses and the squared radius is the moment of inertia of the ski about that axis. Note that the SI units of moment of inertia are $kg \cdot m^2$.

The formula for moment of inertia shows that an object's resistance to rotation depends more on distribution of mass ($\mathbf{r}^2$) than mass (m). This large increase in moment of inertia from changes in location of mass relative to the axis of rotation (because **r** is squared) is very important in human movement. Modifications in the mo-

Activity: Moment of Inertia

Take a long object like a baseball bat, tennis racket, or golf club and hold it in one hand. Slowly swing the object back and forth in a horizontal plane to eliminate gravitational torque from the plane of motion. Try to sense how difficult it is to initiate or reverse the object's rotation. You are trying to subjectively evaluate the moment of inertia of the object. Grab the object in several locations and note how the moment of inertia changes. Add mass to the object (e.g., put a small book in the racket cover) at several locations. Does the moment of inertia of the object seem to be more related to mass or the location of the mass?

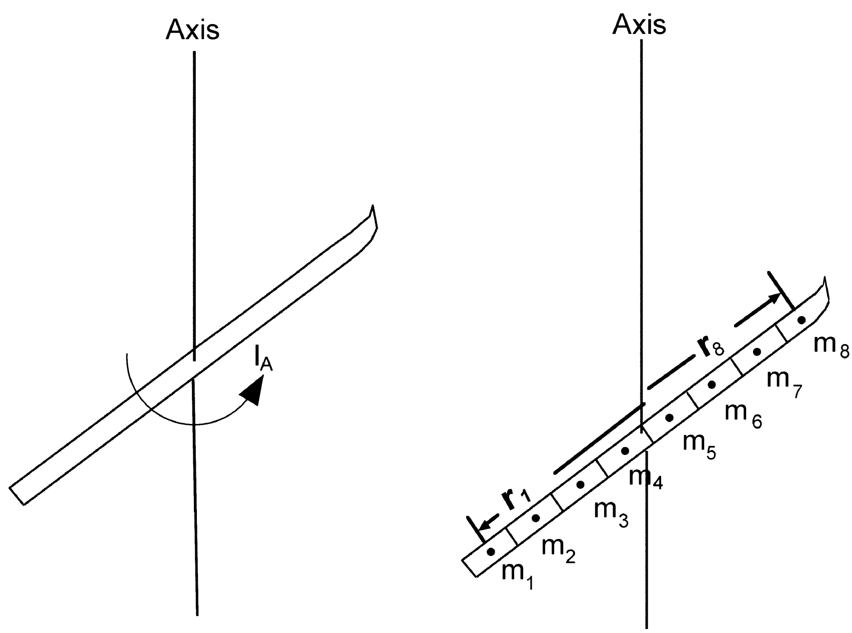

Figure 7.7. The moment of inertia of a ski about a specific axis can be calculated by summing the products of the masses of small elements (m) and the square of the distance from the axis (**r**).

ment of inertia of body segments can help or hinder movement, and the moment of inertia of implements or tools can dramatically affect their effectiveness.

Most all persons go through adolescence with some short-term clumsiness. Much of this phenomenon is related to motor control problems from large changes in limb moment of inertia. Imagine the balance and motor control problems from a major shift in leg moment of inertia if a young person grows two shoe sizes and 4 inches in a 3-month period. How much larger is the moment of inertia of this teenager's leg about the hip in the sagittal plane if this growth (dimension and mass) was about 8%? Would the increase in the moment of inertia of the leg be 8% or larger? Why?

When we want to rotate our bodies we can skillfully manipulate the moment of inertia by changing the configuration of our body segments relative to the axis of rotation. Bending the joints of the upper and lower extremities brings segmental masses close to an axis of rotation, dramatically decreasing the limb's moment of inertia. This bending allows for easier angular acceleration and motion. For example, the faster a person runs the greater the knee flexion in the swing limb, which makes the leg easy to rotate and to get into position for another footstrike. Diving and skilled gymnastic tumbling both rely on decreasing the moment of inertia of the human body to allow for more rotations, or increasing the length of the body to slow rotation down. Figure 7.8 shows the dramatic differences in the moment of inertia for a human body in the sagittal plane for different body segment configurations relative to the axis of rotation.

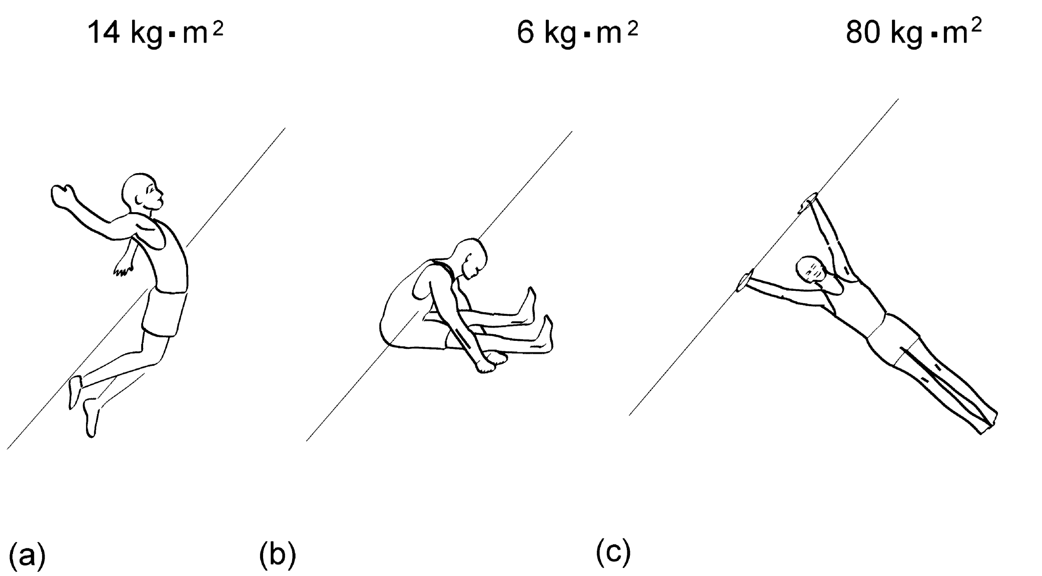

Figure 7.8. The movement of body segments relative to the axis of rotation makes for large variations in the moment of inertia of the body. Typical sagittal plane moments of inertia and axes of rotation for a typical athlete are illustrated for long jump (a,b) and high bar (c) body positions.

Variations in the moment of inertia of external objects or tools are also very important to performance. Imagine you are designing a new unicycle wheel. You design two prototypes with the same mass, but with different distributions of mass. Which wheel design (see Figure 7.9) do you think would help a cyclist maintain balance: wheel A or wheel B? Think about the movement of the wheel when a person balances on a unicycle. Does agility (low inertia) or consistency of rotation (high inertia) benefit the cyclist? If, on the other hand, you are developing an exercise bike that would provide slow and smooth changes in resistance, which wheel would you use? A heavy ski boot and ski dramatically affect the moments of inertia of your legs about the hip joint. Which joint axis do you think is most affected?

The moment of inertia of many sport implements (golf clubs and tennis rackets) is commonly called the "swing weight." A longer implement can have a similar swing weight to a shorter implement by keeping mass proximal and making sure the added length has low mass. It is important to realize that the three-dimensional nature of sports equipment means that there are moments of inertia about the three principal or dimensional axes of the equipment. Tennis players often add lead tape to their rackets so as to increase shot speed and racket stability. Tape is often added to the perimeter of the frame for stability (by increasing the polar moment of inertia) against off-center impacts in the lateral directions. Weight at the top of the frame would not affect this lateral stability, but would increase the moments of inertia for swinging the racket forward and upward. The large radius of this mass (from his grip to the tip of the racket), however, would make the racket more difficult to swing. Recent baseball/softball bat designs allow for variations in where bat mass is located, making for wide variation in the moment of inertia for a swing. It turns out that an individual

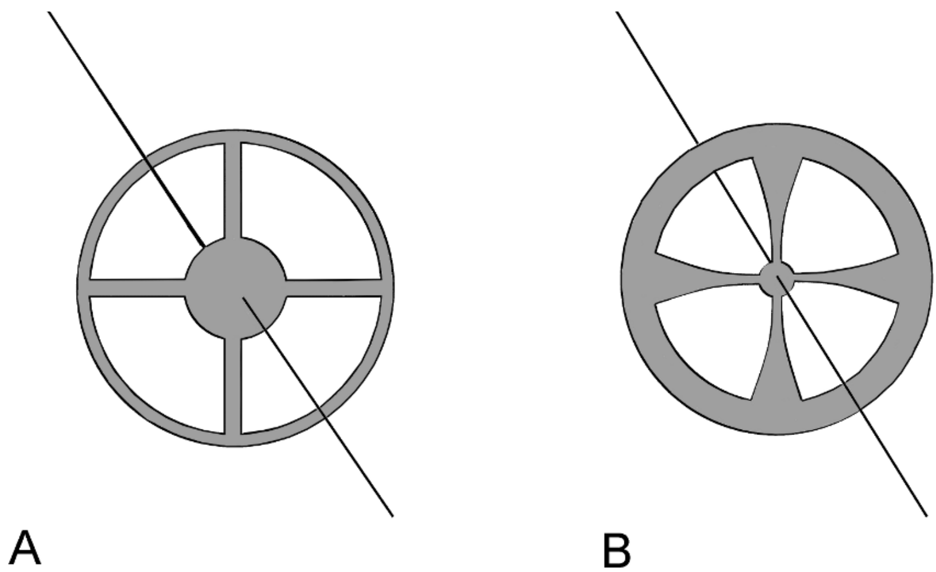

Figure 7.9. The distribution of mass most strongly affects moment of inertia, so wheel A with mass close to the axle would have much less resistance to rotation than wheel B. Wheel A would make it easier for a cyclist to make quick adjustments of the wheel back and forth to balance a unicycle.

batting style affects optimal bat mass (Bahill & Freitas, 1995) and moment of inertia (Watts & Bahill, 2000) for a particular batter.

You can now see that the principle of inertia can be extended to angular motion of biomechanical systems. This application of the concepts related to moment of inertia are a bit more complex than mass in linear kinetics. For example, a person putting on snowshoes will experience a dramatic increase (larger than the small mass of the shoes implies) in the moment of inertia of the leg about the hip in the sagittal plane because of the long radius for this extra mass. A tennis player adding lead tape to the head of their racket will more quickly modify the angular inertia of the racket than its linear inertia. Angular inertia is most strongly related to the distribution of mass, so an effective strategy to decrease this inertia is to bring segment masses close to the axis of rotation. Coaches can get players to "compact" their extremities or body to make it easier to initiate rotation.

NEWTON'S ANGULAR ANALOGUES

Newton's laws of motion also apply to angular motion, so each may be rephrased using angular variables. The angular analogue of Newton's third law says that for every torque there is an equal and opposite torque. The angular acceleration of an object is proportional to the resultant torque, is in the same direction, and is inversely proportional to the moment of inertia. This is the angular expression of Newton's second law. Likewise, Newton's first law demonstrates that objects tend to stay in their state of angular motion unless acted upon by an unbalanced torque. Biomechanists often use rigid body models of the human body and apply Newton's laws to calculate the net forces and torques acting on body segments.

This working backward from video measurements of acceleration (second derivatives) using both the linear and angular versions of Newton's second law is called **inverse dynamics**. Such analyses to understand the resultant forces and torques that create movement were first done using laborious hand calculations and graphing (Bressler & Frankel, 1950; Elftman, 1939), but they are now done with the assistance of powerful computers and mathematical computation programs. The resultant or net joint torques calculated by inverse dynamics do not account for co-contraction of muscle groups and represent the sum of many muscles, ligaments, joint contact, and other anatomical forces (Winter, 1990).

Despite the imperfect nature of these net torques (see Hatze, 2000; Winter 1990), inverse dynamics provides good estimates of the net motor control signals to create human movement (Winter & Eng, 1995), and can detect changes with fatigue (Apriantono *et al.*, 2006) or practice/learning (Schneider *et al.*, 1989; Yoshida, Cauraugh, & Chow, 2004). Figure 7.10 illus-

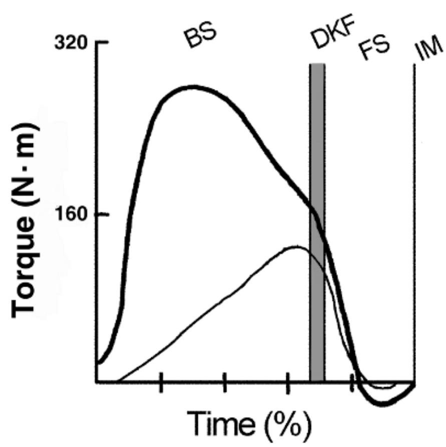

Figure 7.10. The net joint hip (thick line) and knee (thin line) joint torques in a soccer kick calculated from inverse dynamics. The backswing (BS), range of deepest knee flexion (DKF), forward swing (FS), and impact (IMP) are illustrated. Adapted with permission from Zernicke and Roberts (1976).

trates the net joint torques at the hip and knee in a soccer toe kick. These torques are similar to the torques recently reported in a three-dimensional study of soccer kicks (Nunome *et al.*, 2002). The kick is initiated by a large hip flexor torque that rapidly decreases before impact with the soccer ball. The knee extensor torque follows the hip flexor torque and also decreases to near zero at impact. This near-zero knee extensor torque could be expected because the foot would be near peak speed at impact, with the body protecting the knee from hyperextension. If the movement were a punt, there would usually be another rise and peak in hip flexor torque following the decline in knee torque (Putnam, 1983). It is pretty clear from this planar (2D) example of inverse dynamics that the hip flexor musculature may make a larger contribution to kicking than the knee extensors. It is not as easy to calculate or interpret 3D kinetics since a large joint torque might have a very small resistance arm and not make a large contribution to a desired motion, or a torque might be critical to positioning a segment for another torque to be able to accelerate the segment (Sprigings *et al.*, 1994; Bahamonde, 2000).

The resultant joint torques calculated in inverse dynamics are often multiplied by the joint angular velocity to derive net *joint powers*. When the product of a net joint torque and joint angular velocity are positive (in the same direction), the muscle action is hypothesized to be primarily concentric and generating positive work. Negative joint powers are hypothesized to represent eccentric actions of muscle groups slowing down an adjacent segment. These joint powers can be integrated with respect to time to calculate the net work done at joints. Other studies first calculated mechanical energies (kinetic and potential energies), and summed them to estimate work and eventually calculate power. Unfortunately, these summing of mechanical energy analyses do not agree well with direct calculation of joint power from torques because of difficulties in modeling the transfer of mechanical energies between external forces and body segments (Aleshinsky, 1986a,b; Wells, 1988) and coactivation of muscles (Neptune & van den Bogert, 1998).

EQUILIBRIUM

An important concept that grows out of Newton's first and second laws is *equilibrium*. **Mechanical equilibrium** occurs when the forces and torques acting on an object sum to zero. Newton's second law accounts for both linear and angular conditions of **static equilibrium** ($\Sigma \mathbf{F} = 0$, $\Sigma \mathbf{T} = 0$), where an object is motionless or moving at a constant velocity. **Dynamic equilibrium** is used to refer to the kinetics of accelerated bodies using Newton's second law ($\Sigma \mathbf{F} = m \cdot \mathbf{a}$, $\Sigma \mathbf{T} = I \cdot \boldsymbol{\alpha}$). In a sense, dynamic equilibrium fits the definition of equilibrium if you rearrange the equations (i.e., $\Sigma \mathbf{F} - m \cdot \mathbf{a} = 0$). The $m \cdot \mathbf{a}$ term in the previous equation is often referred to as the **inertial force**. This inertial force is not a real force and can cause confusion in understanding the kinetics of motion.

This text will focus on static equilibrium examples because of their simplicity and because summation of forces and torques is identical to dynamic equilibrium. Biomechanics studies often use static or quasi-static analyses (and thus employ static equilibrium equations and avoid difficulties in calculating accurate accelerations) in order to study slow movements with small accelerations. The occupational lifting standards set by the National Institute for Occupational Safety and Health (NIOSH) were based in large part on static biomechanical models and analyses of lifting. Static equilibrium will also be used in the following section to calculate the center of gravity of the human body.

Equilibrium and angular kinetics are the mechanical tools most often used in the study of balance. We will see in the next two sections that the center of gravity of the human body can be calculated by summing moments in a static equilibrium form, and these kinds of data are useful in examining the state of mobility and stability of the body. This control of stability and ability to move is commonly called *balance*. What mechanics tells us about balance is summarized in the Principle of Balance.

CENTER OF GRAVITY

A natural application of angular kinetics and anthropometrics is the determination of the center of gravity of the body. The **center of gravity** is the location in space where the weight (gravitational force) of an object can be considered to act. The center of small rigid objects (pencil, pen, bat) can be easily found by trying to balance the object on your finger. The point where the object balances is in fact the center of gravity, which is the theoretical point in space where you could replace the weight of the whole object with one downward force. There is no requirement for this location to be in a high-mass area, or even within or on the object itself. Think about where the center of gravity of a basketball would be.

The center of gravity of the human body can move around, because joints allow the masses of body segments to move. In the anatomical position, the typical location of a body's center of gravity in the sagittal plane is at a point equivalent to 57

Interdisciplinary Issue: The Spine and Low-Back Pain

One of the most common complaints is low-back pain. The medical literature would say that the etiology (origin) of these problems is most often idiopatic (of unknown origin). The diagnostic accuracy of advanced imaging techniques like magnetic resonance imaging (MRI) for identifying spinal abnormalities (e.g., disk herniation) that correlate with function and symptoms of low-back pain is poor (Beattie & Meyers, 1998). The causes of low-back pain are complicated and elusive. Biomechanics can contribute clues that may help solve this mystery. Mechanically, the spine is like a stack of blocks separated by small cushions (McGill, 2001). Stability of the spine is primarily a function of the ligaments and muscles, which act like the guy wires that stabilize a tower or the mast of a boat. These muscles are short and long and often must simultaneously stabilize and move the spine. Total spine motion is a summation of the small motions at each intervertebral level (Ashton-Miller & Schultz, 1988). Biomechanical studies of animal and cadaver spines usually examine loading and rotation between two spinal levels in what is called a motion segment. Individuals even exhibit different strategies for rotation of motion segments in simple trunk flexion movements (Gatton & Pearcy, 1999; Nussbaum & Chaffin, 1997), so that neuromuscular control likely plays an important role in injury and rehabilitation (Ebenbichler, Oddsson, Kollmitzer, & Erim, 2001). Occasionally a subject is unfortunate and gets injured in a biomechanical study. Cholewicki and McGill (1992) reported x-ray measurements of the "buckling" of a single spinal segment that occurred during a heavy deadlift. Biomechanics research using computer models and EMG are trying to understand how muscles and loads affect the spine, and the nature of this motion segment buckling (Preuss & Fung, 2005). This information must be combined with occupational, epidemiological, neurologic, and rehabilitative research to understand the development and treatment of low-back pain.

and 55% of the height for males and females, respectively (Hay & Reid, 1982). Can you name some structural and weight distribution differences between the genders that account for this general difference? Knowing where the force of gravity acts in various postures of the human body allows biomechanists to study the kinetics and stability of these body positions.

There are two main methods used to calculate the center of gravity of the human body, and both methods employ the equations of static equilibrium. One lab method, which requires a person to hold a certain body position, is called the **reaction change** or *reaction board* method. The other method used in research is called the *segmental method*. The **segmental method** uses anthropometric data and mathematically breaks up the body into segments to calculate the center of gravity.

The reaction board method requires a rigid board with special feet and a scale (2D) or scales (3D) to measure the ground reaction force under the feet of the board. The "feet" of a reaction board are knife-like edges or small points similar to the point of a nail. A 2D reaction board, a free-body diagram, and static equilibrium equations to calculate the center of gravity in the sagittal plane are illustrated in Figure 7.11. Note that the weight force of the board itself is not included. This force can be easily added to the computation, but an efficient biomechanist zeros the scale with the board in place to exclude extra terms from the calculations. The subject in Figure 7.11 weighs 185 pounds, the distance between the edges is 7 feet, and the scale reading is 72.7 pounds. With only three forces acting on this system and everything known but the location of the center of gravity, it is rather simple to apply the static equilibrium equation for torque and solve for the center of gravity ($\mathbf{d}_\perp$). Note how the sign of the torque created by the subject's body is negative according to convention, so a negative $\mathbf{d}_\perp$ (to the left) of the reaction board edge fits this standard, and horizontal displacement to the left is negative. In this case, the

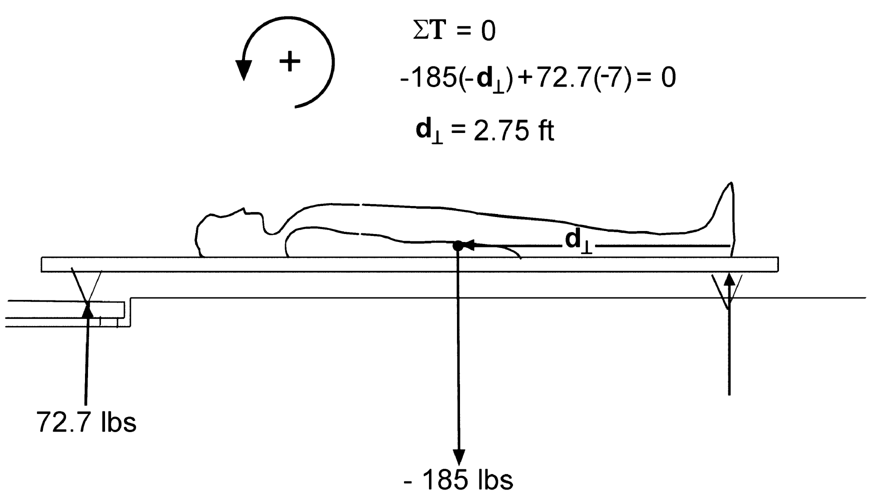

Figure 7.11. Application of static equilibrium and a reaction board to calculate whole body center of gravity. Summing torques about the reaction board edge at the feet and solving for the moment arm ($\mathbf{d}_\perp$) for gravity locates the center of gravity.

subject's center of gravity is 2.75 feet up from the edge of the reaction board. If the subject were 5.8 feet in height, his center of gravity in this position would be 47% of his or her height.

In the segmental method, the body is mathematically broken up into segments. The weight of each segment is then estimated from mean anthropometric data. For example, according to Plagenhoef, Evans, & Abdelnour (1983), the weight of the forearm and hand is 2.52 and 2.07% for a man and a woman, respectively. Mean anthropometric data are also used to locate the segmental centers of gravity (percentages of segment length) from either the proximal or distal point of the segment. Figure 7.12 depicts calculation of the center of gravity of a high jumper clearing the bar using a three-segment biomechanical model. This simple model (head+arms+trunk, thighs, legs+feet) illustrates the segmental method of calculating the center of gravity of a linked biomechanical system. Points on the feet, knee, hip, and shoulder are located and combined with anthropometric data to

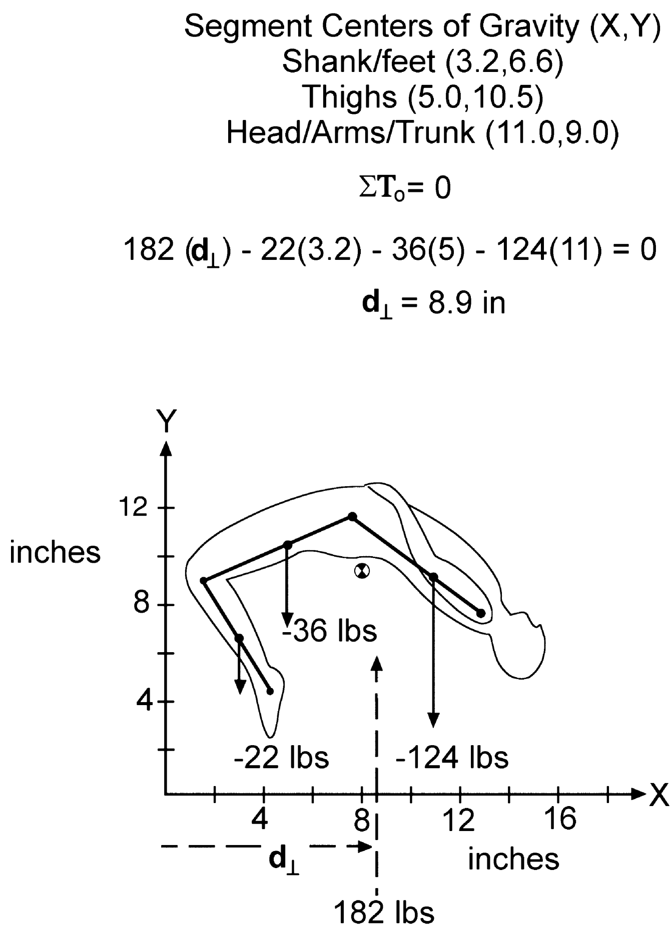

Figure 7.12. Calculating the horizontal position of the whole body center of gravity of a high jumper using the segmental method and a three-segment model of the body. Most sport biomechanical models use more segments, but the principle for calculating the center of gravity is the same.

calculate the positions of the centers of gravity of the various segments of the model. Most biomechanical studies use rigid-body models with more segments to more accurately calculate the whole-body center of gravity and other biomechanical variables. If a biomechanist were studying a high jump with high-speed video (120 Hz), a center of gravity calculation much like this would be made for every image (video snapshot) of the movement.

The segmental method is also based on static equilibrium. The size and location (moment arm) of the segmental forces are used to calculate and sum the torques created by each segment. If this body posture in the snapshot were to be balanced by a torque in the opposite direction (product of the whole bodyweight acting in the opposite direction times the center of gravity location: $182 \cdot \mathbf{d}_{\perp}$), the total torque would be zero. By applying the law of statics and summing torques about the origin of our frame of reference, we calculate that the person's bodyweight acts 8.9 inches from the origin. These distances are small because the numbers represent measurements on an image. In a 2D biomechanical analysis, the image-size measurements are scaled to real-life size by careful set-up procedures and imaging a control object of known dimensions.

Finding the height of the center of gravity is identical, except that the y coordinates of the segmental centers of gravity are used as the moment arms. Students can then imagine the segment weight forces acting to the left, and the height of the center of gravity is the y coordinate that, multiplied by the whole bodyweight acting to the right, would cancel out the segmental torques toward the left. Based on the subject's body position and the weights of the three segments, guess the height in centimeters of the center of gravity. Did the center of gravity pass over the bar? Finish the calculation in Figure 7.12 to check your guess. The segmental method can be applied using any number of segments, and in all three dimensions during 3D kinematic analysis. There are errors associated with the segmental method, and more complex calculations are done in situations where errors (e.g., trunk flexion/extension, abdominal obesity) are likely (Kingma, Toussaint, Commissaris, Hoozemans, & Ober, 1995).

Activity: Center of Gravity and Moment of Inertia

Take a 12-inch ruler and balance it on your finger to locate the center of gravity. Lightly pinch the ruler between your index finger and thumb at the 1-inch point, and allow the ruler to hang vertically below your hand. Swing the ruler in a vertical plane and sense the resistance of the ruler to rotation. Tape a quarter to various positions on the ruler and note how the center of gravity shifts and how the resistance to rotation changes. Which changes more: center of gravity or moment of inertia? Why? What factors make it difficult to sense changes in ruler moment of inertia?

PRINCIPLE OF BALANCE

We have seen than angular kinetics provides mathematical tools for understanding rotation, center of gravity, and rotational equilibrium. The movement concept of balance is closely related to these angular kinetic variables. **Balance** is a person's ability to control their body position relative to some base of support (Figure 7.13). This ability is needed in both static equilibrium conditions (e.g., handstand on a balance beam) and during dynamic movement (e.g., shifting the center of gravity from the

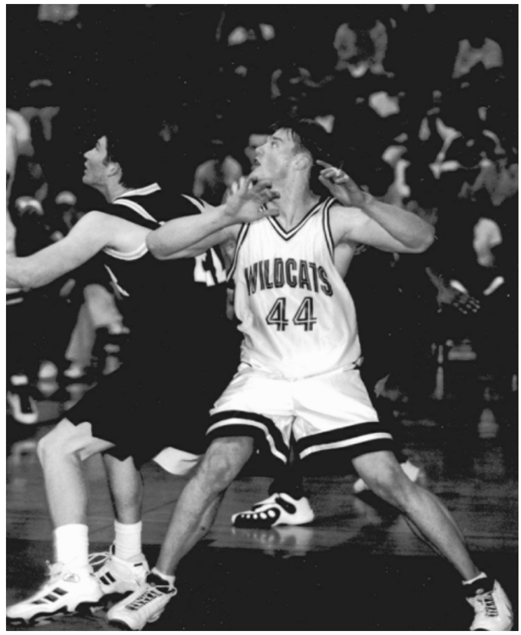

Figure 7.13. Balance is the degree of control a person has over their body. Balance is expressed in static (track start) and dynamic conditions (basketball player boxing out an opponent). Track image used with permission from Getty Images.

rear foot to the forward foot). Balance can be enhanced by improving body segment positioning or posture. These adjustments should be based on mechanical principles. There are also many sensory organs and cognitive processes involved in the control of movement (balance), but this section focuses on the mechanical or technique factors affecting balance and outlines application of the Principle of Balance.

Before we apply this principle to several human movements, it is important to examine the mechanical paradox of stability and mobility. It turns out that optimal posture depends on the right mix of stability and mobility for the movement of interest. This is not always an easy task, because stability and mobility are inversely related. Highly stable postures allow a person to resist changes in position, while the initiation of movement (mobility) is facilitated by the adoption of a less stable posture. The skilled mover learns to control the position of their body for the right mix of stability and mobility for a task.

The biomechanical factors that can be changed to modify stability/mobility are the base of support, and the position and motion of the center of gravity relative to the base of support. The base of support is the two-dimensional area formed by the supporting segments or areas of the body (Figure 7.14). A large base of support provides greater stability because there is greater area over which to keep the bodyweight. Much of the difficulty in many gymnastic balancing skills (e.g., handstand or scale) comes from the small base of support on which to center bodyweight.

The posture of the body in stance or during motion determines the position of the center of gravity relative to the base of support. Since gravity is the major external force our body moves against, the horizon-

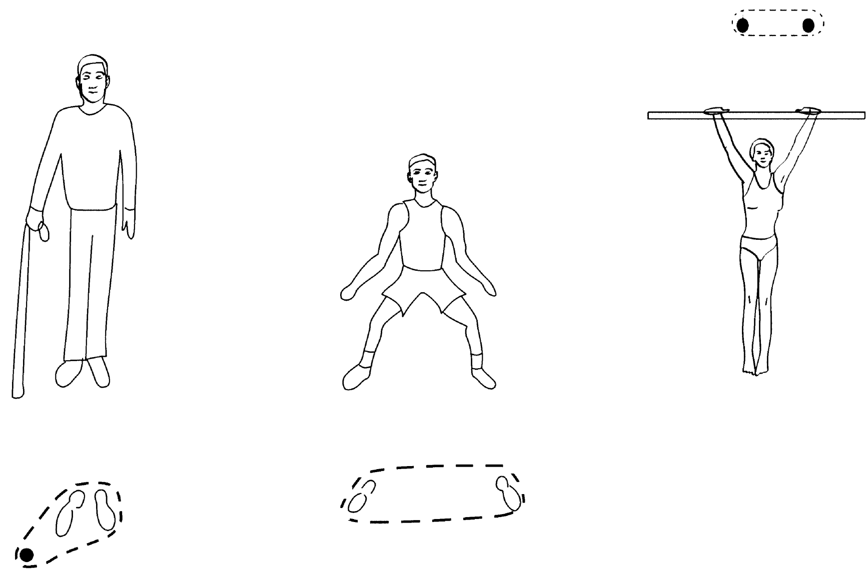

Figure 7.14. The base of support is the two-dimensional area within all supporting or suspending points of the biomechanical system.

tal and vertical positions of the center of gravity relative to the base of support are crucial in determining the stability/mobility of that posture. The horizontal distance from the edge of the base of support to the center of gravity (line of action of gravity) determines how far the weight must be shifted to destabilize a person (Figure 7.15a). If the line of gravity falls outside the base of support, the gravitational torque tends to tip the body over the edge of the base of support. The vertical distance or height of the center of gravity affects the geometric stability of the body. When the position of the center of gravity is higher, it is easier to move beyond the base of support than in postures with a lower center of gravity. Positioning the line of gravity outside the base of support can facilitate the rotation of the body by the force of gravity (Figure 7.15b).

Biomechanical studies of balance often document the motion of the two important forces of interest, body weight and the reaction force under the base of support. Video measurements using the segmental method measure the motion of the center of gravity over the base of support. Imagine where the center of gravity would be and how it would move in the base of supports illustrated in Figure 7.14. Force platforms allow the measurement of the misnomer **center of pressure**, the location of the resultant reaction force relative to the base of support. In quiet standing, the center of gravity sways around near the center of the base of support, while the center of pressure moves even faster to push the weight force back to the center of the base of support. The total movement and velocities of these two variables are potent measures of a person's balance.

Recall that the inertia (mass and moment of inertia), and other external forces like friction between the base and supporting surface all affect the equilibrium of an object. There are also biomechanical factors (muscle mechanics, muscle moment arms,

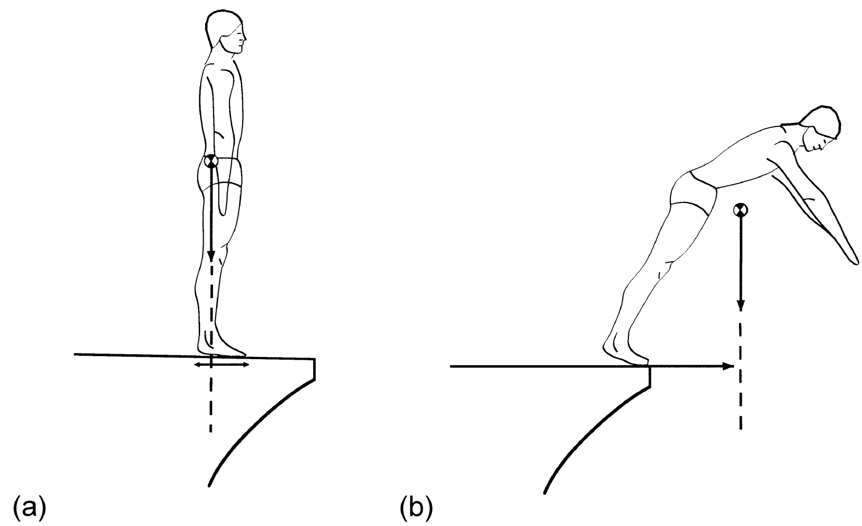

Figure 7.15. The position of the line of gravity relative to the limits of the base of support determines how far the weight must be shifted for gravity to tend to topple the body (a) or the size of the gravitational torque helps create desired rotation (b).

angles of pull, and so on) that affect the forces and torques a person can create to resist forces that would tend to disrupt their balance. The general base of support and body posture technique guidelines in many sports and exercises must be based on integration of the biological and mechanical bases of movement. For example, many sports use the "shoulder width apart" cue for the width of stances because this base of support is a good compromise between stability and mobility. Wider bases of support would increase potential stability but put the limbs in a poor position to create torques and expend energy, creating opposing friction forces to maintain the base of support.

The Principle of Balance is based on the mechanical tradeoff between stability and mobility. The Principle of Balance is similar to the Coordination Continuum because the support technique can be envisioned as a continuum between high stability and high mobility. The most appropriate technique for controlling your body depends on where the goal of the movement falls on the stability–mobility continuum. Coaches, therapists, and teachers can easily improve the ease of maintaining stability or initiating movement (mobility) in many movements by modifying the base of support and the positions of the segments of the body. It is important to note that good mechanical posture is not always required for good balance. High levels of skill and muscular properties allow some people to have excellent balance in adverse situations. A skater gliding on one skate and a basketball player caroming off defenders and still making a lay-up are examples of good balance in less than ideal conditions.

Imagine that a physical therapist is helping a patient recover from hip joint replacement surgery. The patient has regained enough strength to stand for short lengths of time, but must overcome some discomfort and instability when transitioning to walking. The patient can walk safely between parallel bars in the clinic, so the therapist has the patient use a cane. This effectively increases the base of support, because the therapist thinks increasing stability (and safety) is more important. If we combine angular kinetics with the Principle of Balance, it is possible to determine on what side of the body the cane should be held. If the cane were held on the same (affected) side, the base of support would be larger, but there would be little reduction in the pain of the hip implant because the gravitational torque of the upper body about the stance hip would not be reduced. If the patient held the cane in the hand on the opposite (unaffected) side, the base of support would also be larger, and the arm could now support the weight of the upper body, which would reduce the need for hip abductor activity by the recovering hip. Diagram the increase in area of the base of support from a single-leg stance in walking to a single-leg stance with a cane in each hand. Estimate the percentage increase in base of support area using the cane in each hand.

Classic examples of postures that would maximize mobility are the starting positions during a (track or swimming) race where the direction of motion is known. The track athlete in Figure 7.16 has elongated his stance in the direction of his start, and in the "set" position moves his center of gravity near the edge of his base of support. The blocks are not extended too far backwards because this interacts with the athlete's ability to shift weight forward and generate forces against the ground. For a summary of the research on the effect of various start postures on sprint time, see Hay (1993). Hay also provides a good summary of early research on basic footwork and movement technique factors in many sports.

In many sports, athletes must take on defensive roles that require quick movement in many directions. The Principle of Balance suggests that postures that foster mobility over stability have smaller bases of support, with the center of gravity of the

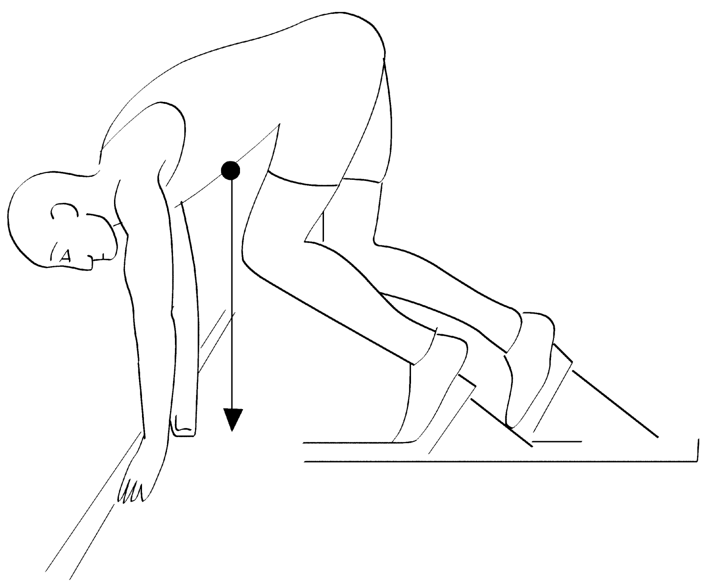

Figure 7.16. The starting position of a sprinter in the blocks shifts the line of gravity toward the front of the stance and the intended direction of motion. This stance favors mobility forward over stability.

body not too close to the base of support. When athletes have to be ready to move in all directions, most coaches recommend a slightly staggered (one foot slightly forward) stance with feet about shoulder width apart. Compare the stance and posture of the volleyball and basketball players in Figure 7.17. Compare the size of the base of support and estimate the location of the center of gravity in both body positions. What posture differences are apparent, and are these related to the predominant motion required in that sport? Bases of support need only be enlarged in directions where stability is needed or the direction of motion is known.

There are movement exceptions to strict application of the Principle of Balance because of high skill levels or the interaction of other biomechanical factors. In well-learned skills like walking, balance is easily maintained without conscious attention over a very narrow base of support. Gymnasts can maintain balance on very small bases of support as the result of considerable skill and training. A platform div-

Interdisciplinary Issue: Gender Differences

It is generally considered that the lower center of gravity in women gives them better balance than men. What is the biomechanical significance of the structural and physiological differences between men and women? While there is substantial research on the physiological differences between the genders, there is less comparative research on the biomechanical differences. Motor control and ergonomic studies have observed significant differences in joint angles during reaching (Thomas, Corcos, & Hasan, 1998) and lifting (Lindbeck & Kjellberg, 2000). Greater interest in gender differences seems to focus on issues related to risk of injury, for example, to like the anterior collateral ligament (ACL) (Charlton, St. John, Ciccotti, Harrison, & Schweitzer, 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001).

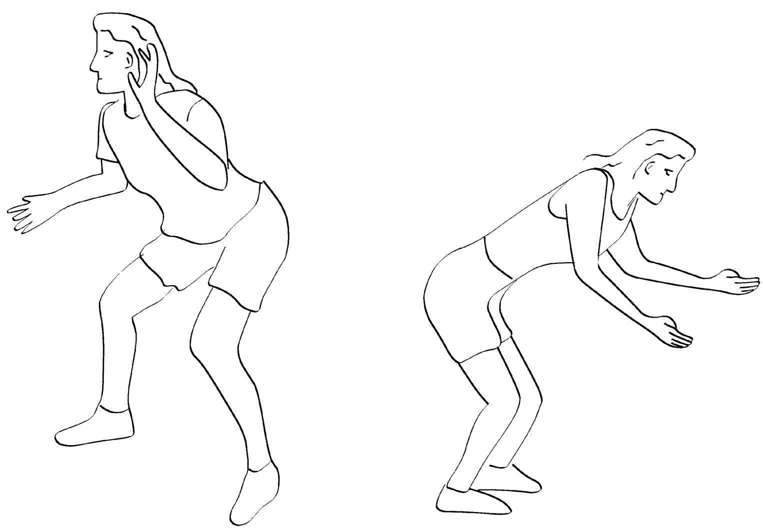

Figure 7.17. Comparison of the ready positions of a basketball player and a volleyball player. How are the mechanical features of their stance adapted to the movement they are preparing for?

Application: Inverse Dynamics of Walking

The ground reaction forces measured by force platforms in walking are used in clinical biomechanics labs to calculate net forces and torques in joints (inverse dynamics). For the sagittal and frontal planes illustrated (Figure 7.18), can you see how the typical ground reaction force creates a knee flexor and adductor torques in stance? Can you draw the moment arms relative to the knee joint axis for these forces? The stance limb activates muscles to create a net knee extensor torque to support body weight in the sagittal plane (A), and a knee abductor torque to stabilize the knee in the frontal plane (B).

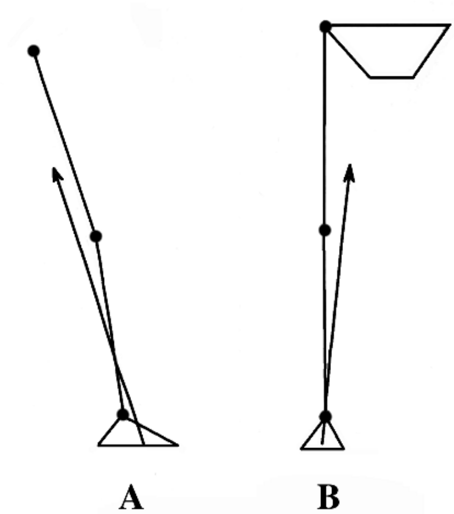

Figure 7.18. Typical ground reaction force vectors in the stance phase of walking in the sagittal plane (A) and frontal plane (B). What torques do these forces make about the knee joint axes?

er doing a handstand prior to a dive keeps their base of support smaller than one shoulder width because extra side-to-side stability is not needed and the greater shoulder muscle activity that would be required if the arms were not directly underneath the body. Another example might be the jump shot in basketball. Many coaches encourage shooters to "square up" or face the basket with the body when shooting. Ironically, the stance most basketball players spontaneously adopt is staggered, with the shooting side foot slightly forward. This added base of support in the forward–backward direction allows the player to transition from pre-shot motion to the primarily vertical motion of the jump. It has also been hypothesized that this stagger in the stance and trunk (not squaring up) helps the player keep the shooting arm aligned with the eyes and basket, facilitating side-to-side accuracy (Knudson, 1993).

Balance is a key component of most motor skills. While there are many factors that affect the ability to control body mobility and stability, biomechanics focuses on the base of support and position of the center of gravity. Mechanically, stability and mobility are inversely related. Coaches can apply the Principle of Balance to select the base of support and postures that will provide just the right mix of stability/mobility for a particular movement. Angular kinetics is the ideal quantitative tool for calculating center of gravity, and for examining the torques created by gravity that the neuromuscular system must balance.

SUMMARY

The key mechanical variable in understanding the causes of rotary motion is the moment of force or torque. The size of the torque that would rotate an object is equal to the force times its moment arm. The moment of inertia is a variable expressing the angular inertia of an object about a specific axis of rotation. The moment of inertia most strongly depends on the distribution of mass relative to the axis of rotation of interest. When all the torques acting on an object sum to zero, the object is said to be in static equilibrium. The equations of static equilibrium are often used to calculate the center of gravity of objects. Biomechanics most often uses the reaction change and segmental methods to calculate the center of gravity of the human body. Balance is the ability of a person to control their body position relative to some base of support. The Balance Principle deals with the mechanical factors that affect balance, and the tradeoff between stability and mobility in various body postures.

REVIEW QUESTIONS

1. What are the two most important parameters that determine the size of a torque or moment of force?

2. What is the inertial resistance to angular acceleration object about an axis, and what factors affect its size?

3. Give examples of how the human body can position itself to increase or decrease its inertial resistance to rotation.

4. Calculate the shoulder flexion torque required to hold an 80-lb barbell just above your chest in a bench press. The horizontal distance from your shoulder axis to the barbell is 0.9 feet.

5. Restate Newton's three laws of motion in angular kinetic terms.

6. Explain how static equilibrium can be used to calculate the center of gravity of the human body.

7. Draw or trace a few freeze-frame images of the human body in several positions from sport or other human movements. Estimate the location of the center of gravity.

8. A mischievous little brother runs ahead of his sister and through a revolving door at a hotel. The little brother pushes in the opposite direction of his sister trying to exit. If the brother pushes with a maximum horizontal force of 40 pounds acting at a right angle and 1.5 feet from the axis of the revolving door, how much force will the sister need to create acting at 2.0 feet from the axis of rotation to spoil his fun?

9. What mechanical factors can be used to maximize stability? What does this do to a person's mobility?

10. What movement factors can a kinesiology professional qualitatively judge that show a person's balance in dynamic movements?

11. Say the force $\mathbf{F}_2$ applied by the student in Figure 7.3 acted 55º in from the tangent to the merry-go-round. Calculate the torque created by the student.

12. Draw a free-body diagram of a person standing on a reaction board (hint: the system is the body plus the board). Estimate the length of the board and the horizontal distance to the person's center of gravity. Calculate the reaction force on the board if you were the person on it.

13. If the rotary component of a brachialis force is 70 N and the muscle attaches 0.4 m from the axis of rotation, what is the flexor torque created by the muscle? What other information do you need in order to calculate the resultant force created by the brachialis?

KEY TERMS

Balance Principle
center of gravity
inertial force
moment arm
moment or moment of force
moment of inertia
reaction change
segmental method
static equilibrium
torque

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WEB LINKS

Torque tutorial—part of the physics tutorials at University of Guelph.
http://eta.physics.uoguelph.ca/tutorials/torque/Q.torque.intro.html

Support moment—torques in leg joints in walking are examined in this teach-in exercise from the Clinical Gait Analysis website.
http://guardian.curtin.edu.au:16080/cga/teach-in/support/

Center of mass and center of pressure from the Clinical Gait Analysis website.
http://guardian.curtin.edu.au:16080/cga/teach-in/grv/