CHAPTER 6

Linear Kinetics

In the previous chapter we learned that kinematics or descriptions of motion could be used to provide information for improving human movement. This chapter will summarize the important laws of kinetics that show how forces overcome inertia and how other forces create human motion. Studying the causes of linear motion is the branch of mechanics known as **linear kinetics**. Identifying the causes of motion may be the most useful kind of mechanical information for determining what potential changes could be used to improve human movement. The biomechanical principles that will be discussed in this chapter are **Inertia**, **Force–Time**, and **Segmental Interaction**.

LAWS OF KINETICS

Linear kinetics provides precise ways to document the causes of the linear motion of all objects. The specific laws and mechanical variables a biomechanist will choose to use in analyzing the causes of linear motion often depends on the nature of the movement. When instantaneous effects are of interest, Newton's Laws of Motion are most relevant. When studying movements over intervals of time is of interest, the Impulse–Momentum Relationship is usually used. The third approach to studying the causes of motion focuses on the distance covered in the movement and uses the Work–Energy Relationship. This chapter summarizes these concepts in the context of human movement. Most importantly, we will see how these laws can be applied to human motion in the biomechanical principles of Force–Motion, Force–Time, and Coordination Continuum Principles.

NEWTON'S LAWS OF MOTION

Arguably, some of the most important discoveries of mechanics are the three laws of motion developed by the Englishman, Sir Isaac Newton. Newton is famous for many influential scientific discoveries, including developments in calculus, the Law of Universal Gravitation, and the Laws of Motion. The importance of his laws cannot be overemphasized in our context, for they are the keys to understanding how human movement occurs. The publication of these laws in his 1686 book *De Philosophiae Naturalis Principia Mathematica* marked one of the rare occasions of scientific breakthrough. Thousands of years of dominance of the incorrect mechanical views of the Greek philosopher Aristotle were overturned forever.

Newton's First Law and First Impressions

Newton's first law is called the **Law of Inertia** because it outlines a key property of matter related to motion. Newton stated that all objects have the inherent property to resist a change in their state of motion.

His first law is usually stated something like this: objects tend to stay at rest or in uniform motion unless acted upon by an unbalanced force. A player sitting and "warming the bench" has just as much inertia as a teammate of equal mass running at a constant velocity on the court. It is vitally important that kinesiology professionals recognize the effect inertia and Newton's first law have on movement technique. The linear measure of inertia (Figure 6.1) is mass and has units of kg in the SI system and slugs in the English system. This section is an initial introduction to the fascinating world of kinetics, and will demonstrate how our first impressions of how things work from casual observation are often incorrect.

Understanding kinetics, like Newton's first law, is both simple and difficult: simple because there are only a few physical laws that govern all human movement, and these laws can be easily understood and demonstrated using simple algebra, with only a few variables. The study of biomechanics can be difficult, however, because the laws of mechanics are often counterintuitive for most people. This is because the observations of everyday life often lead to incorrect assumptions about the nature of the world and motion. Many children and adults have incorrect notions about inertia, and this view of the true nature of motion has its own "cognitive inertia," which is hard to displace. The natural state of objects in motion is to slow down, right? Wrong! The natural state of motion is to continue whatever it is doing! Newton's first law shows that objects tend to resist changes in motion, and that things only seem to naturally slow down because forces like friction and air or water resistance that tend to slow an object's motion. Most objects around us appear at rest, so isn't there something natural about being apparently motionless? The answer is yes, if the object is initially at rest! The same object in linear motion has the same natural or inertial tendency to keep moving. In short, the mass (and consequently its linear inertia) of an object is the same whether it is motionless or moving.

We also live in a world where most people take atmospheric pressure for granted. They are aware that high winds can create very large forces, but would not believe that in still air there can be hundreds of pounds of force on both sides of a house window (or a person) due to the pressure of the atmosphere all around us. The true nature of mechanics in our world often becomes more apparent under extreme conditions. The pressure of the sea of air we live in becomes real when a home explodes or implodes from a passing tornado, or a

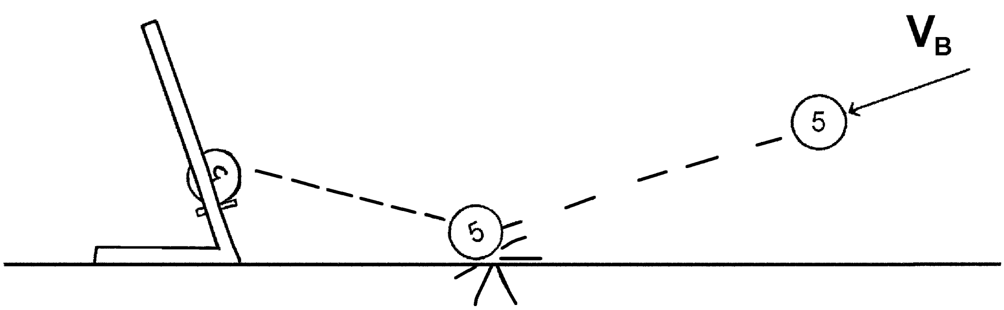


Figure 6.1. All objects have the inherent property of inertia, the resistance to a change in the state of motion. The measure of linear motion inertia is mass. A medicine ball has the same resistance to acceleration (5 kg of mass) in all conditions of motion, assuming it does not travel near the speed of light.

fast-moving weather system brings a change in pressure that makes a person's injured knee ache. People interested in scuba diving need to be knowledgeable about pressure differences and the timing of these changes when they dive.

So casual observation can often lead to incorrect assumptions about the laws of mechanics. We equate forces with objects in contact or a collision between two objects. Yet we live our lives exercising our muscles against the consistent force of gravity, a force that acts at quite a distance whether we are touching the ground or not. We also tend to equate the velocity (speed and direction) of an object with the force that made it. In this chapter we will see that the forces that act on an object do not have to be acting in the direction of the resultant motion of the object (Figure 6.2). It is the skilled person that creates muscle forces to precisely combine with external forces to balance a bike or throw the ball in the correct direction.

Casual visual observation also has many examples of perceptual illusions about the physical realities of our world. Our brains work with our eyes to give us a mental image of physical objects in the world, so that most people routinely mistake this constructed mental image for the actual object. The color of objects is also an illusion based on the wavelengths of light that are reflected from an object's surface. So what about touch? The solidity of objects is also a perceptual illusion because the vast majority of the volume in atoms is "empty" space. The forces we feel when we touch things are the magnetic forces of electrons on the two surfaces repelling each other, while the material strength of an object we bend is related to its physical structure and chemical bonding. We also have a distorted perception of time and the present. We rely on light waves bouncing off objects and toward our eyes. This time delay is not a problem at all, unless we want to observe very high-speed or distant objects like in astronomy. There are many other examples of our molding or construction of the nature of reality, but the important point is that there is a long history of careful scientific measurements which demonstrate that certain laws of mechanics represent the true nature of object and their motion. These laws provide a simple structure that should be used for understanding and modifying motion, rather than erroneous perceptions about the nature of things. Newton's first law is the basis for the Inertia Principle in applying biomechanics.

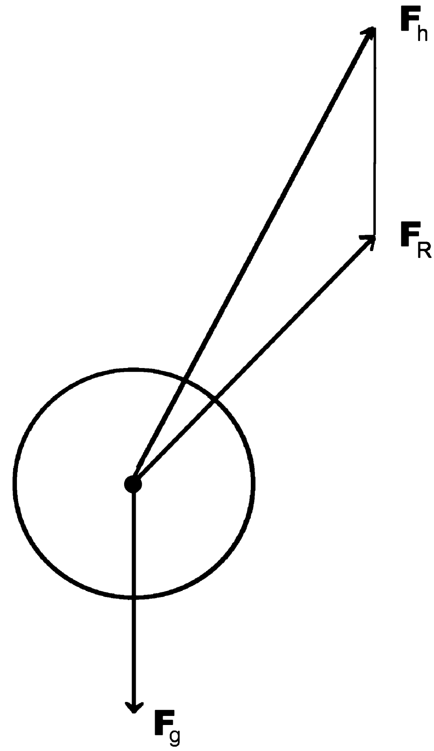


Figure 6.2. Force and motion do not always act in the same direction. This free-body diagram of the forces and resultant force ($\mathbf{F}_R$) on a basketball before release illustrates how a skilled player applies a force to an object ($\mathbf{F}_h$) that combines with the force of gravity ($\mathbf{F}_g$) to create the desired effect. The motion of the ball will be in the direction of $\mathbf{F}_R$.

Interdisciplinary Issue: Body Composition

A considerable body of kinesiology research has focused on the percentage of fat and lean mass in the human body. There are metabolic, mechanical, and psychological effects of the amount and location of fat mass. In sports performance, fat mass can be both an advantage (increased inertia for a football lineman or sumo wrestler) and a disadvantage. Increasing lean body mass usually benefits performance, although greater mass means increasing inertia, which could decrease agility and quickness. When coaches are asked by athletes “How much should I weigh?” they should answer carefully, focusing the athlete's attention first on healthy body composition. Then the coach can discuss with the athlete the potential risks and benefits of changes in body composition. How changes in an athlete's inertia affect their sport performance should not be evaluated without regard to broader health issues.

Newton's Second Law

Newton's second law is arguably the most important law of motion because it shows how the forces that create motion (kinetics) are linked to the motion (kinematics). The second law is called the **Law of Momentum** or **Law of Acceleration**, depending on how the mathematics is written. The most common approach is the famous $\mathbf{F} = m\mathbf{a}$. This is the law of acceleration, which describes motion (acceleration) for any instant in time. The formula correctly written is $\Sigma\mathbf{F} = m \cdot \mathbf{a}$, and states that the acceleration an object experiences is proportional to the resultant force, is in the same direction, and is inversely proportional to the mass. The larger the unbalanced force in a particular direction, the greater the acceleration of the object in that direction. With increasing mass, the inertia of the object will decrease the acceleration if the force doesn't change.

Let's look at an example using skaters in the push-off and glide phases during ice skating (Figure 6.3). If the skaters have a mass of 59 kg and the horizontal forces are known, we can calculate the acceleration of the skater. During push-off the net horizontal force is +200 N because air resistance is negligible, so the skater's horizontal acceleration is: $\Sigma\mathbf{F} = m \cdot \mathbf{a}$, $200 = 59\mathbf{a}$, so $\mathbf{a} = 3.4$ m/s/s. The skater has a positive acceleration and would tend to speed up 3.4 m/s every second if she could maintain her push-off force this much over the air resistance. In the glide phase, the friction force is now a resistance rather than a propulsive force. During glide the skater's acceleration is –0.08 m/s/s because: $\Sigma\mathbf{F} = m \cdot \mathbf{a}$, $-5 = 59\mathbf{a}$, so $\mathbf{a} = -0.08$ m/s/s.

The kinesiology professional can qualitatively break down movements with Newton's second law. Large changes in the speed or direction (acceleration) of a person means that large forces must have been applied. If an athletic contest hinges on the agility of an athlete in a crucial play, the coach should select the lightest and quickest player. An athlete with a small mass is easier to accelerate than an athlete with a larger mass, provided they can create sufficient forces relative to body mass. If a smaller player is being overpowered by a larger opponent, the coach can substitute a larger more massive player to defend against this opponent. Note that increasing force or decreasing mass are both important in creating acceleration and movement.

Newton's second law plays a critical role in quantitative biomechanics. Biomechanists wanting to study the net forces that create human motion take acceleration and body segment mass measurements and apply $\mathbf{F} = m\mathbf{a}$. This working backward from kinematics to the resultant kinetics is called

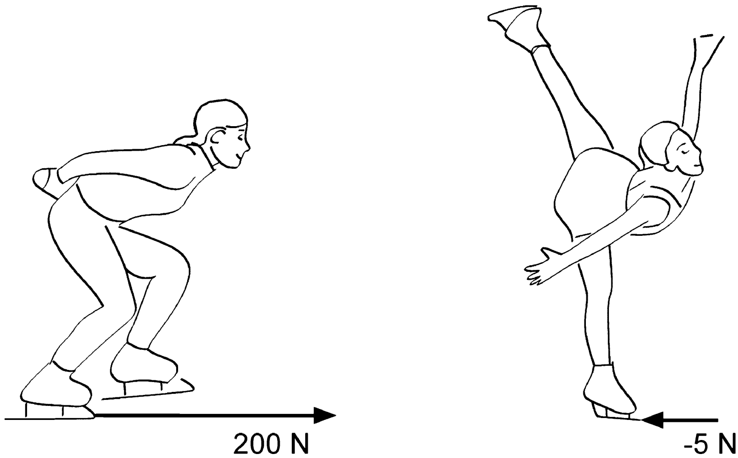


Figure 6.3. Friction forces acting on ice skaters during push-off and gliding. Newton' Second Law of Motion applied in the horizontal direction (see text) will determine the horizontal acceleration of the skater.

inverse dynamics. Other scientists build complex computer models of biomechanical systems and use **direct dynamics**, essentially calculating the motion from the "what-if" kinetics and body configurations they input.

Newton's Third Law

Newton's third law of motion is called the **Law of Reaction**, because it is most often translated as: for every action there is an equal and opposite reaction. For every force exerted, there is an equal and opposite force being exerted. If a patient exerts a sideways force of +150 N on an elastic cord, there has to be –150-N reaction force of the cord on the patient's hand (Figure 6.4). The key insight that people often miss is that a force is really a mutual interaction between two bodies. It may seem strange that if you push horizontally against a wall, the wall is simultaneously pushing back toward you, but it is. This is *not* to say that a force on a free-body diagram should be represented by two vectors, but a person must understand that the effect of a force is not just on one object. A free body diagram is one object or mechanical system and the forces acting on it, so the double vectors in Figures 6.4 and 6.5 can sometimes be confusing because they are illustrating both objects and are not true free body diagrams. If someone ever did not seem to kiss you back, you can always take some comfort in the fact that at least in mechanical terms they did.

An important implication of the law of reaction is how reaction forces can change the direction of motion opposite to our applied force when we exert our force on objects with higher force or inertia (Figure 6.5a). During push-off in running the athlete exerts downward and backward push with the foot, which creates a **ground reaction force** to propel the body upward and forward. The extreme mass of the earth easily overcomes our inertia, and the ground reaction force accelerates our body in the opposite direction of force applied to the ground. Another example would be eccentric muscle actions where we use our muscles as brakes, pushing in the opposite direction to another force. The force exerted

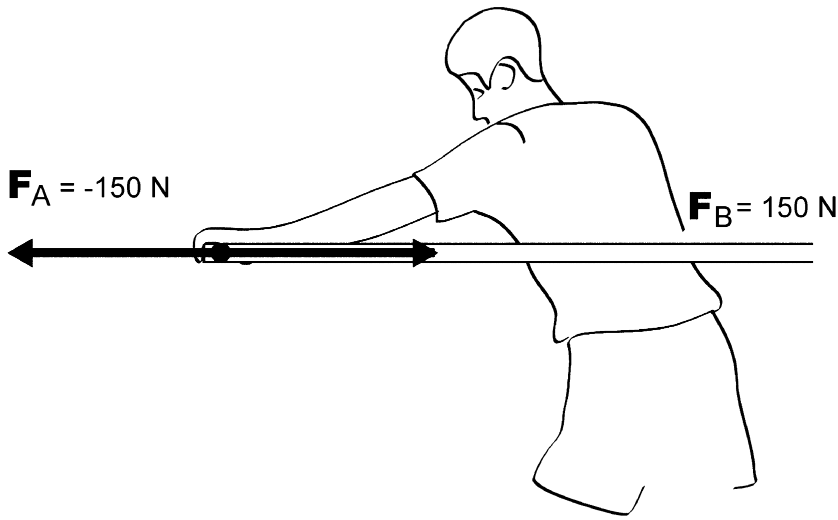


Figure 6.4. Newton's third law states that all forces have an equal and opposite reaction forces on the other object, like in this elastic exercise. The –150-N (**F_A**) force created by the person on the elastic cord coincides with a 150-N reaction force (**F_B**) exerted on the person by the cord.

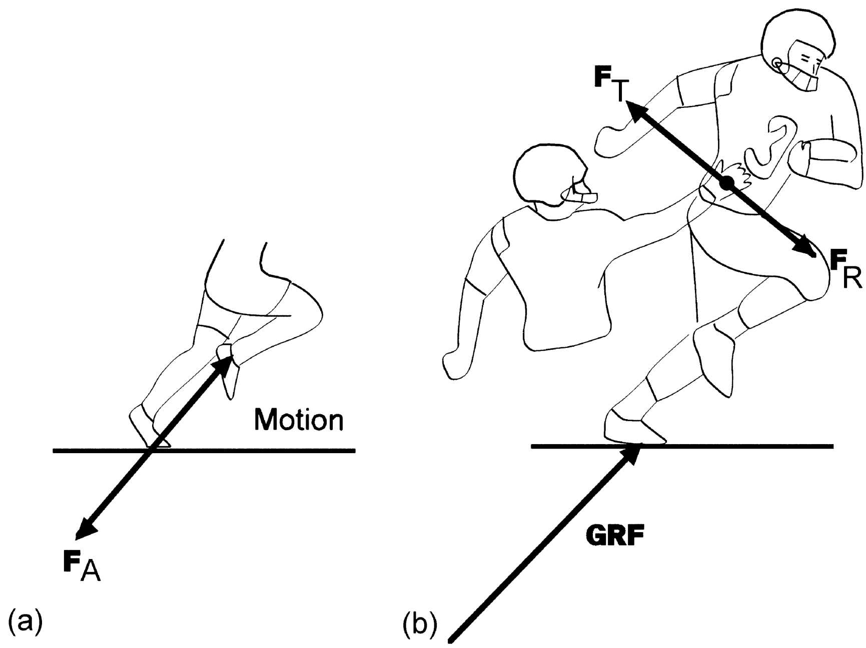


Figure 6.5. A major consequence of Newton's third law is that the forces we exert on an object with larger inertia often create motion in the direction opposite of those forces. In running, the downward backward push of the foot on the ground (**F_A**) late in the stance (a) creates a ground reaction force which acts forward and upward, propelling the runner through the air. A defensive player trying to make a tackle (**F_T**) from a poor position (b) may experience reaction forces (**F_R**) that create eccentric muscle actions and injurious loads.

by the tackler in Figure 6.5b ends up being an eccentric muscle action as the inertia and ground reaction forces created by the runner are too great. Remember that when we push or pull, this force is exerted on some other object and the object pushes or pulls back on us too!

There are several kinds of force-measuring devices used in biomechanics to study how forces modify movement. Two important devices are the **force platform** (or force plates) and pressure sensor arrays. A force plate is a rigid platform that measures the forces and torques in all three dimensions applied to the surface of the platform (Schieb, 1987). Force plates are often mounted in a floor to measure the ground reaction forces that are equal and opposite to the forces people make against the ground (see Figure 6.5). Since the 1980s, miniaturization of sensors has allowed for rapid development of arrays of small-force sensors that allow measurement of the distribution of forces (and pressure because the area of the sensor is known) on a body. Several commercial shoe insoles with these sensors are available for studying the pressure distribution under a person's foot (see McPoil, Cornwall, & Yamada, 1995). There are many other force-measuring devices (e.g., load cell, strain gauge, isokinetic dynamometer) that help biomechanics scholars study the kinetics of movement.

INERTIA PRINCIPLE

Newton's first law of motion, or the **Law of Inertia**, describes the resistance of all objects to a change in their state of linear motion. In linear motion, the measure of inertia is an object's mass. Application of Newton's first law in biomechanics is termed the **Inertia Principle**. This section will discuss how teachers, coaches, and therapists adjust movement inertia to accommodate the task. Our focus will be on the linear inertia (mass) of movement, so the inertial resistance to rotation will be summarized in chapter 7.

The first example of application of the inertia principle is to reduce mass in order to increase the ability to rapidly accelerate. Obvious examples of this principle in track are the racing flats/shoes used in competition versus the heavier shoes used in training. The heavier shoes used in training provide protection for the foot and a small inertial overload. When race day arrives, the smaller mass of the shoes makes the athlete's feet feel light and quick. We will see in chapter 7 that this very small change in mass, because of its position, makes a much larger difference in resistance to rotation (angular inertia). Let's add a little psychology and conditioning to the application of lowering inertia. Warm-up for many sports involves a gradual increase in intensity of movements, often with larger inertia. In baseball or golf, warm-up swings are often taken with extra weights, which when taken off make the “stick” feel very light and fast (Figure 6.6).

In movements where stability is desired over mobility, the Inertia Principle suggests that mass should be increased. Linemen in football and centers in basketball have tasks that benefit more from increasing muscle mass to increase inertia, than from decreasing inertia to benefit quickness. Adding mass to a golf club or tennis racket will make for faster and longer shots if the implement can be swung with the same velocity at impact. If an exercise machine tends to slide around in the weight room, a short-term solution might be to store some extra weights on the base or legs of the machine. If these new weights are not a safety risk (in terms of height or potential for tripping people), the increased inertia of the station would likely make the machine safer.

Another advantage of increased inertia is that the added mass can be used to mod-

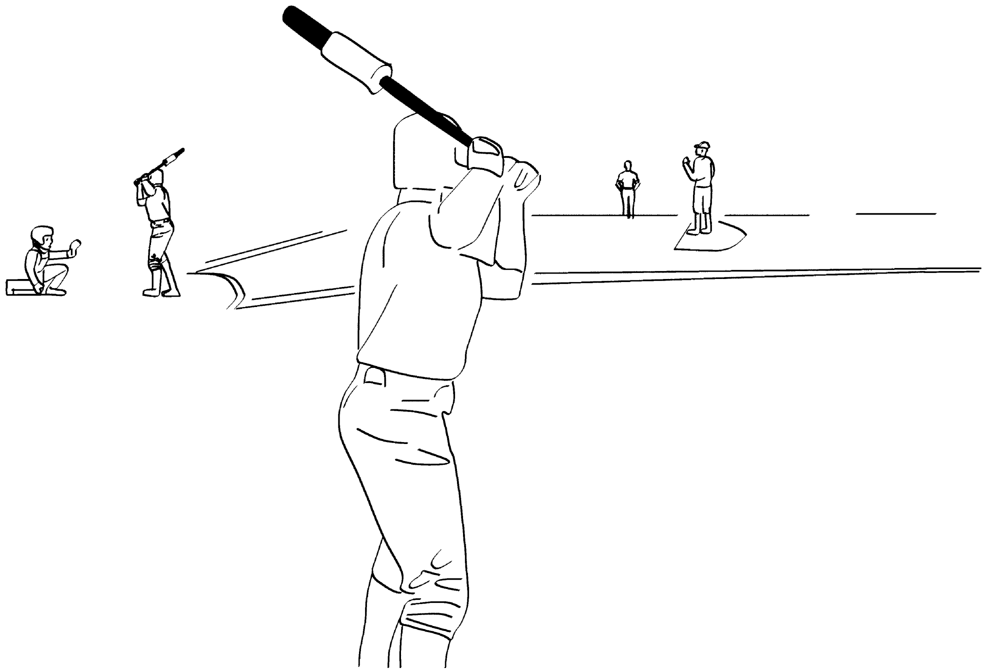


Figure 6.6. Mass added to sporting implements in warm-up swings makes the inertia of the regular implement (when the mass is removed) feel very light and quick. Do you think this common sporting ritual of manipulating inertia is beneficial? If so, is the effect more biomechanical or psychological?

ify the motion of another body segment. The preparatory leg drives and weight shifts in many sporting activities have several benefits for performance, one being putting more body mass in motion toward a particular target. The forward motion of a good percentage of body mass can be transferred to the smaller body segments just prior to impact or release. We will be looking at this transfer of energy later on in this chapter when we consider the **Segmental Interaction Principle**. The defensive moves of martial artists are often designed to take advantage of the inertia of an attacker. An opponent striking from the left has inertia that can be directed by a block to throw to the right.

An area where modifications in inertia are very important is strength and conditioning. Selecting masses and weights for training and rehabilitation is a complicated issue. Biomechanically, it is very important because the inertia of an external object has a major influence on amount of muscular force and how those forces can be applied (Zatsiorsky & Kraemer, 2006). Baseball pitchers often train by throwing heavier or lighter than regulation baseballs (see, e.g., Escamilla, Speer, Fleisig, Barrentine, & Andrews, 2000). Think about the amount of force that can be applied in a bench press exercise versus a basketball chest pass. The very low inertia of the basketball allows it to accelerate quickly, so the peak force that can be applied to the basketball is much lower than what can be applied to a barbell. The most appropriate load, movement, and movement speed in conditioning for a particular human movement is often difficult to define. The principle of specificity says the movement, speed, and load should be similar to the actual activity; therefore, the overload should only come from moderate changes in these variables so as to not adversely affect skill.

Suppose a high school track coach has shot put athletes in the weight room throwing medicine balls. As you discuss the program with the coach you find that they are using loads (inertia) substantially lower than the shot in order to enhance the speed of upper extremity extension. How might you apply the principle of inertia in this situation? Are the athletes fully using their lower extremities in a similar motion to shot putting? Can the athletes build up large enough forces before acceleration of the medicine ball, or will the force–velocity relationship limit muscle forces? How much lower is the mass of the medicine ball than that of the shot? All these questions, as well as technique, athlete reaction, and actual performance, can help you decide if training is appropriate. The biomechanical research on power output in multi-segment movements suggests that training loads should be higher than the 30 to 40% of 1RM seen in individual muscles and muscle groups (see the following section on muscle power; Cronin *et al.*, 2001a,b; and Funato, Matsuo, & Fukunaga, 1996). Selecting the inertia for weight training has come a long way from "do three sets of 10 reps at 80% of your maximum."

MUSCLE ANGLE OF PULL: QUALITATIVE AND QUANTITATIVE ANALYSIS OF VECTORS

Before moving on to the next kinetic approach to studying the causes of movement, it is a good time to review the special mathematics required to handle vector quantities like force and acceleration. The linear kinetics of a biomechanical issue called *muscle angle of pull* will be explored in this section. While a qualitative understanding of adding force vectors is enough for most kinesiology professionals, quantifying forces provides a deeper level of explanation and understanding of the causes of human movement. We will see that the linear kinetics of the pull of a muscle often changes dramatically because of changes in its geometry when joints are rotated.

Qualitative Vector Analysis of Muscle Angle of Pull

While the attachments of a muscle do not change, the angle of the muscle's pull on bones changes with changes in joint angle. The angle of pull is critical to the linear and angular effects of that force. Recall that a force can be broken into parts or components. These pulls of a muscle's force in two dimensions are conveniently resolved into longitudinal and rotational components. This local or relative frame of reference helps us study how muscle forces affect the body, but do not tell us about the orientation of the body to the world like absolute frames of reference do. Figure 6.7 illustrates typical angles of pull and these components for the biceps muscle at two points in the range of motion. The linear kinetic effects of the biceps on the forearm can be illustrated with arrows that represent force vectors.

The component acting along the longitudinal axis of the forearm ($\mathbf{F}_L$) does not create joint rotation, but provides a load that stabilizes or destabilizes the elbow joint. The component acting at right angles to the forearm is often called the rotary component ($\mathbf{F}_R$) because it creates a torque that contributes to potential rotation. Remember that vectors are drawn to scale to show their magnitude with an arrowhead to represent their direction. Note that

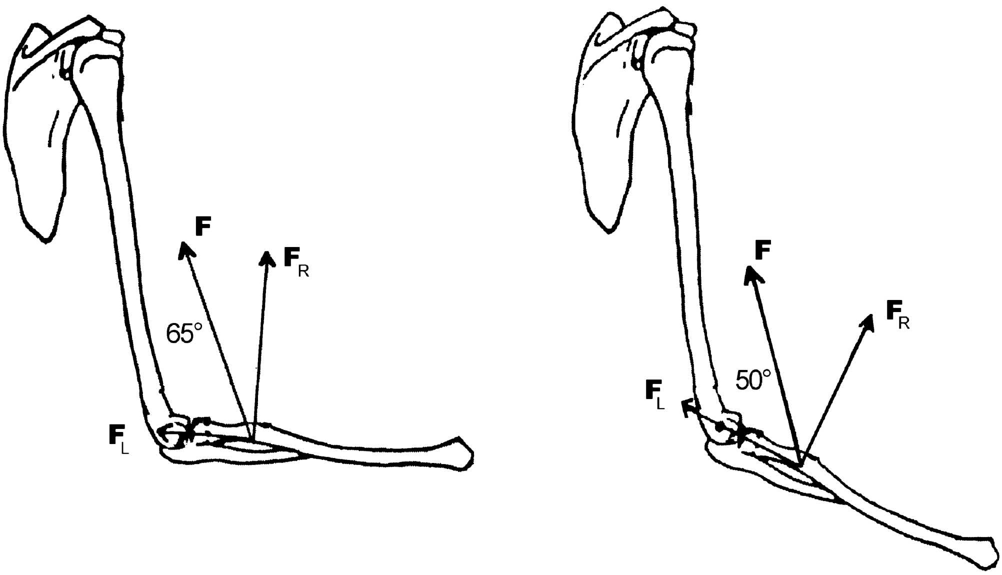


Figure 6.7. Typical angles of pull of the biceps brachii muscle in an arm curl. The angular positions of the shoulder and elbow affect the angle of pull of the muscle, which determines the size of the components of the muscle force. Muscle forces (**F**) are usually resolved along the longitudinal axis of the distal segment ($\mathbf{F}_L$) and at right angles to the distal segment to show the component that causes joint rotation ($\mathbf{F}_R$).

in the extended position, the rotary component is similar to the stabilizing component. In the more flexed position illustrated, the rotary component is larger than the smaller stabilizing component. In both positions illustrated, the biceps muscle tends to flex the elbow, but the ability to do so (the rotary component) varies widely.

This visual or qualitative understanding of vectors is quite useful in studying human movement. When a muscle pulls at a 45° angle, the two right-angle components are equal. A smaller angle of pull favors the longitudinal component, while the rotary component benefits from larger angles of pull. Somewhere in the midrange of the arm curl exercise the biceps has an angle of pull of 90°, so all the bicep's force can be used to rotate the elbow and there is no longitudinal component.

Vectors can also be qualitatively added together. The rules to remember are that the forces must be drawn accurately (size and direction), and they then can be added together in tip-to-tail fashion. This graphical method is often called drawing a *parallelogram of force* (Figure 6.8). If the vastus lateralis and vastus medialis muscle forces on the right patella are added together, we get the resultant of these two muscle forces. The resultant force from these two muscles can be determined by drawing the two muscle forces from the tip of one to the tail of the other, being sure to maintain correct length and direction. Since these diagrams can look like parallelograms, they are called a parallelogram of force. Remember that there are many other muscles, ligaments, and joint forces not shown that affect knee function. It has been hypothesized that an imbalance of greater lateral forces in the quadriceps may contribute to patellofemoral pain syndrome (Callaghan & Oldham, 1996). Does the resultant force ($\mathbf{F}_R$)

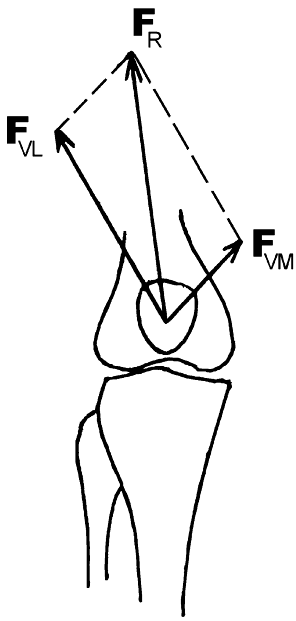


Figure 6.8. Any vectors acting on the same object, like the vastus medialis ($\mathbf{F}_{VM}$) and vastus lateralis ($\mathbf{F}_{VL}$) of the right knee, can be added together to find a resultant ($\mathbf{F}_R$). This graphical method of adding vectors is called a *parallelogram of forces*.

in Figure 6.8 appear to be directed lateral to the longitudinal axis of the femur?

Quantitative Vector Analysis of Muscle Angle of Pull

Quantitative or mathematical analysis provides precise answers to vector resolution (in essence subtraction to find components) or vector composition. Right-angle trigonometry provides the perfect tool for this process. A review of the major trigonometric relationships (sine, cosine, tangent) is provided in Appendix D. Suppose an athlete is training the isometric stabilization ability of their abdominals with leg raises in a Roman chair exercise station. Figure 6.9a illustrates a typical orientation and magnitude of the major hip flexors (the iliopsoas group) that hold their legs elevated. The magnitude of the weight of the legs and the hip flexor forces provide a large resistance for the abdominal muscles to stabilize. This exercise is not usually appropriate for untrained persons.

If an iliopsoas resultant muscle force of 400 N acts at a 55° angle to the femur, what are the rotary ($\mathbf{F}_R$) and longitudinal ($\mathbf{F}_L$) components of this force? To solve this problem, the rotating component is moved tip to tail to form a right triangle (Figure 6.9b). In this triangle, right-angle trigonometry says that the length of the adjacent side to the 55° angle ($\mathbf{F}_L$) is equal to the resultant force times cos 55°. So the stabilizing component of the iliopsoas force is: $\mathbf{F}_L = 400(\cos 55°) = 229$ N, which would tend to compress the hip joint along the longitudinal axis of the femur. Likewise, the rotary component of this force is the side opposite the 55° angle, so this side is equal to the resultant force times sin 55°. The component of the 400-N iliopsoas force that would tend to rotate the hip joint, or in this example isometrically hold the legs horizontally, is: $\mathbf{F}_R = 400 \sin 55° = 327$ N upward. It is often a good idea to check calculations with a qualitative assessment of the free body diagram. Does the rotary component look larger than the longitudinal component? If these components are the same at 45°, does it make sense that a higher angle would increase the vertical component and decrease the component of force in the horizontal direction?

When the angle of pull ($\boldsymbol{\theta}$) or push of a force can be expressed relative to a horizontal axis (2D analysis like above), the horizontal component is equal to the resultant times the cosine of the angle $\boldsymbol{\theta}$. The vertical component is equal to the resultant times the sine of the angle $\boldsymbol{\theta}$. Consequently, how the angle of force application affects the size of the components is equal to the shape of a sine or cosine wave. A qualitative understanding of these functions helps one

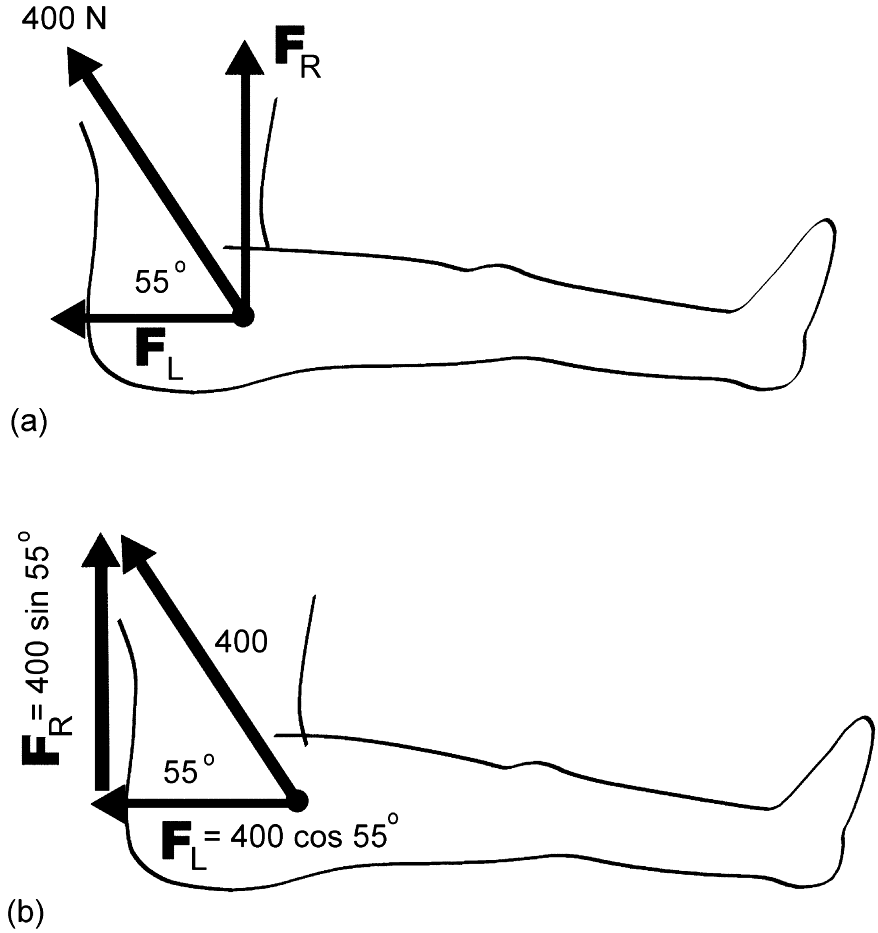


Figure 6.9. Right-angle trigonometry is used to find the components of a vector like the iliopsoas muscle force illustrated. Notice the muscle force is resolved into components along the longitudinal axis of the femur and at right angles to the femur. The right angle component is the force that creates rotation ($\mathbf{F}_R$).

understand where the largest changes occur and what angles of force application are best. Let's look at a horizontal component of a force in two dimensions. This is analogous to our iliopsoas example, or how any force applied to an object will favor the horizontal over the vertical component. A cosine function is not a linear function like our spring example in chapter 2. Figure 6.10 plots the size of the cosine function as a percentage of the resultant for angles of pull from 0 to 90°.

A 0° (horizontal) angle of pull has no vertical component, so all the force is in the horizontal direction. Note that, as the angle of pull begins to rise (0 to 30°), the cosine or horizontal component drops very slowly, so most of the resultant force is directed horizontally. Now the cosine function begins to change more rapidly, and from 30 to 60° the horizontal component has dropped from 87 to 50% the size of the resultant force. For angles of pull greater than 60°, the cosine drops off very fast, so there is a dra-

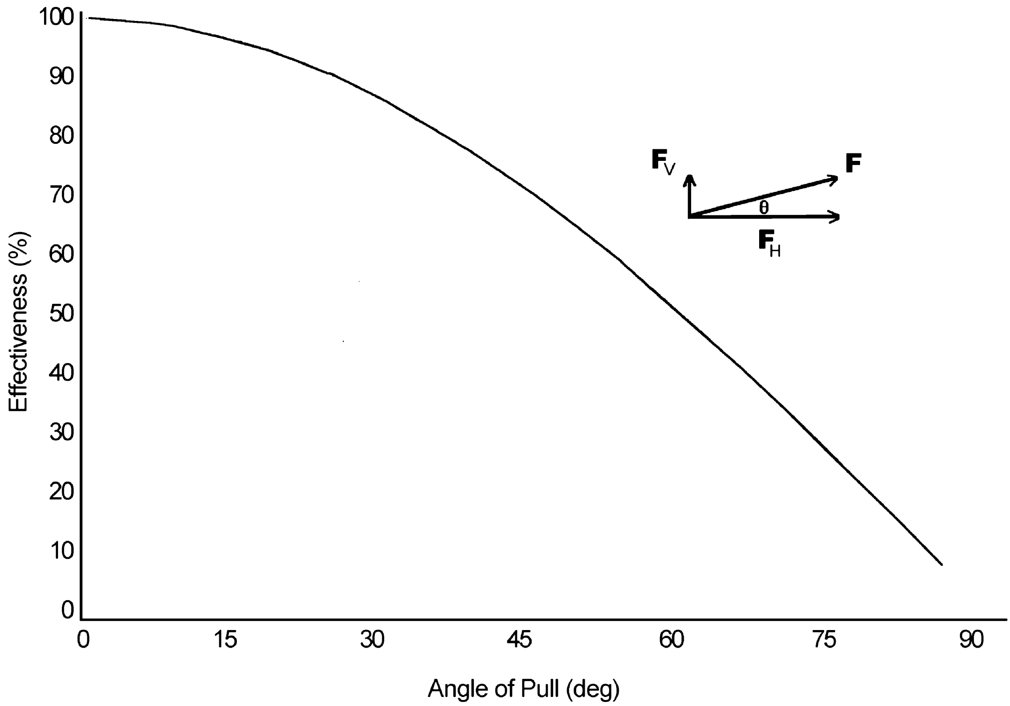


Figure 6.10. Graph of the cosine of angle **θ** between 0 and 90° (measured from the right horizontal) shows the percentage effectiveness of a force (**F**) in the horizontal direction ($\mathbf{F}_H$). This horizontal component is equal to **F** cos(**θ**), and angle **θ** determines the tradeoff between the size of the horizontal and vertical components. Note that the horizontal component stays large (high percentage of the resultant) for the first 30° but then rapidly decreases. The sine and cosine curves are the important nonlinear mathematical functions that map linear biomechanical variables to angular.

matic decrease in the horizontal component of the force, with the horizontal component becoming 0 when the force is acting at 90° (vertical). We will see that the sine and cosine relationships are useful in angular kinetics as well. These curves allow for calculation of several variables related to angular kinetics from linear measurements. Right-angle trigonometry is also quite useful in studying the forces between two objects in contact, or precise kinematic calculations.

CONTACT FORCES

The linear kinetics of the interaction of two objects in contact is also analyzed by resolving the forces into right-angle components. These components use a local frame of reference like the two-dimensional muscle angle of pull above, because using horizontal and vertical components are not always convenient (Figure 6.11). The forces between two objects in contact are resolved into the **normal reaction** and **friction**. The normal reaction is the force at right angles to the surfaces in contact, while friction is the force acting in parallel to the surfaces. Friction is the force resisting the sliding of the surfaces past each other.

When the two surfaces are dry, the force of friction (**F**) is equal to the product of the coefficient of friction (μ) and the normal reaction ($\mathbf{F}_N$), or $\mathbf{F} = \mu \cdot \mathbf{F}_N$. The coefficient

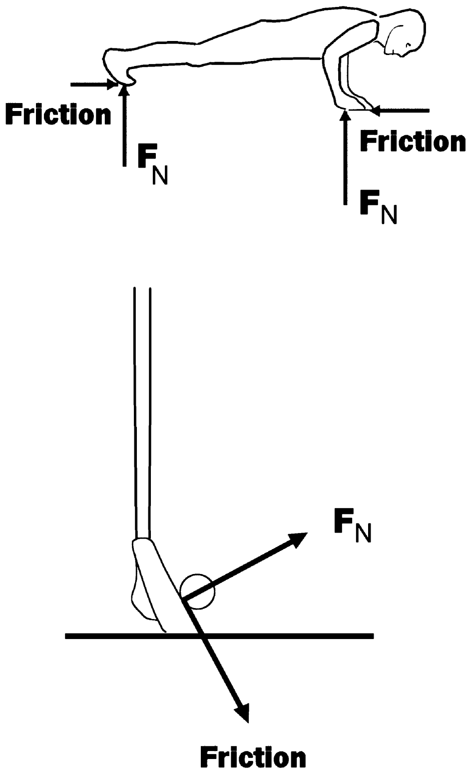


Figure 6.11. Forces of contact between objects are usually resolved into the right-angle components of *normal reaction* ($\mathbf{F}_N$) and *friction*.

of friction depends on the texture and nature of the two surfaces, and is determined by experimental testing. There are coefficients of static (non-moving) friction (μ_S) and kinetic (sliding) friction (μ_K). The coefficients of kinetic friction are typically 25% smaller than the maximum static friction. It is easier to keep an object sliding over a surface than to stop it and start the object sliding again. Conversely, if you want friction to stop motion, preventing sliding (like with anti-lock auto brakes) is a good strategy. Figure 6.12 illustrates the friction force between an athletic shoe and a force platform as a horizontal force is increased. Please note that the friction grows in a linear fashion until the limiting friction is reached ($\mu_S \cdot \mathbf{F}_N$), at which point the shoe begins to slide across the force platform. If the weight on the shoe created a normal reaction of 300 N, what would you estimate the μ_S of this rubber/metal interface?

Typical coefficients of friction in human movement vary widely. Athletic shoes have coefficients of static friction that range from 0.4 to over 1.0 depending on the shoe and sport surface. In tennis, for example, the linear and angular coefficients of friction range from 0.4 to over 2.0, with shoes responding differently to various courts

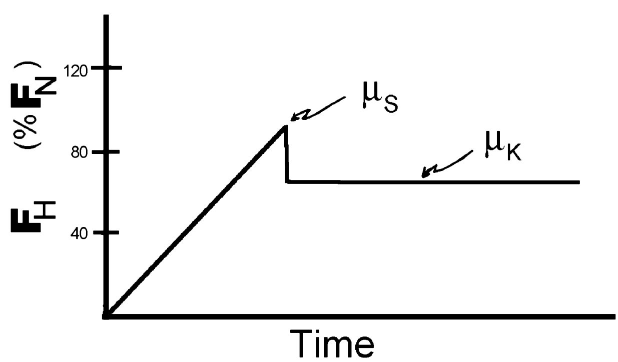


Figure 6.12. The change in friction force between an athletic shoe and a force platform as a horizontal force is applied to the shoe. The ratio of the friction force ($\mathbf{F}_H$) on this graph to the normal force between the shoe and force platform determine the coefficient of friction for these two surfaces.

(Nigg, Luthi, & Bahlsen, 1989). Epidemiological studies have shown that playing on lower-friction courts (clay) had a lower risk of injury (Nigg *et al.*, 1989). Many teams that play on artificial turf use flat shoes rather than spikes because they believe the lower friction decreases the risk of severe injury. The sliding friction between ice and a speed skating blade has been measured, demonstrating coefficients of kinetic friction around 0.005 (van Ingen Schenau, De Boer, & De Groot, 1989).

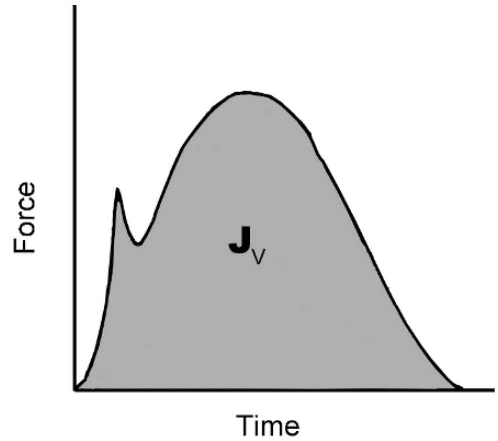


Figure 6.13. The vertical impulse (J_V) of the vertical ground reaction force for a footstrike in running is the area under the force–time graph.

IMPULSE–MOMENTUM RELATIONSHIP

Human movement occurs over time, so many biomechanical analyses are based on movement-relevant time intervals. For example, walking has a standardized gait cycle (Whittle, 2001), and many sport movements are broken up into phases (usually, preparatory, action, and follow-through). The mechanical variables that are often used in these kinds of analyses are impulse (**J**) and momentum (**p**). These two variables are related to each other in the original language of Newton's second law: the change in momentum of an object is equal to the impulse of the resultant force in that direction. The impulse–momentum relationship is Newton's Second law written over a time interval, rather than the instantaneous (**F** = m**a**) version.

Impulse is the effect of force acting over time. Impulse (**J**) is calculated as the product of force and time (**J** = **F** · t), so the typical units are N·s and lb·s. Impulse can be visualized as the area under a force–time graph. The vertical ground reaction force during a foot strike in running can be measured using a force platform, and the area under the graph (integral with respect to time) represents the vertical impulse (Figure 6.13). A person can increase the motion of an object by applying a greater impulse, and both the size of the force and duration of force application are equally important. Impulse is the mechanical variable discussed in the following section on the "Force–Time Principle." In movement, the momentum a person can generate, or dissipate in another object, is dependent on how much force can be applied and the amount of time the force is applied.

Newton realized that the mass of an object affects its response to changes in motion. Momentum is the vector quantity that Newton said describes the quantity of motion of an object. Momentum (**p**) is calculated as the product of mass and velocity (**p** = m · **v**). The SI unit for momentum is kg·m/s. Who would you rather accidentally run into in a soccer game at a 5-m/s closing velocity: a 70- or 90-kg opponent? We will return to this question and mathematically apply the impulse–momentum relationship later on in this chapter once we learn about a similar kinetic variable called *kinetic energy*.

The association between impulse (force exerted over time) and change in momentum (quantity of motion) is quite useful in gaining a deeper understanding of many sports. For example, many impacts create very large forces because the time interval of many elastic collisions is so short. For a golf ball to change from zero momentum to a very considerable momentum over the 0.0005 seconds of impact with the club requires a peak force on the golf ball of about 10,000 N, or greater than 2200 pounds (Daish, 1972). In a high-speed soccer kick, the ball is actually on the foot for about 0.016 seconds, so that peak forces on the foot are above 230 pounds (Tol, Slim, van Soest, & van Dijk, 2002; Tsaousidis & Zatsiorsky, 1996). Fortunately, for many catching activities in sport an athlete can spread out the force applied to the ball over longer periods of time. The Impulse–Momentum Relationship is the mechanical law that underlies the **Force–Time Principle** introduced earlier in chapters 2 and 4. Let's revisit the application of the **Force–Time Principle** with our better understanding of linear kinetics.

Interdisciplinary Issue: Acute and Overuse Injuries

A very important area of research by many kinesiology and sports medicine scholars is related to musculoskeletal injuries. Injuries can be subclassified into acute injuries or overuse injuries. Acute injuries are single traumatic events, like a sprained ankle or breaking a bone in a fall from a horse. In an acute injury the forces create tissue loads that exceed the ultimate strength of the biological tissues and cause severe physical disruption. Overuse injuries develop over time (thus, chronic) from a repetitive motion, loading, inadequate rest, or a combination of the three. Injuries from repetitive vocational movements or work-related musculoskeletal disorders (WMSDs) are examples of chronic injuries (Barr & Barbe, 2002). Stress fractures and anterior tibial stress syndrome (shin splits) are classic examples of overuse injuries associated with running. Runners who overtrain, run on very hard surfaces, and are susceptible can gradually develop these conditions. If overuse injuries are untreated, they can develop into more serious disorders and injuries. For example, muscle overuse can sometimes cause inflammation of tendons (tendinitis), but if the condition is left untreated degenerative changes begin to occur in the tissue that are called tendinoses (Khan, Cook, Taunton, & Bonar, 2000). Severe overuse of the wrist extensors during one-handed backhands irritates the common extensor tendon attaching at the lateral epicondyle, often resulting in "tennis elbow."

The etiology (origin) of overuse injuries is a complex phenomenon that requires interdisciplinary research. The peak force or acceleration (shock) of movements is often studied in activities at risk of acute injury. It is less clear if peak forces or total impulse are more related to the development of overuse injuries. Figure 6.14 illustrates the typical vertical ground reaction forces measured with a force platform in running, step aerobics, and walking. Note that the vertical forces are normalized to units of bodyweight. Notice that step aerobics has peak forces near 1.8 BW because of the longer time of force application and the lower intensity of movement. Typical vertical ground reaction forces in step aerobics look very much like the forces in walking (peak forces of 1.2 BW and lower in double support) but tend to be a bit larger because of the greater vertical motion. The peak forces in running typically are about 3 BW because of the short amount of time the foot is on the ground. Do you think the vertical impulses of running and step aerobics are similar? Landing from large heights and the speed involved in gymnastics are very close to injury-producing loads. Note the high peak force and rate of force development (slope of the **F**–t curve) in the running ground reaction force. Gymnastic coaches should limit the number of landings during practice and utilize thick mats or landing pits filled with foam rubber to reduce the risk of injury in training because the rate of loading and peak forces are much higher (8 BW) than running.

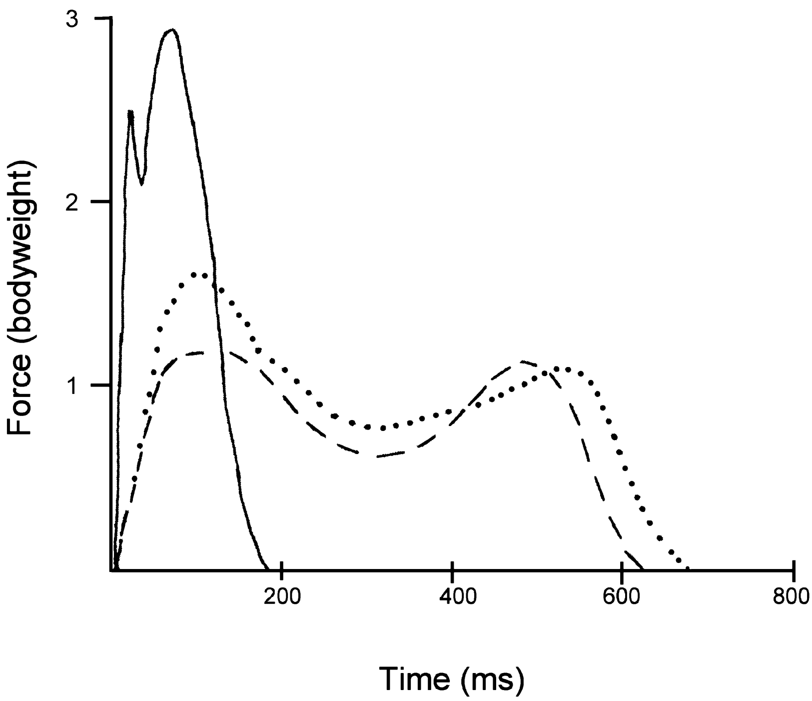


Figure 6.14. Typical vertical ground reaction forces (in units of bodyweight) for running (solid), walking (dashed), and step aerobic exercise (dotted).

FORCE-TIME PRINCIPLE

The applied manifestation of Newton's Second Law of Motion as the Impulse–Momentum Relationship is the **Force–Time Principle**. If a person can apply force over a longer period of time (large impulse), they will be able to achieve a greater speed (change in momentum) than if they used similar forces in a shorter time interval. Unfortunately, in many human movements there is not an unlimited amount of time to apply forces, and there are several muscle mechanical characteristics that complicate application of this principle. Recall from chapter 4 that maximizing the time force application is not always the best strategy for applying the **Force–Time Principle**. The movement of interest, muscle characteristics, and the mechanical strengths of tissues all affect optimal application of forces to create motion.

There are a few movements that do allow movers to maximize the time of force application to safely slow down an object. In landing from a jump, the legs are extended at contact with the ground, so there is near maximal joint range of motion to flex the joints and absorb impact forces. A softball infielder is taught to lean forward and extend her glove hand to field a ground ball so that she can absorb the force of the ball over a longer time interval. Figure 6.15 illustrates two people catching balls: which athlete is using a technique that is correctly applying the Force–Time Principle? Young children often catch by trapping the object against the body and even turn their heads in fear. Even professional football players (6.15, below) occasionally rely on their

Figure 6.15. Catching the ball close to the body (the American football example) is a poor application of the Force–Time Principle because there is minimal time or range of motion to slow down the ball. The softball catcher has increased the time and range of motion that can be used to slow down the ball.

talent or sense of self-preservation more than coaching and use a similar catching technique. For how much time can forces be applied to slow the balls in these cases? The momentum of the ball in these situations is often so great that the force between the person's body and the ball builds up so fast that the ball bounces out of their grasp. If these people extended their arms and hands to the ball, the time the force is applied to slow down the ball could be more than ten times longer. Not only does this increase the chance of catching the ball, but it decreases the peak force and potential discomfort involved in catching.

Athletes taught to reach for the ground and "give" with ankle, hip, and knee flexion dramatically increase the time of force application in landing and decrease the peak ground reaction forces. Exactly how the muscles are positioned and pre-tensed prior to landing affects which muscle groups are used to cushion landing (DeVita & Skelly, 1992; Kovacs *et al.*, 1999; Zhang, Bates, & Dufek, 2000). How to teach this important skill has not been as well researched. The sound of an impact often tells an athlete about the severity of a collision, so this has been used as a teaching point in catching and landing. It has also been shown that focusing attention on decreasing the sound of landing is an effective strategy to decrease peak forces during landing (McNair, Prapavessis, & Callender, 2000). Increasing the "give" of the cushioning limbs increases the time of force appli-

Activity: Impulse–Momentum Relationship

Fill a few small balloons with water to roughly softball size. Throw the water balloon vertically and catch it. Throw the balloon several times trying to maximize the vertical height thrown. Imagine that the water balloon represents your body falling and the catching motions represent your leg actions in landing. What catching technique points modify the force and time of force application to the balloon to create a vertical impulse to reduce the momentum of the balloon to zero?

cation and decreases the tone and intensity of the sound created by the collision.

In some movements there are other biomechanical factors involved in the activity that limit the amount of time that force can be applied. In these activities, increasing time of force application would decrease performance, so the only way to increase the impulse is to rapidly create force during the limited time available. A good example of this is long jumping. Recall that in the kinematics chapter we learned that long jumpers have low takeoff angles (approximately 20º). The takeoff foot is usually on the board for only 100 ms, so there is little time to create vertical velocity. Skilled long jumpers train their neuromuscular system to strongly activate the leg muscles prior to foot strike. This allows the jumper to rapidly increase ground reaction forces so they can generate vertical velocity without losing too much horizontal velocity. Similar temporal limitations are at work in running or throwing. In many sports where players must throw the ball quickly to score or prevent an opponent scoring, the player may make a quicker throw than they would during maximal effort without time restrictions. A quick delivery may not use maximal throwing speed or the extra time it takes to create that speed, but it meets the objective of that situation. Kinesiology professionals need to instruct movers as to when using more time of force application will result in safer and more effective movement, and when the use of longer force application is not the best movement strategy.

WORK–ENERGY RELATIONSHIP

The final approach to studying the kinetics of motion involves laws from a branch of physics dealing with the concepts of work and energy. Since much of the energy in the human body, machines, and on the earth are in the form of heat, these laws are used in thermodynamics to study the flow of heat energy. Biomechanists are interested in how mechanical energies are used to create movement.

Mechanical Energy

In mechanics, **energy** is the capacity to do work. In the movement of everyday objects, energy can be viewed as the mover of stuff (matter), even though at the atomic level matter and energy are more closely related. Energy is measured in Joules (J) and is a scalar quantity. One Joule of energy equals 0.74 ft·lbs. Energy is a scalar because it represents an ability to do work that can be transferred in any direction. Energy can take many forms (for example, heat, chemical, nuclear, motion, or position). There are three mechanical energies that are due to an object's motion or position.

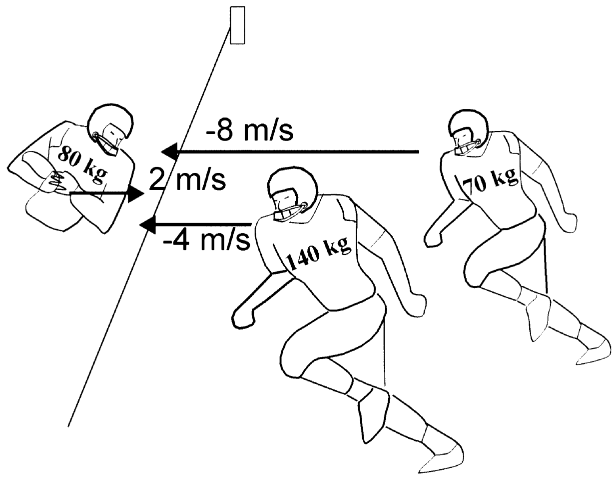
The energies of motion are linear and angular **kinetic energy**. Linear or translational kinetic energy can be calculated using the following formula: $KE_T = ½m\mathbf{v}^2$. There are several important features of this formula. First, note that squaring velocity makes the energy of motion primarily dependent on the velocity of the object. The energy of motion varies with the square of the velocity, so doubling velocity increases the kinetic energy by a factor of 4 (2^2). Squaring velocity also eliminates the effect of the sign (+ or –) or vector nature of velocity. Angular or rotational kinetic energy can be calculated with a similar formula: $KE_R = ½I\omega^2$. We will learn more about angular kinetics in chapter 7.

The mathematics of kinetic energy ($½m\mathbf{v}^2$) looks surprisingly similar to momentum ($m\mathbf{v}$). However, there are major differences in these two quantities. First, momentum is a vector quantity describing the quantity of motion in a particular direction. Second, kinetic energy is a scalar that describes how much work an object in motion could perform. The variable momentum is used to document the current state of motion, while kinetic energy describes the potential for future interactions. Let's consider a numerical example from American football. Imagine you are a small (80-kg) halfback spinning off a tackle with one yard to go for a touchdown. Who would you rather run into just before the goal line: a quickly moving defensive back or a very large lineman not moving as fast? Figure 6.16 illustrates the differences between kinetic energy and momentum in an inelastic collision.

Applying the impulse–momentum relationship is interesting because this will tell us about the state of motion or whether a touchdown will be scored. Notice that both defenders (small and big) have the same amount of momentum (–560 kg·m/s), but because the big defender has greater mass you will not fly backwards as fast as in the collision with the defensive back. The impulse–momentum relationship shows that you do not score either way (negative velocity after impact: $\mathbf{V}_2$), but the defensive back collision looks very dramatic because you reverse directions with a faster negative velocity. The work–energy relationship tells us that the total mechanical energy of the collision will be equal to the work the defender can do on you. Some of this energy is transferred into sound and heat, but most of it will be transferred into deformation of your pads and body! Note that the sum of the energies of the two athletes and the strong dependence of kinetic energy on velocity results in nearly twice (2240 versus 1280 J) as much energy in the collision with the defensive back. In short, the defensive back hurts the most because it is a very high-energy collision, potentially adding injury to the insult of not scoring.

There are two types of mechanical energy that objects have because of their position or shape. One is gravitational potential energy and the other is strain energy. Gravitational **potential energy** is the energy of the mass of an object by virtue of its position relative to the surface of the earth. Potential energy can be easily calculated with the formula: $PE = mgh$. Potential energy depends on the mass of the object, the acceleration due to gravity, and the height of the object. Raising an object with a mass of 35 kg a meter above the ground stores 343 J of energy in it ($PE = 35 \cdot 9.81 \cdot 1 = 343$). If this object were to be released, the potential energy would gradually be converted to kinetic energy as gravity accelerated the object toward the earth. This simple example of transfer of mechanical energies is an example of one of the most important laws of physics: the **Law of Conservation of Energy**.

The **Law of Conservation of Energy** states that energy cannot be created or destroyed; it is just transferred from one form to another. The kinetic energy of a tossed ball will be converted to potential energy or possibly strain energy when it collides with another object. A tumbler taking off from a mat has kinetic energy in the vertical direction that is converted into potential energy on the way up, and back into kinetic energy on the way down. A bowler who increases the potential energy of the ball during the



Kinetic Energy

$KE_{Back} = \frac{1}{2}\ 80(2)^2 = 160\ J$

$KE_{Small} = \frac{1}{2}\ 70(-8)^2 = 2240\ J$

$KE_{Big} = \frac{1}{2}\ 140(-4)^2 = 1120\ J$

$Total_{Small} = 2400\ J$

$Total_{Big} = 1280\ J$

Conservation of Momentum

$m_1V_1 + m_2V_2 = m_1V_2 + m_2V_2$

Small $80(2) - 70(8) = (70 + 80)\ V_2$

$V_2 = -2.7\ m/s$

Big $80(2) - 140(4) = (80 + 140)\ V_2$

$V_2 = -1.8\ m/s$

Figure 6.16. Comparison of the kinetic energy (scalar) and momentum (vector) in a football collision. If you were the running back, you would not score a touchdown against either defender, but the work done on your body would be greater in colliding with the smaller defender because of their greater kinetic energy.

approach can convert this energy to kinetic energy prior to release (Figure 6.17). In a similar manner, in golf or tennis a forward swing can convert the potential energy from preparatory movement into kinetic energy. A major application area of conservation of energy is the study of heat or thermodynamics.

The First Law of Thermodynamics is the law of conservation of energy. This is the good news: when energy is added into a machine, we get an equal amount of other forms of energy out. Unlike these examples, examination of the next mechanical energy (strain energy) will illustrate the bad news of the Second Law of Thermodynamics: that it is impossible to create a machine that converts all input energy into some useful output energy. In other words, man-made devices will always lose

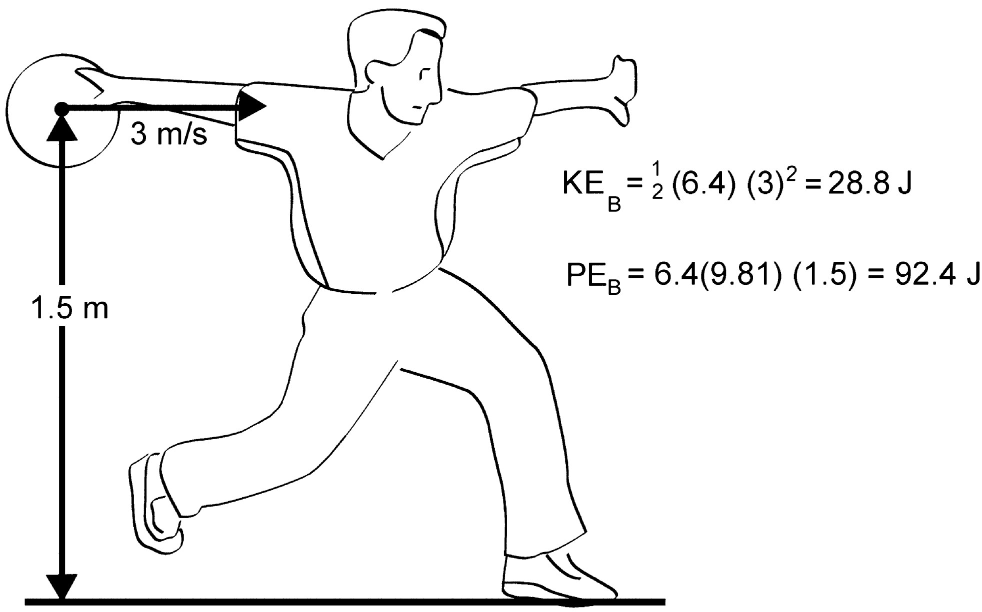


Figure 6.17. Raising a bowling ball in the approach stores more potential energy in the ball than the kinetic energy from the approach. The potential energy of the ball can be converted to kinetic energy in the downswing.

energy in some non-useful form and never achieve 100% efficiency. This is similar to the energy losses (hysteresis) in strain energy stored in deformed biological tissues studied in chapter 4.

Strain energy is the energy stored in an object when an external force deforms that object. Strain energy can be viewed as a form of potential energy. A pole vaulter stores strain energy in the pole when loading the pole by planting it in the box. Much of the kinetic energy stored in the vaulter's body during the run up is converted into strain energy and back into kinetic energy in the vertical direction. Unfortunately, again, not all the strain energy stored in objects is recovered as useful energy. Often large percentages of energy are converted to other kinds of energy that are not effective in terms of producing movement. Some strain energy stored in many objects is essentially lost because it is converted into sound waves or heat. Some machines employ heat production to do work, but in human movement heat is a byproduct of many energy transformations that must be dissipated. Heat is often even more costly than the mechanical energy in human movement because the cardiovascular system must expend more chemical energy to dissipate the heat created by vigorous movement.

The mechanical properties of an object determine how much of any strain energy is recovered in restitution as useful work. Recall that many biomechanical tissues are viscoelastic and that the variable hysteresis (area between the loading and unloading force-displacement curves) determines the amount of energy lost to unproductive energies like heat. The elasticity of a material is defined as its stiffness. In many sports involving elastic collisions, a simpler variable can be used to get an estimate of the elasticity or energy losses of an object *relative to another object*. This variable is called the **coefficient of restitution** (COR and e are common abbreviations). The coefficient of restitution is a dimensionless number usually ranging from 0 (perfectly plastic collision: mud on your mother's kitchen floor) to near 1 (very elastic pairs of materials). The coefficient of restitution cannot be equal to or greater than 1 because of the second law of thermodynamics. High coefficients of restitution represent elastic collisions with little wasted energy, while lower coefficients of restitution do not recover useful work from the strain energy stored in an object.

The coefficient of restitution can be calculated as the relative velocity of separation divided by the relative velocity of approach of the two objects during a collision (Hatze, 1993). The most common use of the coefficient of restitution is in defining the relative elasticities of balls used in sports. Most sports have strict rules governing the dimensions, size, and specifications, including the ball and playing surfaces. Officials in basketball or tennis drop balls from a standard height and expect the ball to rebound to within a small specified range allowed by the rules. In these uniformly accelerated flight and impact conditions where the ground essentially doesn't move, e can be calculated with this formula: $e = (\text{bounce}/\text{drop})^{1/2}$. If a tennis ball were dropped from a 1-meter height and it rebounded to 58 cm from a concrete surface, the coefficient of restitution would be $(58/100)^{1/2} = 0.76$. Dropping the same tennis ball on a short pile carpet might result in a 45-cm rebound, for an e = 0.67. The coefficient of restitution for a sport ball varies depending on the nature of the other object or surface it interacts with (Cross, 2000), the velocity of the collision, and other factors like temperature. Squash players know that it takes a few rallies to warm up the ball and increase its coefficient of restitution. Also, putting softballs in a refrigerator will take some of the slugging percentage out of a strong hitting team.

Most research on the COR of sport balls has focused on the elasticity of a ball in the vertical direction, although there is a COR in the horizontal direction that affects friction and the change in horizontal ball velocity for oblique impacts (Cross, 2002). The horizontal COR strongly affects the spin created on the ball following impact. This is a complicated phenomenon because balls deform and can slide or rotate on a surface during impact. How spin, in general, affects the bounce of sport balls will be briefly discussed in the section on the spin principle in chapter 8.

Mechanical Work

All along we have been defining mechanical energies as the ability to do mechanical work. Now we must define **work** and understand that this mechanical variable is not exactly the same as most people's common perception of work as some kind of effort. The mechanical work done on an object is defined as the product of the force and displacement in the direction of the force ($W = \mathbf{F} \cdot \mathbf{d}$). Joules are the units of work: one joule of work is equal to one Nm. In the English system, the units of work are usually written as foot-pounds (ft·lb) to avoid confusion with the angular kinetic variable torque, whose unit is the lb·ft. A patient performing rowing exercises (Figure 6.18) performs positive work ($W = 70 \cdot 0.5 = +35$ Nm or Joules) on the weight. In essence, energy flows from the patient to the weights (increasing their potential energy) in the concentric phase of the exercise. In the eccentric phase of the exercise the work is negative, meaning that potential energy is being transferred from the load to the patient's body. Note that the algebraic formula assumes the force applied to the

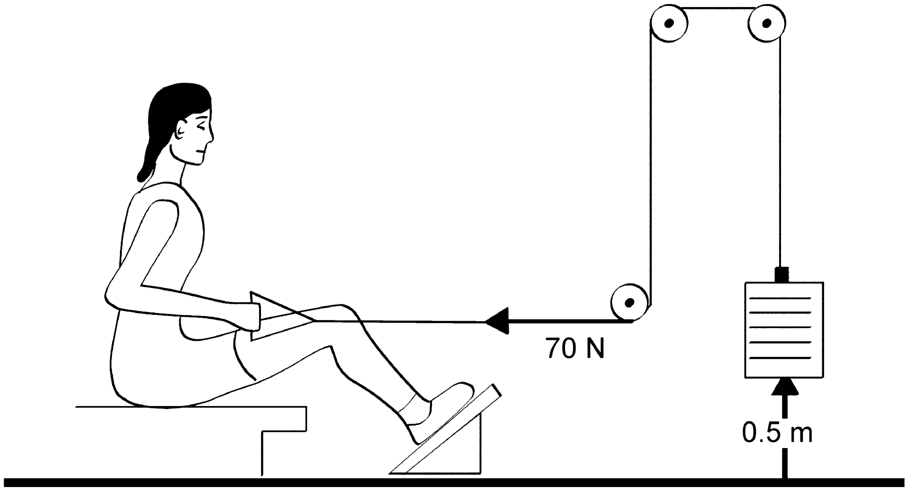


Figure 6.18. The mechanical work done on a weight in this rowing exercise is the product of the force and the displacement.

load is constant over the duration of the movement. Calculus is necessary to calculate the work of the true time-varying forces applied to weights in exercises. This example also assumes that the energy losses in the pulleys are negligible as they change the direction of the force created by the patient.

Note that mechanical work can only be done on an object when it is moved relative to the line of action of the force. A more complete algebraic definition of mechanical work in the horizontal (x) direction that takes into account the component of motion in the direction of the force on an object would be $W = (\mathbf{F} \cos \theta) \cdot \mathbf{d}_x$. For example, a person pulling a load horizontally on a dolly given the data in Figure 6.19 would do 435 Nm or Joules of work. Only the horizontal component of the force times the displacement of object determines the work done. Note also that the angle of pull in this example is like the muscle angle of pull analyzed earlier. The smaller the angle of pull, the greater the horizontal component of the force that does work to move the load.

The vertical component of pull does not do any mechanical work, although it may decrease the weight of the dolly or load and, thereby decrease the rolling friction to be overcome. What is the best angle to pull in this situation depends on many factors. Factoring in rolling friction and the strength (force) ability in various pulling postures might indicate that a higher angle of pull that doesn't maximize the horizontal force component may be "biomechanically" effective for this person. The inertia of the load, the friction under the person's feet, and the biomechanical factors of pulling from different postures all interact to determine the optimal angle for pulling an object. In fact, in some closed kinematic chain movements (like cycling) the optimal direction of force application does not always maximize the effectiveness or the component of force in the direction of motion (Doorenbosch *et al.*, 1997).

Mechanical work does not directly correspond to people's sense of muscular effort. Isometric actions, while taking considerable effort, do not perform mechanical

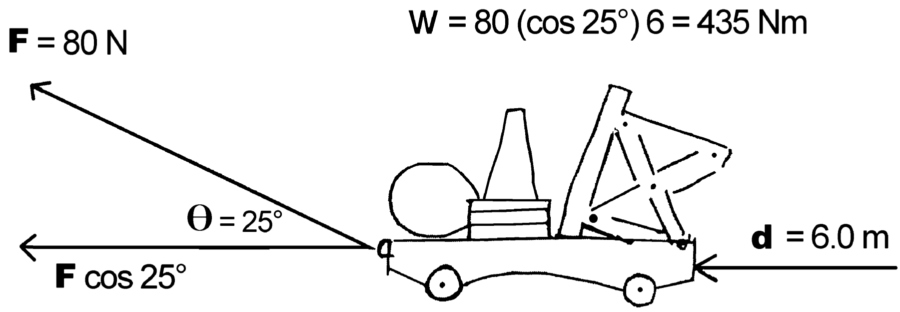


Figure 6.19. Mechanical work is calculated as displacement of the object in the direction of the force. This calculation is accurate if the 80-N force is constant during horizontal displacement of the dolly. If you were pulling this dolly, what angle of pull would you use?

work. This dependence on the object's displacement of mechanical work makes the work–energy relationship useful in biomechanical studies where the motion of an object may be of more interest than temporal factors.

This brings us to the **Work–Energy Relationship**, which states that the mechanical work done on an object is equal to the change in mechanical energy of that object. Biomechanical studies have used the work–energy relationship to study the kinetics of movements. One approach calculates the changes in mechanical energies of the segments to calculate work, while the other calculates mechanical power and integrates these data with respect to time to calculate work. The next section will discuss the concept of mechanical power.

Mechanical Power

Mechanical power is an important kinetic variable for analyzing many human movements because it incorporates time. Power is defined as the rate of doing work, so mechanical power is the time derivative of mechanical work or work divided by time (P = W/t). Note that a capital "P" is used because lower-case "**p**" is the symbol for momentum. Typical units of power are Watts (one J/s) and horsepower. One horsepower is equal to 746 W. Maximal mechanical power is achieved by the right combination of force and velocity that maximizes the mechanical work done on an object. This is clear from the other formula for calculating power: P = **F** · **v**. Prove to yourself that the two equations for power are the same by substituting the formula for work W and do some rearranging that will allow you to substitute **v** for its mechanical definition.

If the concentric lift illustrated in Figure 6.18 was performed within 1.5 seconds, we could calculate the average power flow to the weights. The positive work done on the weights was equal to 35 J, so P = W/t = 35/1.5 = 23.3 W. Recall that these algebraic definitions of work and power calculate a mean value over a time interval for constant forces. The peak instantaneous power flow to the weight in Figure 6.18 would be higher than the average power calculated over the whole concentric phase of the lift. The Force–Motion Principle would say that the patient increased the vertical force on the resistance to more than the weight of the stack to positively accelerate it and would reduce this force to below the weight of the stack to gradually stop the weight at the end of the concentric phase. Instantaneous power flow to the weights also follows a complex pattern based on a combination of the force applied and the motion of the object.

What movements do you think require greater peak mechanical power delivered to a barbell: the lifts in the sport of Olympic weight lifting or power lifting? Don't let the names fool you. Since power is the rate of doing work, the movements with the greatest mechanical power must have high forces and high movement speeds. Olympic lifting has mechanical power outputs much higher than power lifting, and power lifting is clearly a misnomer given the true definition of power. The dead lift, squat, and bench press in power lifting are high-strength movements with large loads but very slow velocities. The faster movements of Olympic lifting, along with smaller weights, clearly create a greater power flow to the bar than power lifting. Peak power flows to the bar in power lifting are between 370 and 900 W (0.5–1.2 hp), while the peak power flow to a bar in Olympic lifts is often as great as 4000 W or 5.4 hp (see Garhammer, 1989). Olympic lifts are often used to train for "explosive" movements, and Olympic weight lifters can create significantly more whole-body mechanical power than other athletes (McBride, Triplett-McBride, Davie, & Newton, 1999).

Many people have been interested in the peak mechanical power output of whole-body and multi-segment movements. It is believed that higher power output is critical for quick, primarily anaerobic movements. In the coaching and kinesiology literature these movements have been described as "explosive." This terminology may communicate the point of high rates of force development and high levels of both speed and force, but a literal interpretation of this jargon is not too appealing! Remember that the mechanical power output calculated for a human movement will strongly depend on the model (point mass, linked segment, etc.) used and the time interval used in the calculation. The average or instantaneous power flows within the body and from the body to external objects are quite different. In addition, other biomechanical factors affect how much mechanical power is developed during movements.

The development of maximal power output in human movement depends on the direction of the movement, the number of segments used, and the inertia of the object. If we're talking about a simple movement with a large resistance, the right mix of force and velocity may be close to 30 to 45% of maximal isometric strength because of the Force–Velocity Relationship (Izquierdo *et al.*, 1999; Kaneko *et al.*, 1983; Wilson *et al.*, 1993). Figure 6.20 shows the *in vitro* concentric power output of skeletal muscle derived from the product of force and velocity in the Force–Velocity Relationship. In movements requiring multi-joint movements, specialized dynamometer measurements indicate that the best resistances for peak power production and training are likely to be higher than the 30–45% and differ between the upper and lower extremi-

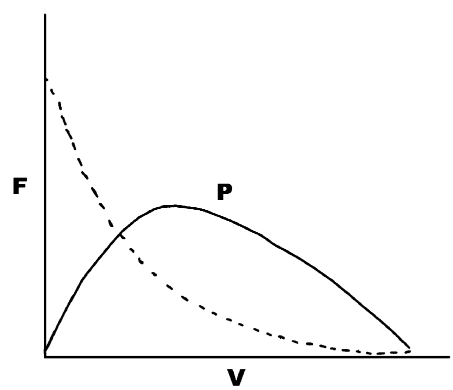


Figure 6.20. The *in vitro* mechanical power output of skeletal muscle. Note that peak power in concentric actions does not occur at either the extremes of force or velocity.

Interdisciplinary Issue: Efficiency

One area of great potential for interdisciplinary cooperation is in determining the efficiency of movement. This efficiency of human movement is conceptually different from the classical definition of efficiency in physics. Physics defines efficiency as the mechanical work output divided by the mechanical work input in a system, a calculation that helps engineers evaluate machines and engines. For endurance sports like distance running, adjusting a formula to find the ratio of mechanical energy created to metabolic cost appears to be an attractive way to study human movement (van Ingen Schenau & Cavanagh, 1999). Progress in this area has been hampered by the wide variability of individual performance and confusion about the various factors that contribute to this movement efficiency (Cavanagh & Kram, 1985). Cavanagh and Kram argued that the efficiency of running, for example, could be viewed as the sum of several efficiencies (e.g., biochemical, biomechanical, physiological, psychomotor) and other factors. Examples of the complexity of this area are the difficulty in defining baseline metabolic energy expenditure and calculating the true mechanical work because more work is done than is measured by ergometers. For instance, in cycle ergometry the mechanical work used to move the limbs is not measured. Biomechanists are also struggling to deal with the zero-work paradox in movements where there no net mechanical work is done, like in cyclic activities, co-contracting muscles, or forces applied to the pedal in an ineffective direction. Figure 6.21 illustrates the typical forces applied to a bicycle pedal at 90° (from vertical). The normal component of the pedal force does mechanical work in rotating the pedal ($\mathbf{F}_N$), while the other component does no work that is transferred to the bike's flywheel. Movement efficiency is an area where cooperative and interdisciplinary research may be of interest to many scientists and may be an effective tool for improving human movement.

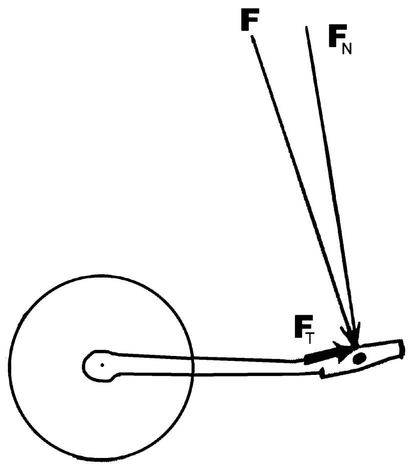


Figure 6.21. Only some of the force applied to a bicycle pedal creates work and mechanical power. Note how the angle of the pedal illustrated means that a small component of $\mathbf{F}_T$ actually resists the normal force ($\mathbf{F}_N$) creating rotation.

ties (Funato *et al.*, 1996, 2000; Newton *et al.*, 1996). The best conditioning for "explosive" movements may be the use of moderate resistances (just less than strength levels that are usually >70% 1RM), which are moved as quickly as possible. Oftentimes these exercises use special equipment like the Plyometric Power System, which allows for the resistance to be thrown (Wilson *et al.*, 1993). The disadvantage of high-speed exercise is that it focuses training on the early concentric phase, leaving much of the range of motion submaximally trained. Even slow, heavy weight training exercises have large submaximal percentages (24–52%) of range of motion due to negative acceleration of the bar at the end of the concentric phase (Elliott, Wilson, & Kerr, 1989).

There are several field tests to estimate short-term explosive leg power, but the utility and accuracy of these tests are controversial. The Margaria test (Margaria, Aghemo, & Rovelli, 1966) estimates power from running up stairs, and various vertical jump equations (see Johnson & Bahamonde, 1996; Sayers, Harackiewicz, Harman, Frykman, & Rosenstein, 1999) have been proposed that are based on the original Sargent (1921) vertical jump test. Companies now sell mats that estimate the height and power of a vertical jump (from time and projectile equations). Although mechanical power output in such jumps is high, these tests and devices are limited because the resistance is limited to body mass, the many factors that affect jump height, and the assumptions used in the calculation. There has been a long history of criticism of the assumptions and logic of using vertical jump height to estimate muscular power (Adamson & Whitney, 1971; Barlow, 1971; Winter, 2005). Instantaneous measurements of power from force platforms or kinematic analysis are more accurate but are expensive and time-consuming. Future studies will help determine the role of mechanical power in various movements, how to train for these movements, and what field tests help coaches monitor athletes.

SEGMENTAL INTERACTION PRINCIPLE

Human movement can be performed in a wide variety of ways because of the many kinematic **degrees of freedom** our linked segments provide. In chapter 5 we saw that coordination of these kinematic chains ranges along a continuum from simultaneous to sequential. Kinetics provides several ways in which to examine the potential causes of these coordination patterns. The two expressions of Newton's second law and the work–energy relationship have been employed in the study of the coordination of movement. This section proposes a Principle of Segmental Interaction that can be used to understand the origins of movement so that professionals can modify movement to improve performance and reduce risk of injury.

The **Segmental Interaction Principle** says that forces acting between the segments of a body can transfer energy between segments. The biomechanics literature has referred to this phenomenon in several ways (Putnam, 1993). The contribution of body segments to movement has been called coordination of temporal impulses (Hochmuth & Marhold, 1978), the kinetic link principle (Kreighbaum & Barthels, 1996), summation of speed (Bunn, 1972), summation or continuity of joint torques (Norman, 1975), the sequential or proximal-to-distal sequencing of movement (Marshall & Elliott, 2000), and the transfer of energy or transfer of momentum (Lees & Barton, 1996; Miller, 1980). The many names for this phenomenon and the three ways to document kinetics are a good indication of the difficulty of the problem

Application: Strength vs. Power

The force–velocity relationship and domains of strength discussed in chapter 4, as well as this chapter's discussion of mechanical power should make it clear that muscular strength and power are not the same thing. Like the previous discussion on power lifting, the common use of the term *power* is often inappropriate. Muscular strength is the expression of maximal tension in isometric or slow velocities of shortening. We have seen that peak power is the right combination of force and velocity that maximizes mechanical work. In cycling, the gears are adjusted to find this peak power point. If cadence (pedal cycles and, consequently, muscle velocity of shortening) is too high, muscular forces are low and peak power is not achieved. Similarly, power output can be submaximal if cadence is too slow and muscle forces high. The right mix of force and velocity seems to be between 30 and 70% of maximal isometric force and depends on the movement. Kinesiology professionals need to keep up with the growing research on the biomechanics of conditioning and sport movements. Future research will help refine our understanding of the nature of specific movements and the most appropriate exercise resistances and training programs.

and the controversial nature of the causes of human motion.

Currently it is not possible to have definitive answers on the linear and angular kinetic causes for various coordination strategies. This text has chosen to emphasize the forces transferred between segments as the primary kinetic mechanism for coordination of movement. Most electromyographic (EMG) research has shown that in sequential movements muscles are activated in short bursts that are timed to take advantage of the forces and geometry between adjacent segments (Feldman *et al.*, 1998; Roberts, 1991). This coordination of muscular kinetics to take advantage of "passive dynamics" or "motion-dependent" forces (gravitational, inertial forces) has been observed in the swing limb during walking (Mena, Mansour, & Simon, 1981), running (Phillips, Roberts, & Huang, 1983), kicking (Roberts, 1991), throwing (Feltner, 1989; Hirashima, Kadota, Sakurai, Kudo, & Ohtsuki, 2002), and limb motions toward targets (Galloway & Koshland, 2002) and limb adjustments to unexpected obstacles (Eng, Winter, & Patla, 1997).

Some biomechanists have theorized that the segmental interaction that drives the sequential strategy is a transfer of energy from the proximal segment to the distal segment. This theory originated from observations of the close association between the negative acceleration of the proximal segment (see the activity on Segmental Interaction below) with the positive acceleration of the distal segment (Plagenhoef, 1971; Roberts, 1991). This mechanism is logically appealing because the energy of large muscle groups can be transferred distally and is consistent with the large forces and accelerations of small segments late in baseball pitching (Feltner & Dapena, 1986; Fleisig, Andrews, Dillman, & Escamilla, 1995; Roberts, 1991). Figure 6.22 illustrates a schematic of throwing where the negative angular acceleration of the arm ($\boldsymbol{\alpha}_A$) creates

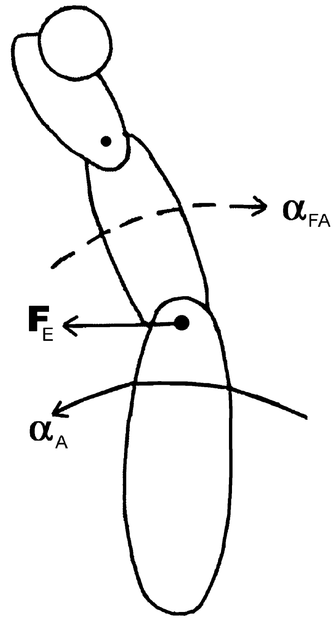


Figure 6.22. Simple sagittal plane model of throwing illustrates the Segmental Interaction Principle. Joint forces ($\mathbf{F}_E$) from a slowing proximal segment create a segmental interaction to angularly accelerate the more distal segments ($\boldsymbol{\alpha}_{FA}$).

a backward elbow joint force ($\mathbf{F}_E$) that accelerates the forearm ($\boldsymbol{\alpha}_{FA}$). This view of the Segment Interaction Principle states that slowing the larger proximal segment will transfer energy to the distal segment. It is clear that this movement strategy is highly effective in creating high-speed movements of distal segments, but the exact mechanism of the segmental interaction principle is not clear.

When you get down to this level of kinetics, you often end up with a chicken-or-egg dilemma. In other words, which force/torque was created first and which is the reaction force/torque (Newton's third law)? There are some scholars who have derived equations that support the proximal-to-distal transfer of energy (Hong, Cheung, & Roberts, 2000; Roberts, 1991), while others show that the acceleration of the distal segment causes slowing of the proximal segment (Putnam, 1991, 1993; Nunome *et al.*, 2002, 2006; Sorensen *et al.*, 1996). Whatever the underlying mechanism or direction of transfer, fast human movements utilize a sequential (proximal-to-distal) coordination that relies on the transfer of forces/energy between segments. We are truly fortunate to have so many muscles and degrees of freedom to create a wide variety and speeds of motion.

A good example of the controversy related to the Segmental Interaction Principle is the role of the hand and wrists in the golf swing. Skilled golf shots can be accurately modeled as a two-segment (arm and club) system with motion occurring in a diagonal plane. Golf pros call this the swing plane. Some pros say the golfer should actively drive the club with wrist action, while others teach a relaxed or more passive wrist release. A recent simulation study found that correctly timed wrist torques could increase club head speed by 9% (Sprigings & Neal, 2000), but the small percentage and timing of these active contributions suggests that proximal joint forces are the primary accelerator of the club. Jorgensen (1994) has provided simple qualitative demonstrations and convincing kinetic data that support the more relaxed use of wrist action and explain how weight shifts can be timed to accelerate the golf club.

It is clear that forces are transferred between segments to contribute to the motion of the kinematic chain (Zajac & Gordon, 1989). The exact nature of that segmental interaction remains elusive, so kinesiology professionals can expect performers to have a variety (sequential to simultaneous) of combinations of joint motion. It would be unwise to speculate too much on the muscular origins of that transfer. This view is consistent with the EMG and biomechanical modeling research reviewed in chapter 3. So how can kinesiology professionals prescribe conditioning exercises and learning progressions so as to maximize the segmental interaction effect? Currently, there are few answers, but we can make a few tentative generalizations about conditioning and learning motor skills.

Physical conditioning for any human movement should clearly follow the training principle of *specificity*. Biomechanically, this means that the muscular actions and movements should emulate the movement as much as possible. Since the exact kinetic mechanism of segmental interaction is not clear, kinesiology professionals should select exercises that train all the muscles involved in a movement. In soccer kicking, it is not clear whether it is the activity of the quadriceps or hip flexors that predominantly contribute to acceleration of the lower leg. Selecting exercises that train both

Activity: Segmental Interaction

Segmental interaction or the transfer of energy from a proximal to a distal segment can be easily simulated using a two-segment model. Suspend a rigid stick (ruler, yardstick, racket) between the tips of your index finger and thumb. Using your hand/forearm as the proximal segment and the stick as the distal segment, simulate a kick. You can make the stick extend or kick without any extensor muscles by using intersegmental reaction forces. Accelerate your arm in the direction of the kick (positive). When you reach peak speed, rapidly slow (negatively accelerate) your arm and observe the positive acceleration of the stick. Positive acceleration of your arm creates an inertial lag in the stick, while negative acceleration of your arm creates a backward force at the joint, which creates a torque that positively accelerates the stick.

muscles is clearly indicated. More recent trends in rehabilitation and conditioning have focused on training with "functional" movements that emulate the movement, rather than isolating specific muscle groups. The resistance, body motion, speed, and balance aspects of "functional" exercises may be more specific forms of training; unfortunately, there has been limited research on this topic.

Interdisciplinary Issue: Kinematic Chain

A *kinematic chain* is an engineering term that refers to a series of linked rigid bodies. The concept of kinematic chains was developed to simplify the mathematics of the kinematics and kinetics of linked mechanical systems. A classic biomechanics textbook (Steindler, 1955) adapted this terminology to refer to the linked segments of the human body as a "kinetic chain" and to classify movements as primarily "open" or "closed" kinetic chains. A closed kinetic chain is a movement where the motion of the distal segment is restrained by "considerable external resistance." Over the years, the rehabilitation and conditioning professions have adopted this terminology, referring to open kinetic chain exercises (knee extension) and closed kinetic chain exercises (leg press or squat). Considerable research has focused on the forces and muscle activation involved in various exercises classified as open or closed kinetic chains. This research has shown both similarities and differences in muscular function between similar open and closed kinetic chain movements. There are, however, problems in uniquely defining a closed chain or what constitutes "considerable resistance." The vague nature of the classification of many exercises has prompted calls to avoid this terminology (Blackard *et al.*, 1999; di Fabio, 1999; Dillman *et al.*, 1994).

Learning the sequential coordination of a large kinematic chain is a most difficult task. Unfortunately, there have been relatively few studies on changes in joint kinetics accompanied by learning. Assuming that the energy was transferred distally in a sequential movement (like our immature volleyball spike in the previous chapter), it would not be desirable to practice the skill in parts because there would be no energy to learn to transfer. Recent studies have reinforced the idea that sequential skills should be learned in whole at submaximal speed, rather than in disconnected parts (see Sorensen, Zacho, Simonsen, Dyhre-Poulsen, & Klausen, 2000). Most modeling and EMG studies of the vertical jump have also shown the interaction of muscle activation and coordination (Bobbert & van Zandwijk, 1999; Bobbert & van Soest, 1994; van Zandwijk, Bobbert, Munneke, & Pas, 2000), while some other studies have shown that strength parameters do not affect coordination (Tomioka, Owings, & Grabiner, 2001). Improvements in computers, software, and biomechanical models may allow more extensive studies of the changes in kinetics as skills are learned. Currently, application of the **Segmental Interaction Principle** involves corrections in body positioning and timing. Practice should focus on complete repetitions of the whole skill performed at submaximal speeds. Improvement should occur with many practice repetitions, while gradually increasing speed. This perspective is consistent with more recent motor learning interest in a dynamical systems theory understanding of coordination, rather than centralized motor program (Schmidt & Wrisberg, 2000).

Application: Arm Swing Transfer of Energy

Many movements incorporate an arm swing that is believed to contribute to performance. How much does arm swing contribute to vertical jump performance? Several studies have shown that the height of a jump increases by about 10% with compared to those without arm swing (see Feltner, Fraschetti, & Crisp, 1999). There are several possible mechanisms involving multiple transfers of energy or momentum between the arms and body (Lees *et al*., 2004). Logically, vigorous positive (upward) acceleration of the arms creates a downward reaction force on the body that increases the vertical ground reaction force. It has also been hypothesized that this downward force creates a pre-loading effect on the lower extremities that limits the speed of knee extension, allowing greater quadriceps forces because of the Force–Velocity Relationship. A detailed kinetic study (Feltner *et al*., 1999) found that augmenting knee torques early in a jump with arm swings combined with slowing of trunk extension late in the jump may be the mechanisms involved in a good arm swing during a vertical jump. Late in the jump, the arms are negatively accelerated, creating a downward force at the shoulder that slows trunk extension and shortening of the hip extensors. While the arms do not weigh a lot, the vigor of these movements does create large forces, which can be easily seen by performing this arm swing pattern standing on a force platform.

What segmental interactions create and transfer this energy? This answer is less clear and depends on the model and kinetic variable used during analysis. The muscular and segmental contributions to a vertical jump have been analyzed using force platforms (Luthanen & Komi, 1978a,b), computer modeling (Bobbert & van Soest, 1994; Pandy, Zajac, Sim, & Levine, 1990), joint mechanical power calculations (Fukashiro & Komi, 1987; Hubley & Wells, 1983; Nagano, Ishige, & Fukashiro, 1998), angular momentum (Lees & Barton, 1996), and net joint torque contributions to vertical motion (Feltner *et al*., 1999, 2004; Hay, Vaughan, & Woodworth, 1981). While the jumping technique may look quite similar, there is considerable between-subject variation in the kinetics of the vertical jump (Hubley & Wells, 1983). The problems involved in partitioning contributions include defining energy transfer, energy transfer of biarticular muscles, muscle co-activation, and bilateral differences between limbs. While there is much yet to learn, it appears that the hip extensors contribute the most energy, closely followed by the knee extensors, with smaller contributions by the ankle plantar flexors. Conditioning for vertical jumping should utilize a variety of jumps and jump-like exercises. If specific muscle groups are going to be isolated for extra training, the hip and knee extensors appear to be the groups with the greatest contribution to the movement.

SUMMARY

Linear kinetics is the study of the causes of linear motion. There are several laws of mechanics that can be applied to a study of the causes of linear motion: Newton's laws, the impulse–momentum relationship, and the work–energy relationship. The most common approach involves Newton's Laws of Motion, called the laws of *Inertia*, *Momentum/Acceleration*, and *Reaction*. Inertia is the tendency of all objects to resist changes in their state of motion. The Inertia Principle suggests that reducing mass will make objects easier to accelerate, while increasing mass will make objects more stable and harder to accelerate. Applying the Inertia Principle might also mean using more mass in activities where there is time to overcome the inertia, so that it can be used later in the

Interdisciplinary Issue: Power in Vertical Jumping

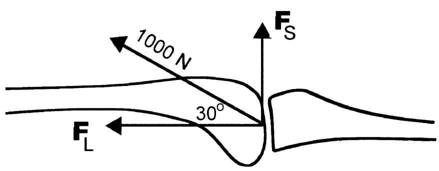
One of the contentious uses of the word "power" occurs in the strength and conditioning literature, specifically as it relates to the use of the vertical jump as a measure of lower extremity muscular function. Soon after the Sargent (1921) jump test that was published, many authors have tried to use the standing vertical jump as a measure of the external power or "explosive" anaerobic power. There is a correlation between measures of external power flow to a force platform and jump height, so many regression equations can be used to estimate average or peak power from jump height and body mass. Despite eloquent arguments, Newton's Second law, and experiments showing net impulse is really the mechanical variable that determines jump height (Adamson & Whitney, 1971; Barlow, 1971; Winter, 2005), the coaching and conditioning literature continues to use the terms "muscular" or "muscle power" in misleading ways related to vertical jump tests. Students can help the field progress by correct use of terminology and contributing to interdisciplinary research in this area. When measurement, biomechanics, strength and conditioning, and exercise physiology scholars collaborate and consistently use terminology, real progress can be made in understanding muscular performance.

movement. When two objects are in contact, the forces of interaction between the bodies are resolved into right-angle directions: normal reaction and friction. The Impulse–Momentum Relationship says that the change in momentum of an object is equal to the impulse of the resultant forces acting on the object. This is Newton's second law when applied over a time interval. The real-world application of this relationship is the Force–Time Principle. Energy is the capacity to do mechanical work; mechanical energies include strain, potential, and kinetic energy. The Work–Energy Relationship says that mechanical work equals the change in mechanical energy. Mechanical power is the rate of doing work, and can also be calculated by the product of force and velocity. The Segmental Interaction Principle says that energy can be transferred between segments. While the exact nature of these transfers has been difficult to determine, both simultaneous and sequentially coordinated movements take advantage of the energy transferred through the linked segment system of the body.

REVIEW QUESTIONS

1. Which has more inertia, a 6-kg bowling ball sitting on the floor or one rolling down the lane? Why?
2. What are the two ways to express Newton's second law?
3. When might it be advantageous for a person to increase the inertia used in a movement?
4. Do smaller or larger muscle angles of pull on a distal segment tend to create more joint rotation? Why?
5. What are strategies to increase the friction between a subject's feet and the floor?
6. What two things can be changed to increase the impulse applied to an object? What kinds of human movement favor one over the other?
7. If the force from the tibia on the femur illustrated below was 1000 N acting at 30° to the femur, what are the longitudinal

(causing knee compression) and normal (knee shear) components of this force? Hint: move one component to form a right triangle and solve.



8. Give human movement examples of the three mechanical energies.

9. Compare and contrast muscular strength and muscular power.

10. How is momentum different from kinetic energy?

11. A rock climber weighing 800 N has fallen and is about to be belayed (caught with a safety rope) by a 1500-N vertical force. Ignoring the weight of the rope and safety harness, what is the vertical acceleration of the climber? Hint: remember to sum forces with correct signs (related to direction).

12. Draw a free-body diagram of a proximal segment of the body showing all forces from adjacent segments. Draw a free body diagram of an adjacent segment using Newton's third law to determine the size and direction at the joint.

13. What are the potential kinetic mechanisms that make a sequential motion of segments in high-speed movements the optimal coordination?

14. Do the angles of pull (relative to the body) of free weights change during an exercises? Why?

15. An Olympic lifter exerts a 4000-N upward (vertical) force to a 30-kg barbell. What direction will the bar tend to move, and what is its vertical acceleration?

KEY TERMS

conservation of energy (Law of Conservation of Energy)
degrees of freedom
direct dynamics
energy
force platform
force–time principle
friction
impulse
impulse–momentum relationship
inverse dynamics
kinetic energy
Law of Acceleration
Law of Inertia
Law of Reaction
momentum
normal reaction
potential energy
power (mechanical)
strain energy
work (mechanical)
work–energy relationship

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WEB LINKS

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http://btc.montana.edu/olympics/physbio/physics/dyn01.html

Ankle power flow tutorial from the Clinical Gait Analysis website.
http://guardian.curtin.edu.au:16080/cga/teach-in/plantarflexors/

Kinetics Concepts—See the Newton's Laws, momentum, and work and energy tutorials from the The Physics Classroom.
http://www.physicsclassroom.com/mmedia/index.html