Fluid Mechanics

External forces that have a major effect on most human movements are related to immersion in or flow of fluids past a body. This chapter reviews the mechanical effect of moving through air and water, the two most common fluids encountered in human movement. Fluid forces usually result in considerable resistance to high-velocity movements through fluids, so many sport techniques and pieces of equipment are designed to minimize fluid resistance. Fluid forces, however, can also be used to create movement, like in the skillful application of spin to projectiles. This chapter concludes with application of this use of fluid forces in the **Principle of Spin**.

FLUIDS

You may have studied the various states of matter in physics or noticed that many substances are not easily classified as totally solid or liquid. Mechanically, fluids are defined as substances that *flow or continuously deform when acted upon by shear forces*. A thorough review of all the nuances of fluid mechanics is not possible, so key concepts related to the supporting force of immersion in fluids and the forces that arise from moving through fluids will be reviewed. Several references are cited to guide students interested in digging deeper into the nuances of fluid mechanics.

FLUID FORCES

For the purposes of this chapter, the major fluid forces that affect human motion are classified according to an object's position or velocity within a fluid. When an object is placed in a fluid there is a resultant upward force or supporting fluid force called **buoyancy**. The fluid force related to how the fluid flows past the object is resolved into right-angle components called **lift** and **drag**. In most movement, people have considerable control over factors that affect these forces. Let's see how these fluid forces affect human movement.

Buoyancy

The vertical, supporting force of a fluid is called buoyancy. When an inanimate object is put in a fluid (like water), the vector sum of gravity and the buoyant force determines whether or not the object will float (Figure 8.1). The **Archimedes Principle** states that the size of the buoyant force is equal to the weight of the fluid displaced by the object. Folklore says that the famous
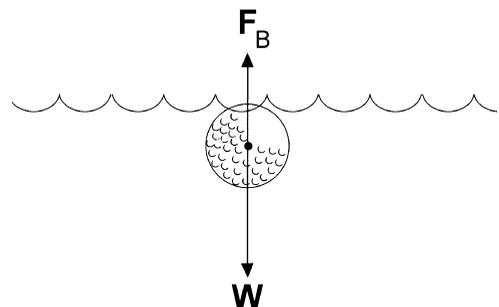

Figure 8.1. The resultant vector of gravity (**W**) and buoyancy (**F**$_B$) will determine if an inanimate object floats. This golf ball will sink to the bottom of the water hazard.

Greek physicist/mathematician realized this important principle when noticing water level changes while taking a bath.

A sailboat floats at a level where the weight of the boat and contents are equal in size to the weight of the volume of water displaced. Flotation devices used for water exercise and safety increase the buoyancy of a person in two ways: having a lower density (mass/volume) than water and having a hollow construction. These flotation devices displace water that weighs more than the device, increasing the buoyancy of the person.

In a gravitational field the mass of a fluid is attracted in a particular direction. The weight of water is typically 9800 N per cubic meter, but this figure gradually increases for water at greater depths. The deeper a scuba diver descends, the greater the fluid pressure around them (because of the greater mass of water essentially "on top" of them). This increased pressure in a particular volume of fluid means that the volume of water weighs more than a similar volume of water at the surface, so the buoyant force on objects tends to slightly increase as depth increases. A similar phenomenon occurs as we descend from a mountain, where the fluid pressure of the atmosphere on us increases. The buoyant force on the human body from the "sea" of atmospheric gases also depends on our depth (opposite of elevation), but is usually a fraction of a pound and can be ignored in vertical kinetic calculations of human movement.

The density of the human body is very close to that of water, largely due to the high water content of all tissue. Lean tissue (muscle and bone) have densities greater than water, while body fat tends to be less dense than water. The buoyant force on a swimmer varies with changes in body composition and when the person inhales or exhales. Taking a deep breath expands the chest, which increases the volume of the

body and increases the buoyant force. If you have ever taught a swimming class you know that people typically fall into three groups based on their somotype and body composition: floaters, conditional floaters, and sinkers. The majority of your swim class can easily float when holding their breath (conditional floaters). There will be a few folks who easily float (floaters) or cannot float (sinkers) without some form of propulsion or flotation device.

The buoyant force in water acts upward at the center of buoyancy. The **center of buoyancy** is essentially the centroid of the volume of water displaced by an object. In the human body, the trunk makes up most of the volume, so the center of buoyancy is located 1–2 cm superior (McLean & Hinrichs, 2000a) to the center of gravity (Figure 8.2). Since so much body volume is in the upper trunk, moving the rest of the body makes smaller changes in the center of buoyancy than in the center of gravity. Note that the weight force and buoyant force create a force couple that will tend to rotate the swimmer's legs down until the
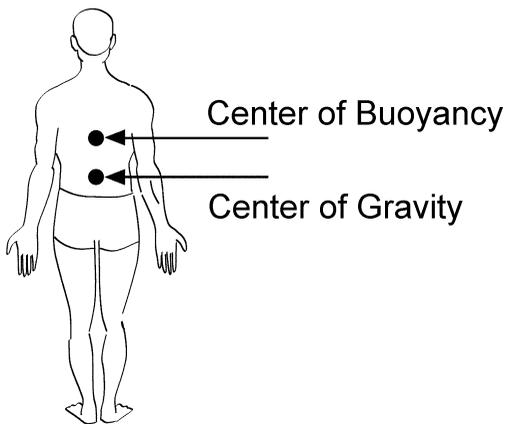
Figure 8.2. The center of buoyancy of the human body is superior to the center of gravity because of the large volume of the upper body.

weight and buoyant force are nearly colinear. Swimmers still scared of the water have great difficulty floating on their back because they tend to pike and lift the head/upper trunk out of the water. The resulting loss of buoyant force (from less water displacement) tends to dip the swimmer's head deeper into the water. If you are having difficulty getting a swimmer to relax and do a back float, how can you shift their limbs to shift the center of gravity and maintain a large buoyant force?

Application: Hydrotherapy

Therapeutic exercises in water utilize its buoyant force to unload the lower extremity. The amount of unloading of the body can be easily manipulated by the extent of submersion. This exercise modality differs from suspension systems that unload the body by pulleys lifting up the trunk because of other fluid forces. The flow of water also creates lift and drag forces that have been shown to create differences in muscle activation in exercise (Poyhonen, Kryolainen, Keskien, Hautala, Savolainen, & Malkia, 2001). Therapy pools that create currents for exercise likely exaggerate the neuromuscular differences between these movements and dry land movement.

We have seen that objects in a fluid experience a supporting force related to the position of the object in the fluid and the density of the object. The next section will deal with the interaction forces between an object and the fluid when there is relative motion between the two. These fluid motion forces can be quite large. The fluid forces between the air and your body are nearly identical if you are falling at 120 km/hr while skydiving in a specific body position or if you are apparently still on top of a column of 120 km/hr airflow in a simulator. In both these situations the drag forces on the body are equal to your body weight. In the first case the body is falling through essentially still air while in the second case the body is essentially stationary with air flowing over it.

Drag

The fluid force resisting motion between an object and a fluid is called **drag**. Drag acts in the same direction (parallel) as the relative flow of the fluid past an object and in the opposite direction of the object's motion in the fluid. Drag forces act on the fisherman (creek) and the fly (air) due to the relative motion of the fluid past the objects (see Figure 8.3). If there are no propulsive forces acting on the object, like a projectile (see chapter 5, p. 113), the drag force tends to slow down the motion of the projectile through the fluid. Since the drag force acts parallel to the relative flow of the fluid, it is much like the contact force of friction studied in chapter 6.

Research has shown that the size of the drag force (F_D) that must be overcome in a fluid can be calculated using the following formula: $F_D = \frac{1}{2}C_D \rho A_P V^2$. The coefficient of drag (C_D) is a dimensionless number much like the coefficient of friction or restitution. We will see later that C_D depends on many object and fluid flow factors. Drag
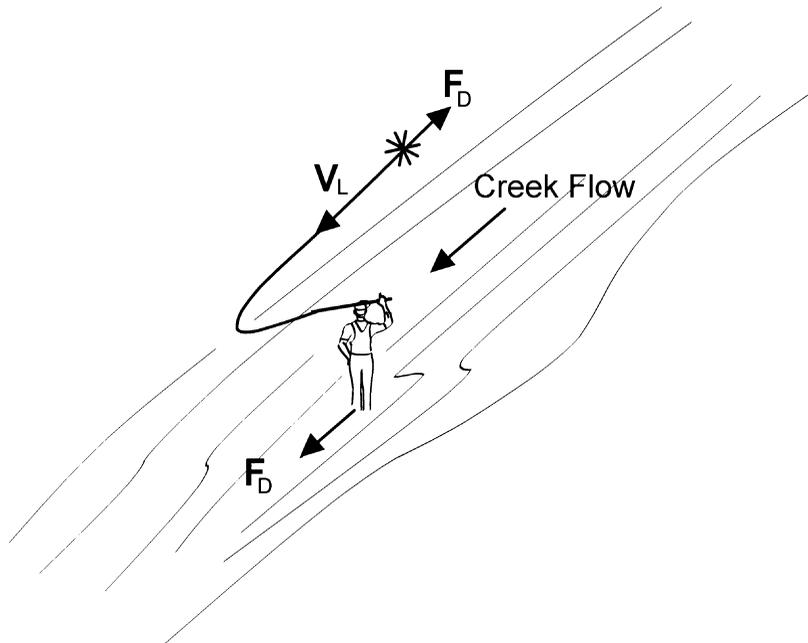
Figure 8.3. The fluid force of drag (F_D) acts in a direction opposing the relative flow of fluid past the object.

also depends on fluid density (ρ) and the projected frontal area (A_P) in the path of the fluid flow. The most important factor affecting drag is the relative velocity (V^2) of the fluid past the object.

Like the velocity term in kinetic energy, the force of drag varies with the square of the relative fluid velocity. This means that, all other things being equal, a cyclist that doubles and then triples his pace increases drag by 4 and 9 times compared to his initial speed! This explains why running faster or into a strong breeze feels much more difficult. The importance of the adjective "relative" can be easily appreciated by noting that it is easier to run with a strong breeze *behind* you. The dramatic effect of drag on sprint performance has forced the International Amateur Athletic Federation to not ratify sprint records if the wind assisting a runner exceeds 2.0 m/s. World records are always a controversial issue, but current weighting of records in many events does

not take into account the effect of altitude (Mureika, 2000) or latitude (Mizera & Horvath, 2002). Remember that relative velocity means that we are talking about a local kinematic frame of reference—in other words, the speed and direction of fluid flow relative to the object of interest. These drag forces increase with the square of velocity and often dramatically affect performance.

The Drag force on an object has several sources: *surface drag*, *pressure drag*, and *wave drag*. Understanding these drag forces is important for minimizing these resistances in many sports and activities.

Surface drag can be thought of as a fluid friction force, much like solid friction force studied in chapter 6. Surface drag is also commonly called friction drag or skin friction drag. It results from the frictional force between fluid molecules moving past the surface of an object and the frictional force between the various layers of the fluid. Viscosity is the internal resistance of a
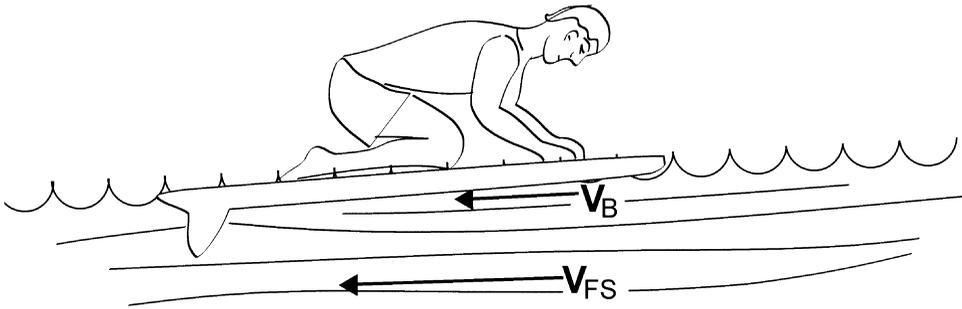
Figure 8.4. The water nearest a surfboard forms a boundary layer that flows more slowly (V_B) past the board than the free stream velocity (V_{FS}) because of friction with the board and fluid friction.

fluid to flow. Air has a lower viscosity than water, which has a lower viscosity than maple syrup.

Suppose a surfer is floating on their board waiting for the right wave (Figure 8.4). The fluid flow below the apparently stationary surfboard creates surface drag from the flow of the ocean under the board. Water molecules immediately adjacent to the board are slowed by shear forces between them and the molecules of the board. So the fluid close to the board moves slower than the ocean water farther from the board. In fact, there is a region of water layers close to the board that moves more slowly because of viscous (fluid friction) forces between the fluid particles. This region of fluid affected by surface drag and viscosity near an object is called the **boundary layer**. Layers of fluid more distant from the object that are not affected by drag forces with the object represent the free stream velocity. Have you ever started driving your car and notice a small insect on the hood or windshield wipers? I am willing to wager that most of you noticed the considerable speed you had to drive to disrupt the boundary layer the insect stood in before it was swept away! We will see that this relative or free stream velocity is one of the most important factors affecting the drag and lift forces between objects and fluids.

Performers cannot change the viscosity of the fluid they move in, but they can modify the roughness of their body or equipment to decrease surface drag. Surfboards and skis are waxed, a swimmer may shave body hair, or very smooth body suits may be worn to decrease surface drag. Some suits actually introduce texture on portions of the fabric to modify both lift and drag forces (Benjanuvatra, Dawson, Blanksby, & Elliott, 2002). While it is important to minimize surface drag, the largest fluid resistance in many sports tends to be from pressure drag.

The second kind of drag force that dominates the fluid resistance in many sports is **pressure drag**. Pressure drag is the resistance force to fluid flow that is created by a pressure differential when the fluid flows around a submerged object. A simplified illustration of this phenomenon is presented in Figure 8.5. The collision of the object and molecules of fluid creates a high pressure on the front of the object, while a lower-pressure region or wake is formed behind the object. The region of higher pressure "upstream" creates a resultant force backward on the object. We will see that the mechanics of this pressure differential is a bit more complicated and related to many factors. Fortunately, many of these factors can be modified to reduce the fluid
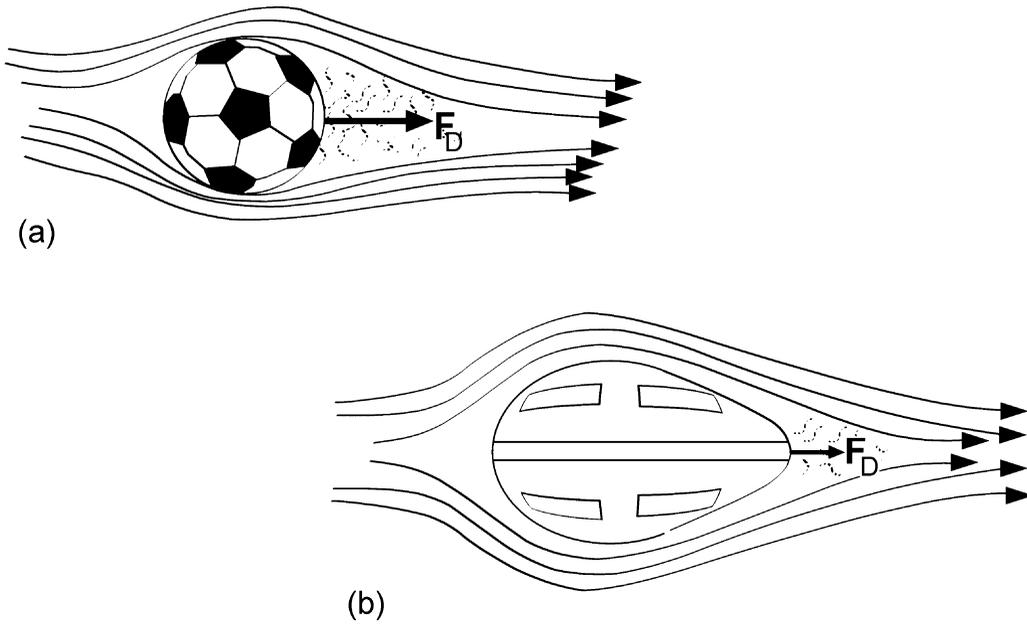
(a)

(b)

Figure 8.5. Form drag forces ($\mathbf{F}_D$) result from a vacuum pressure formed in the pocket formed behind a submerged object (a). Decreasing the pressure in this wake is how contouring the rear profile of an object (streamlining) decreases form drag (b).

resistance to many human movements. Some human movements may also use drag as a propulsive force.

To understand the variations in pressure drag, one must differentiate two different kinds of fluid flow in the boundary layer: *laminar* and *turbulent*. The air flow past a tennis ball can be highlighted by smoke introduced into a wind tunnel, depicted in Figure 8.6, which shows both predominantly laminar and turbulent flow. Laminar flow typically occurs in low-velocity conditions with streamlined objects where the fluid particles can flow relatively undisturbed in parallel layers. Turbulent flow occurs when fluid molecules bounce off the object and each other, mixing in chaotic fashion.

The kind of fluid flow over an object also affects pressure drag. At low velocities the boundary layer is laminar and cannot

flow very far around a non-rotating sphere before peeling away from the surface (Figure 8.7a), creating a large form drag. At
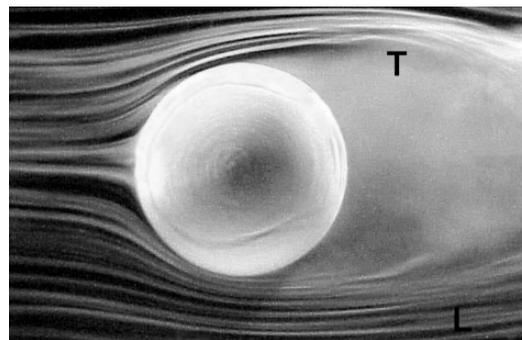

Figure 8.6. The air flow past a tennis ball shows both laminar (L) and turbulent (T) fluid motion. The topspin on the ball deflects the air flow creating another fluid force called lift. Photo courtesy of NASA Ames Research Center Fluid Mechanics Laboratory and Cislunar Aerospace, Inc.

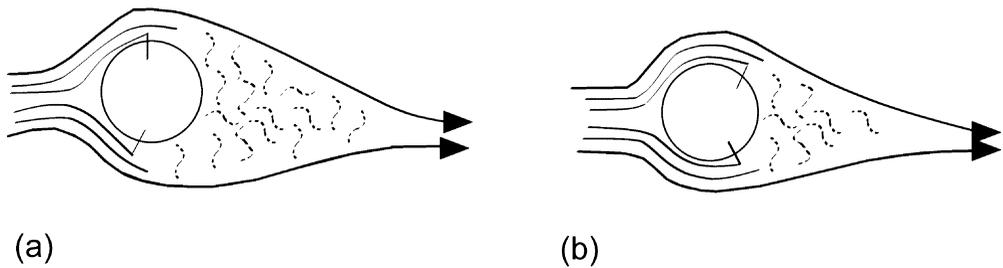(a)   (b)

Figure 8.7. Spheres like sport balls create different fluid flows and drag force depending on many factors. Primarily laminar flow (a) can result in large pressure drag because of early separation of the boundary layer for a large wake, while turbulent flow (b) will often delay boundary separation and decrease pressure drag.

higher velocities, the boundary layer flow is turbulent and more resistant to the pressure gradient as it flows around the object. This results in a later point of separation (Figure 8.7b) and lower pressure drag than laminar flow. In most objects there is not a distinct transition from laminar to turbulent flow, but a critical or transition region where flow is unstable can be either laminar or turbulent. This transition region is important in the flight of spherical balls because the coefficient of drag can drop dramatically, creating a "drag crisis." Increasing the roughness of the ball (scuffing a baseball or putting dimples on a golf ball) can decrease the velocity where these lower drag forces occur. Scientists interested in fluid mechanics use a dimensionless ratio (the Reynolds number: Re) to combine the effects of object geometry on fluid flow. This chapter will not go into detail on Reynolds numbers, but interested students can see Mehta (1985) or Mehta and Pallis (2001a,b) for more information on Reynolds numbers related to sports balls.

Much of the variation in the flight characteristics of many sport balls is related to differences in drag and lift forces that are directly related to variations in fluid flow in the transition region of Reynolds numbers. This provides a great opportunity for skill

and coaching to modify the flight characteristics of many shots or throws in sports. Many of these important effects are counterintuitive. For example, slightly increasing the roughness of a sphere (golf or baseball) might decrease drag by promoting a more turbulent boundary layer, while increasing the lift forces generated. Another example is the nature of the felt on tennis balls. The felt has a major influence on the drag coefficient (Mehta & Pallis, 2001a), so professional tennis players when serving select balls in part based on the amount of felt fluff and wear. In the next section we will study how surface roughness of rotating balls can also be used to increase the fluid force of lift.

The two major techniques employed to decrease pressure drag in human movement are (a) decreasing the frontal area and (b) streamlining. The smaller the frontal area, the less the fluid must be accelerated to flow around the object. Extending the downstream lines of an object also decreases pressure drag by delaying separation and decreasing the turbulent wake behind the object. Swimming strokes often strike a balance between maintaining a streamlined body position and a one that maximizes propulsion. The high speeds and large surface areas in cycling make streamlined

Figure 8.8. High-speed sports like cycling (or skiing) use streamlining to decrease speed losses due to drag forces. Image used with permission from Getty Images.

Application: Drafting

Sports with very high relative velocities of fluid flow are strongly affected by drag. One strategy used to minimize drag forces in these sports (cycling, car racing) is drafting. Drafting means following closely behind another competitor, essentially following in their wake. The athlete in front will use more energy against greater pressure drag, while the drafting athlete experiences less fluid resistance and can use less energy while they draft. The strategy of the drafting athlete is often to outsprint the leader near the end of the race. In many team racing sports it is the teammate who expends the extra energy to be in the front early in the race who makes it possible for other team members to finish in a higher final position. Drafting even has advantages in some lower-velocity events like swimming (Chatard & Wilson, 2003). An athlete running about 1 m behind another runner can decrease air resistance, decreasing the metabolic cost of running by about 7% (Pugh, 1971).

equipment and body positions critical (Figure 8.8).

The third kind of drag is **wave drag**. At the surface of a fluid it is possible that disturbances will create waves within the fluid that resist the motion of an object with area projecting at this surface. Wave drag can constitute a major resistance in swimming (Rushall, Sprigings, Holt, & Cappaert, 1994). Triathletes swimming in the open water must overcome wave drag from both the wind and from their fellow competitors. Swimmers in enclosed pools are less affected by wave drag than those swimming in the open water because of lane makers and gutters designed to dampen waves. Small variations in lane placement, however, may

affect the wave drag experienced by a swimmer.

Lift

The fluid force acting at right angles to the flow of fluid is called **lift** (Figure 8.9). Just like contact forces are resolved into right-angle components (friction and normal reaction), fluid forces are resolved into the right-angle forces of drag and lift. Since lift acts at right angles to the flow of the fluid, the direction of the lift force in space varies and depends on the shape, velocity, and rotation of the object. It is unwise to assume that the lift always acts upward. For example, the wings on race cars are designed to
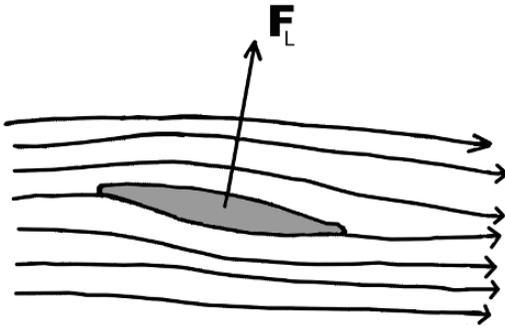
Figure 8.9. The fluid force acting at right angles to the relative flow of fluid is called lift. Lift acts in all directions, not just upward.

create a downward lift force to stabilize the car and keep it in contact with the ground.

The size of the lift force can also be modeled with a coefficient of lift (C_L) and a familiar equation: $\mathbf{F}_L = \frac{1}{2}C_L\ \rho\ A_P\ \mathbf{V}^2$. Just like drag, lift varies with the square of the relative velocity ($\mathbf{V}^2$) of fluid. Earlier we characterized drag as primarily a fluid resistance. Lift tends to be a fluid force and is often used for propulsion. One of the ear-

ly leaders in swimming research, "Doc" Counsilman at Indiana University, used high-speed films of skilled swimmers to measure the complex patterns of arm and leg motions and was instrumental in demonstrating the importance of lift as a propulsive force in swimming (Counsilman, 1971). Whether lift or drag is the primary propulsive force used in swimming is a controversial issue (Sanders, 1998), and other theories like vortices (Arellano, 1999) and axial fluid flow (Toussaint *et al.*, 2002) are currently being examined. The important thing for swim coaches to realize is that precise arm and leg movements are required to use the hands and feet effectively, and that skilled swimmers learn to use both lift and drag forces for propulsion.

Synchronized swimming and competitive swimming tend to use small "sculling" hand movements to create lift forces for propulsion. A skilled swimmer precisely adjusts the pitch of their hands to maximize the down-the-pool resultant of the lift and drag forces (Figure 8.10). This is much like the high-tech propellers in modern air-
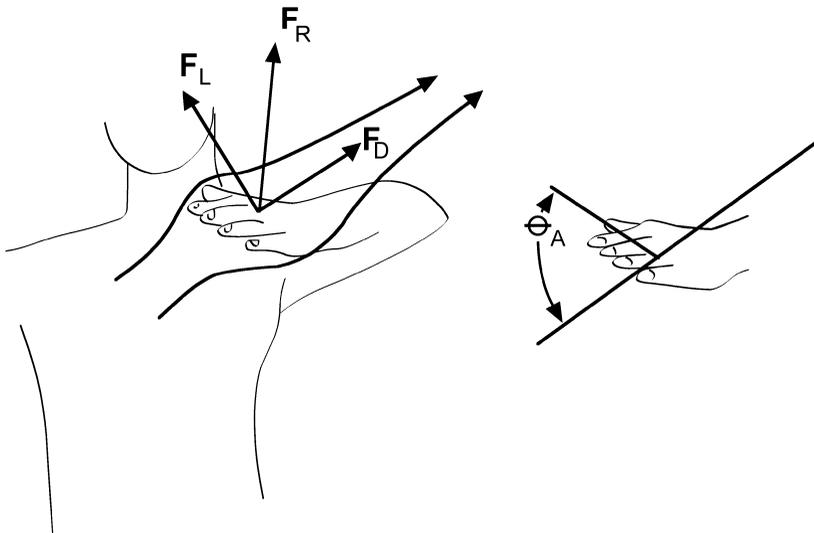

Figure 8.10. The inward sweep skill of a freestyle swimmer's hand may be selected to maximize the down-the-pool resultant of the lift and drag acting on the hand (a). This angle of attack (θ_A) is critical to the lift and drag created (b).

craft that change the pitch of a blade based on flying conditions. The complexity of fluid flow over the human body has made it difficult to resolve the controversy over which fluid forces are most influential in propulsion. Another example of controversy and potential research is to understand why elite swimmers usually keep their fingers slightly spread. It is unknown if this improves performance from increased surface area for the hand, or that the flow through the fingers acts like a slotted airplane wing in modifying the lift created at lower speeds of fluid flow. Coaches should base their instruction on the kinematics of elite swimmers and allow scholars to sort out whether lift, drag, or a vortex (swirling eddies) modifying the flow of fluid is the primary propulsive mechanism for specific swimming strokes.

Activity

After trying the ball-submersion experiment, try out this little activity using freestyle swimming technique. Compare the number of arm pulls it takes to cross the pool using two extremes in arm pull technique. First, try an arm pull with a primarily paddling motion, straight downward under your shoulder. The next arm pull should be more like the traditional freestyle technique, sculling the hand/arm in a narrow "S" pattern (frontal plane view) down the body. The paddle stroke would use primarily drag for propulsion, while the sculling motion would combine lift and drag for propulsion. Attempt to match the speed/tempo of the pulls and employ a flotation assist (like a pull buoy), and no flutter kick for a true comparison. Which fluid force seems to be most effective in pulling your body through the water with the fewest strokes?

There are two common ways of explaining the cause of lift: Newton's Laws and Bernoulli's Principle. Figure 8.11 shows a side view of the air flow past a discus in flight. The lift force can be understood using Newton's second and third laws. The air molecules striking the undersurface of the discus are accelerated or deflected off its surface. Since the fluid is accelerated in the direction indicated, there must have been a resultant force (F_A) acting in that direction on the fluid. The reaction force (F_R) acting on the discus creates the lift and drag forces on the discus.
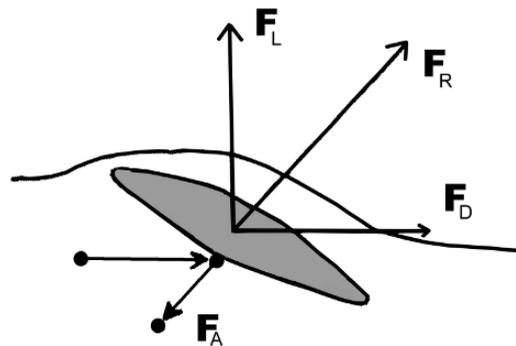

Figure 8.11. The kinetics of the lift and drag forces can be explained by Newton's laws and the interaction of the fluid and the object. The air molecules (·) deflecting off the bottom of the discus creates the lift (F_L) and drag (F_D) acting on the discus.

The other explanation for lift forces is based on pressure differences in fluids with different velocities discovered by the Swiss mathematician Daniel Bernoulli. **Bernoulli's Principle** states that the pressure in a fluid is inversely proportional to the velocity of the fluid. In other words, the faster the fluid flow, the lower the pressure the fluid will exert. In many textbooks this has been used to explain how lift forces are created on airplane wings. Airplane wings are designed to create lift forces from airflow over the wing (Figure 8.12). Fluid mol-
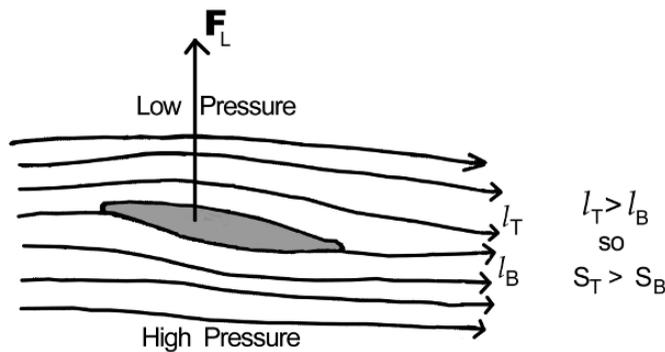
$$\mathbf{F}_L$$

Low Pressure

l_T

l_B

$l_T > l_B$

so

$S_T > S_B$

High Pressure

Figure 8.12. The lift force ($\mathbf{F}_L$) acting on a discus or airplane wing can be explained using Bernoulli's Principle. The greater distance (and faster speed of fluid flow) over the top of the wing (l_T) compared to the distance under the bottom (l_B) creates a pressure differential. The high pressure below and lower pressure above the wing lifts the airplane.

ecules passing over the top of the wing cover a greater distance than molecules passing under the wing in the same amount of time and, therefore, have a greater average speed than the airflow under the wing. The lower pressure above the wing relative to below the wing creates a lift force toward the top of the wing. Unfortunately, this simplistic explanation is not technically correct. Rather, it's an oversimplification of a complex phenomenon (visit the NASA Bernoulli vs. Newton webpage, about the competing theories about lift forces in fluids at http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html). Bernoulli's equation only accounts for force changes due to fluid pressure (no work, heat, or friction) or a frictionless (inviscid) flow. This is not the case in most fluid dynamics situations (airplane wings or hands in the pool). Unfortunately, Bernoulli's Principle has also been overgeneralized to lift forces on sport balls.

The Magnus Effect

Lift forces can also be created by the spin imparted to spherical balls. These lift forces arise because of pressure differences and fluid deflection resulting from ball spin. This phenomenon of lift force in spinning balls is called the **Magnus Effect**, after German engineer Gustav Magnus, though it may have been discovered a century earlier (Watts & Bahill, 2000). Sport balls hit or thrown with topspin have trajectories that curve more downward than balls with minimal spin or backspin. This greater downward break comes from the vertical resultant force from gravity and the primarily downward lift force from the Magnus Effect.

Activity: Bernoulli's Principle

An easy way to demonstrate Bernoulli's Principle is to use a small (5 × 10 cm) piece of regular weight paper to simulate an airplane wing. If you hold the sides of the narrow end of the paper and softly blow air over the top of the sagging paper, the decrease in pressure above the paper (higher pressure below) will lift the paper.

Recall that it was noted that Bernoulli's Principle is often overgeneralized to explain the lift force from the Magnus Effect. This oversimplification of a complex phenomenon essentially begins by noting that a rotating sphere affects motion in the boundary layer of air (Figure 8.13) because of the very small irregularities in the surface of the ball and the viscosity of the fluid molecules. Fluid flow past the ball is slowed where the boundary layer rotation opposes the flow, but the free stream fluid flow will be faster when moving in the same direction as the boundary layer. For the tennis ball with topspin illustrated in Figure 8.13, Bernoulli's Principle would say that there is greater pressure above the ball than below it, creating a resultant downward lift force. As direct and appealing as this explanation is, it is incorrect because Bernoulli's Principle does not apply to the

kinds of fluid flow past sport balls since the fluid flow has viscous properties that create a separation of the boundary layer (Figure 8.6). Bernoulli's Principle may only apply to pressure differences away from or outside the boundary layer of a spinning ball.

A better explanation of the lift force is based on how ball spin creates a deflection of the fluid, as evidenced by the shifted separation point of the boundary layer. At the spin rates that occur in sports, the boundary layers cannot stick to the ball all the way around because of an adverse pressure gradient behind the ball. Note how the topspin on the ball in Figure 8.6 creates earlier separation of the boundary layer on the top of the ball, which results in upward deflection of the wake behind the ball (Mehta & Pallis, 2001a). The backward motion of the boundary layer on the bottom of the ball increases the momentum of the boundary
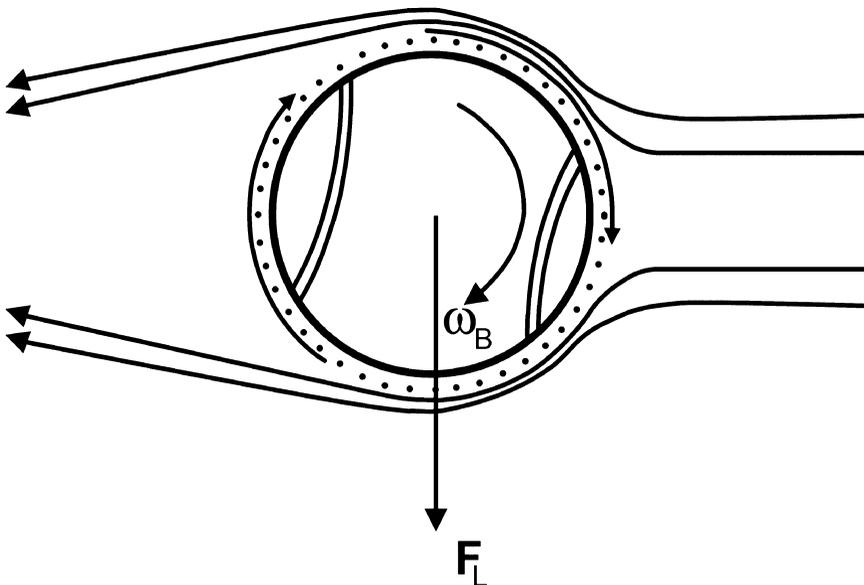

Figure 8.13. The lift forces created on spinning spheres is called the Magnus Effect. An overly simplified application of Bernoulli's Principle is often incorrectly used to explain the cause of this fluid force. Spin on the tennis ball drags the boundary layer of fluid in the direction of the spin. Fluid flow past the ball is slowed where the boundary layer opposes the free stream flow, increasing the fluid pressure. The topspin on this ball (like the ball in figure 8.6) creates a downward lift force that combines with gravity to make a steep downward curve in the trajectory.

layer, allowing it to separate later (down-stream), while the boundary layer separates sooner on top of the ball. This asymmetric separation of the boundary layer results in an upward deflection on the wake. An upward force on the fluid means that an equal and opposite downward lift (Newton's third law) is acting on the ball.

The lift force created by the Magnus Effect is apparent in the curved trajectory of many sport balls. Golf balls are hit with backspin to create lift forces in flight that resist gravity and alter the trajectory of shots. Golf balls given sidespin create lift forces that curve a ball's flight more in the horizontal plane. Figure 8.14 renders a schematic of flight for various golf shots created using different sidespins. A tennis player im-parting sidespin to a ball also creates a lateral lift force that makes the ball curve in flight. The flat trajectory of a fastball pitch in baseball results from an upward component of lift force that decreases the effect of gravity. Lift forces on sport balls are vectorially added to other forces like drag and weight to determine the resultant forces on the ball. The interaction of these forces creates the trajectory or flight path of the ball. The lift forces in a fastball are not larger than the weight of the baseball, so player perceptions of fastballs "rising" is an illusion based on their expectation that the ball will drop more before it crosses the plate. Fastballs don't rise; they just drop less than similar pitches with minimal backspin or topspin.
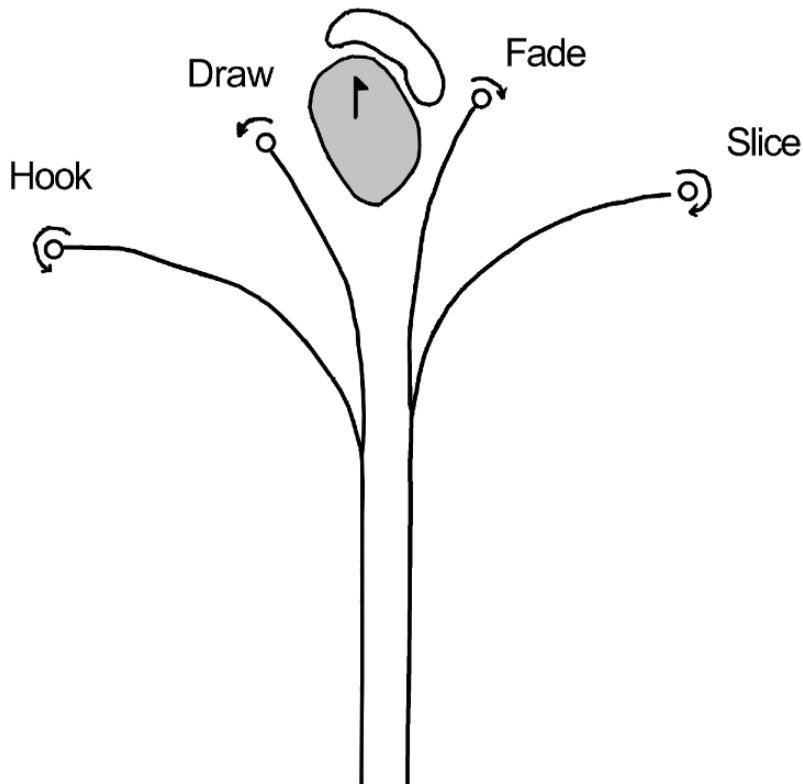

Figure 8.14. Horizontal plane trajectories of various golf shots and the ball spin (curved arrows) creating these curves with Magnus forces.

Much of the skill of baseball pitching relies on a pitcher's ability to vary the speed and spin of pitches. A curveball is pitched with an element of topspin that has a lift component in the same direction as gravity, so there is greater downward break as the ball nears the plate. The steepness of this break has resulted in hitters saying that a good curveball looks like it "drops off the table." Looking at the curveball in baseball (much like topspin shots in other sports, like volleyball and tennis) will provide a nice review of the kinetics of lift forces.

Figure 8.15 shows a three-dimensional reconstruction of a major league curveball from two perspectives. The curveball has a gradual break that looks much steeper from the relatively poor vantage point of the hitter. Why does so much of the ball's break occur late in the trajectory when the hitter is swinging the bat and cannot change their swing? The major factors are the changing direction of the Magnus force in space and the slowing of the ball from drag.

Recall that the Magnus force acts perpendicular to the flow of fluid past the ball. This means that the Magnus force for a curveball primarily acts downward, adding to the drop created by gravity, but the horizontal component of the lift force changes. As the direction of the pitch changes, so does the fluid flow and lift force (Figure 8.16). As the ball breaks downward, the Magnus force has a backward compo-nent that slows the ball even more. This ex-tra slowing and extra downward force con-tribute to the increasing "break" in the pitch late in its trajectory. Novice golfers can experience the same surprise if they consistently have trouble with "hooking" or "slicing" their drives. A "hooked" drive might initially look quite straight when the moderate sideward force is hard to detect due to the great initial speed of the ball. Unfortunately, as they watch their "nice" drive later in its trajectory, the ball seems to begin curving sideways late in flight. Diagram a transverse plane view of a "hooked" shot in golf. Draw the lift force acting on the ball and note its change in di-rection as the direction of the ball changes.

The coefficient of lift (C_L) in spinning balls tends to be less sensitive to variations in Reynolds numbers than drag, so the size of the Magnus force depends mostly on spin and ball roughness (Alaways et al., 2001). Athletes can create more break on balls by increasing spin or increasing the surface roughness of the ball. In baseball, pitches can be thrown with four seams per-pendicular to the throw, which increases C_L two to three times more than a two-seam rotation (Alaways et al., 2001).

Interesting exceptions to the dominant effect of lift forces on the flight of many sport balls are projections with minimal ball spin. A baseball "knuckleball" and a volleyball "floater" serve are examples of

Activity: Lift and Angle of Attack

When driving on an uncrowded road, roll down a window and put your hand out just into the flow of the air rushing past. Drive at a constant speed to standardize air speed and experi-ment with various hand shapes and angles of attack to the air. Think about the sport balls/ob-jects your hand can simulate and note the drag you (and the simulated object) experience at that relative velocity of air flow. How much does the drag increase as you increase the frontal area of your hand? Can you make the lift force act downward? Find the angle of attack that seems to have the most lift and the least drag (maximum lift/drag ratio). See if your classmates have observed similar results.
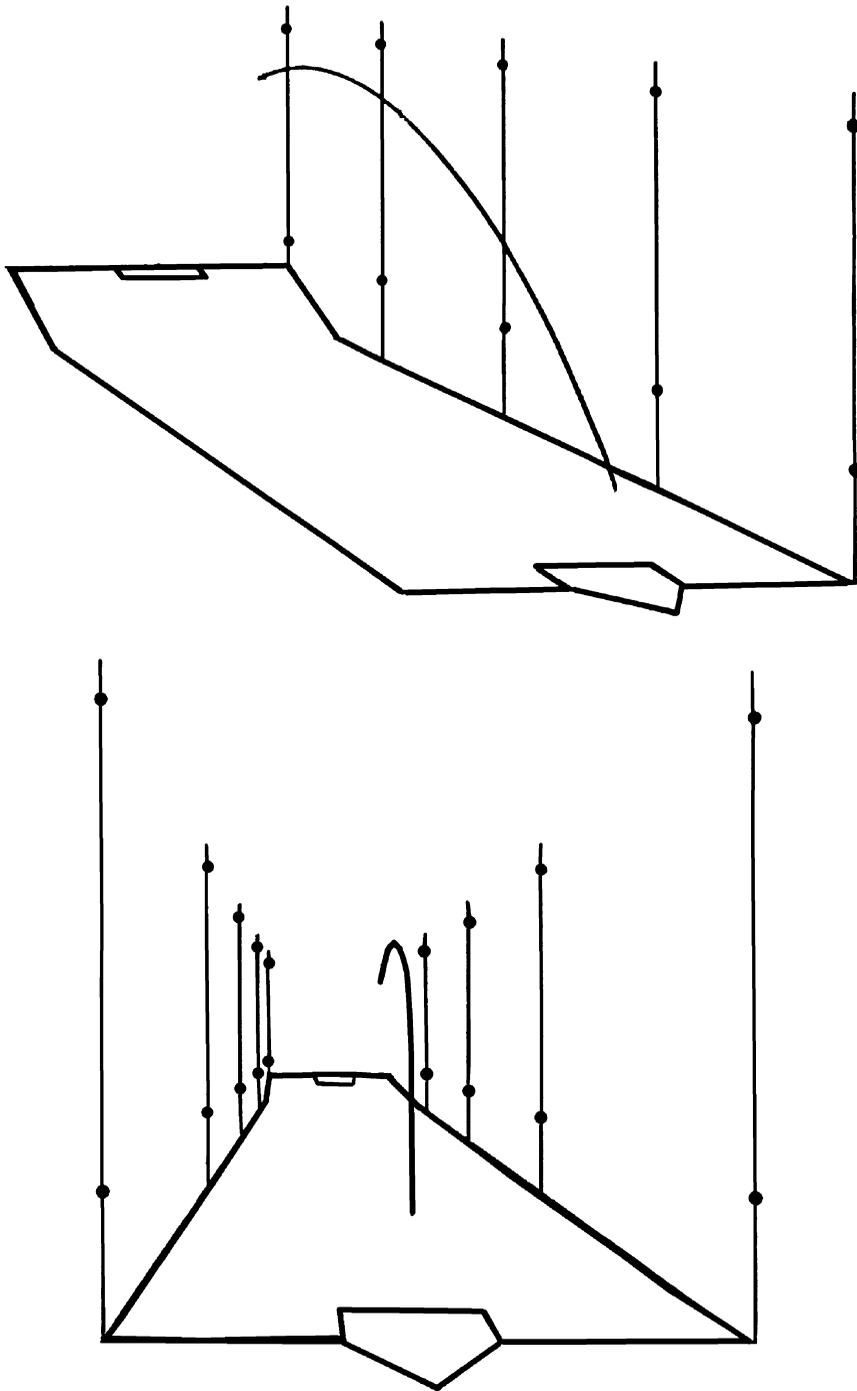
Figure 8.15. Trajectory of the same curveball thrown by a major league player from two perspectives. Note the majority of the downward break occurs late in the trajectory, creating the illusion (to the hitter) of the ball "dropping off the table." Adapted from Allman (1984).
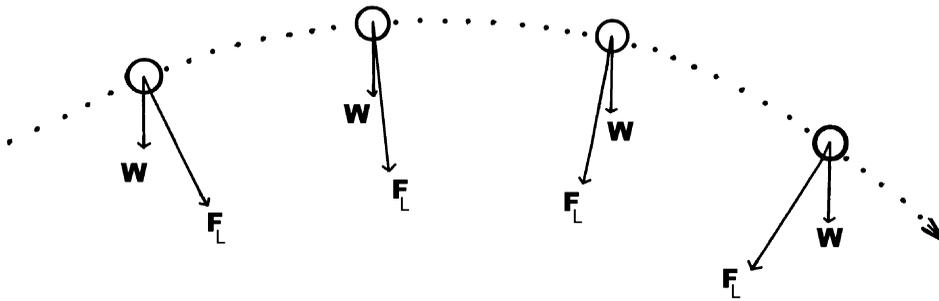
Figure 8.16. The late "break" of a curveball can be explained by the changing direction of the Magnus force ($\mathbf{F}_L$) on the ball and gravity (**W**). The downward deflection of the ball accelerates because the lift forces not only act downward with gravity, but backward (toward the pitcher). Slowing of the ball allows for more downward break.

techniques where the ball is projected with virtually no spin. The erratic trajectory and break of these balls are due to unpredictable variations in air flow past the ball. As the ball gradually rotates, air flow can be diverted by a seam or valve stem, making the ball take several small and unpredictable "breaks" during its trajectory. So spin, and the lack of it, on a sport ball has a major effect on trajectory.

PRINCIPLE OF SPIN

It is clear that fluid forces affect the motion of objects through a fluid. Lift is a key fluid force that can be modified by imparting spin on a projectile. The **Principle of Spin** is related to using the spin on a projectile to obtain an advantageous trajectory or bounce. Kinesiology professionals can use the principle of spin to understand the most successful techniques in many activities. The upward lift force created by backspin in a golf shot increases the distance of a drive (Figure 8.17a), while the backspin on a basketball jump shot is primarily used to keep the ball close to the hoop when impacting the rim or backboard (Figure 8.17b). The bottom of a basketball with backspin is moving faster than the center of the ball be-

cause the ball is rotating. This increases the friction force between the ball and the rim, decreasing the horizontal velocity of the ball, which makes the ball bounce higher. In applying the spin principle, professionals should weigh the trajectory and bounce effects of spin changes.

Applying spin to projectiles by throwing or striking have a key element in common that can be used to teach clients. The body or implement applies force to the ball off-center, creating a torque that produces spin on the projectile. The principles of torque production can be applied to the creation of spin, in that a larger force or a larger moment arm will increase the torque and spin produced. Coaching athletes to project or hit balls with minimal spin to create erratic trajectories requires that the object be in contact with a force in line with the ball's center of gravity. In volleyball, for example, the athlete is taught to strike through the center of the ball with minimal wrist snap. The flat impact through the ball's center of gravity and minimal torque from wrist rotation ensures that the ball will have minimal spin.

Unfortunately, the linear speed of the projectile is inversely proportional to the spin created. In other words, the more spin produced in the throw or hit comes at a cost
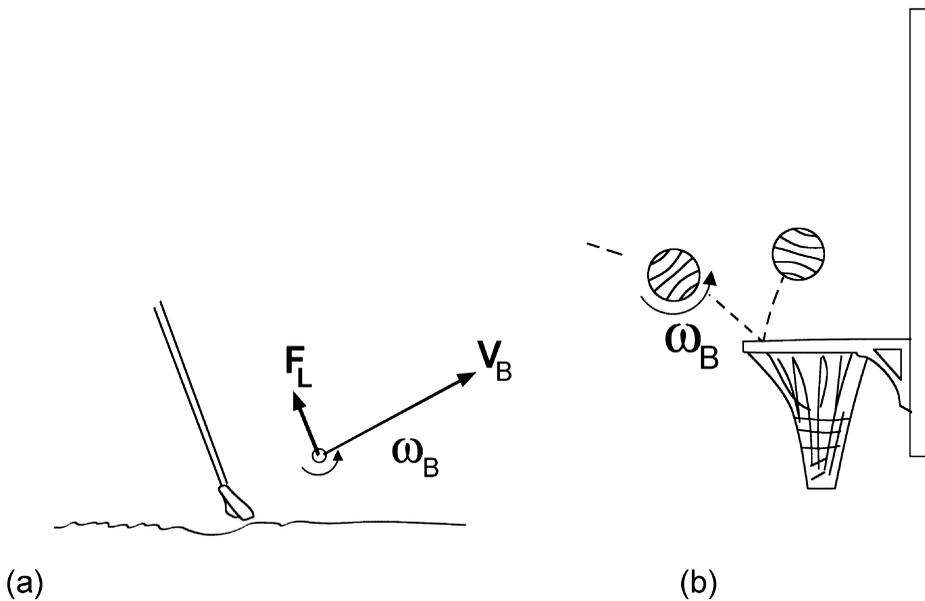
F_L V_B

ω_B

ω_B

(a)   (b)

Figure 8.17. The principle of spin is used on a golf ball to create lift forces ($\mathbf{F}_L$) that affect ball trajectory, while spin on a basketball is primarily used to modify ball rebound to increase the chance of a made basket.

of lower ball speed. In tennis the lateral break of a ball with slice (sidespin) will not travel as fast as a flat serve (minimal spin) hit with the same effort. Much of the art of teaching and coaching is being able to evaluate a person's performance, diagnosing the factors related to spin and speed production that are appropriate for a specific situation.

There is one more advantage of imparting spin to a projectile that is not related to fluid or contact forces on a surface. This third advantage of projectile spin is related to Newton's laws and conservation of angular momentum. Any object in angular motion without external-acting torques (like a projectile) will conserve angular momentum. This inertia in a rotating object can be used to keep the projectile in a certain orientation. A pass in American football does not create significant lift force, but the spin stabilizes the flight of the ball in a streamlined position. Divers and gymnasts

(human body projectiles) can overcome this inertia and move body parts relative to an axis of rotation with internal muscle forces. In these situations athlete can transfer angular momentum from one axis to another (e.g., add a twist in the middle of somersaults) by asymmetric motions of body parts. Coaches of these sports need to be familiar with this interesting application of the spin principle (see Yeadon, 1991, 1997).

Knowing what advantage of spin in a particular situation is important and how to mechanically create it are critical, but this knowledge must be integrated with knowledge from other kinesiology disciplines. A physical educator could ask a junior high student to "use an eccentric force" or "increase the effective moment arm" and may be mechanically correct, but a good teacher selects an appropriate cue that communicates the essential correction without using such technical language. Think about

what would be good cues for hitting a sport ball to create topspin, backspin, right or left sidespin. Deciding whether cues about the ball (target) or body action (technique) are most relevant depends on the situation. This is another example of how a biomechanical principle must be integrated in an interdisciplinary fashion with other kinesiology disciplines (e.g., motor development, motor learning, psychology).

SUMMARY

Fluid forces from air and water have a significant effect on human movement. The main fluid forces are buoyancy, lift, and drag. Buoyancy is the supporting or floating force that a fluid exerts on an object as it is submerged in the fluid. The size of the buoyant force can be determined by Archimedes Principle. The fluid force that acts in the same direction as the relative flow of fluid is drag, while the fluid force acting at right angles to the flow is lift. The size of the lift and drag forces depends on many factors, but they vary with the square of the relative velocity of the fluid. Lift forces can be created on spinning spherical balls through the Magnus Effect. Kinesiology professionals can apply the Spin Principle to help performers create spin on projectiles like sport balls. Imparting more spin to a projectile usually comes at the expense of a loss in some linear velocity, but the lift force can be used to gain an advantage from an altered flight or bounce relative to a no-spin projection.

KEY TERMS

Archimedes Principle
Bernoulli's principle
boundary layer
buoyancy
center of buoyancy
drag
lift
Magnus Effect
spin principle

REVIEW QUESTIONS

1. What are the major fluid forces and in what directions do they act?
2. What factors affect the fluid resistance acting on projectiles? What factor is most influential in creating fluid forces?
3. Compare and contrast the motion of the center of gravity and center of buoyancy with various body segment movements.
4. Explain why streamlining decreases fluid resistance.
5. How do fluid forces affect the optimal projection angles proposed earlier in chapter 5?
6. Why do golf balls have dimples?
7. Draw or trace a person and estimate their center of buoyancy. Trace the person two more times with various exercise and swimming flotation devices and re-estimate the likely center of buoyancy.
8. How is the density of water related to whether an object will float in water?
9. Explain why topspin serves in volleyball curve downward?
10. What are the benefits of imparting spin to round balls in sports?
11. How are the spin and the "break" of a ball in flight related?
12. Draw a free-body diagram of a golf ball in flight and explain how the resultant forces on the ball affect its flight.
13. Why do swimmers and cyclists shave their body, but a baseball pitchers illegally roughen the surface of the ball?
14. What forces increase and decrease when exercising in water?

SUGGESTED READING

Adair, R. (1990). *The physics of baseball*. New York: Harper & Row.

Alaways, L. W., Mish, S. P., & Hubbard, M. (2001). Identification of release conditions and aerodynamic forces in pitched-baseball trajectories. *Journal of Applied Biomechanics*, **17**, 63–76.

Arellano, R. (1999). Vortices and propulsion. In R. Sanders & J. Linsten (Eds.), *SWIMMING: Applied proceedings of the xvii international symposium on biomechanics in sports* (Vol. 1, p. 53–66). Perth, WA: Edith Cowan University.

Berger, M. A. M., de Groot, G., & Hollander, A. P. (1995). Hydrodynamic drag and lift force on human hand/arm models. *Journal of Biomechanics*, **28**, 125–133.

Counsilman, J. E. (1971). The application of Bernoulli's Principle to human propulsion in water. In L. Lewillie and J. Clarys (Eds.), *First international symposium on biomechanics of swimming* (pp.59–71). Brussels: Université Libre de Bruxelles.

McLean, S. P., & Hinrichs, R. N. (2000a). Influence of arm position and lung volume on the center of buoyancy of competitive swimmers. *Research Quarterly for Exercise and Sport*, **71**, 182–189.

McLean, S. P., & Hinrichs, R. N. (2000b). Buoyancy, gender, and swimming performance. *Journal of Applied Biomechanics*, **16**, 248–263.

Mehta, R. D., & Pallis, J. M. (2001b). Sports ball aerodynamics: Effects of velocity, spin and surface roughness. In F. H. Froes, & S. J. Haake (Eds.), *Materials and science in sports* (pp. 185–197). Warrendale, PA: The Minerals, Metals and Materials Society [TMS].

Mureika, J. R. (2000). The legality of wind and altitude assisted performances in the sprints. *New Studies in Athletics*, **15**(3/4), 53–58.

Olds, T. (2001). Modelling of human locomotion: Applications to cycling. *Sports Medicine*, **31**, 497–509.

Toussaint, H. M., van den Berg, C., & Beek, W. J. (2002). "Pumped-up propulsion" during front crawl swimming. *Medicine and Science in Sports and Exercise*, **34**, 314–319.

Watts, R. G., & Bahill, A. T. (2000). *Keep your eye on the ball: The science and folklore of baseball* (2nd ed.). New York: W.H. Freeman.

Yeadon, M. R. (1997). The biomechanics of human flight. *American Journal of Sports Medicine*, **25**, 575–580.

WEB LINKS

Aerodynamics—NASA educational pages on fluid mechanics.
  http://www.grc.nasa.gov/WWW/K-12/airplane/short.html

Aerodynamics in Tennis—NASA/Cislunar Aerospace project to promote science education through sport science.
  http://wings.avkids.com/Tennis/Book/index.html

Cycling Aerodynamics—cycling page by Smits and Royce of Princeton University.
  http://www.princeton.edu/~asmits/Bicycle_web/bicycle_aero.html

Cycling Aerodynamics and power calculation page.
  http://www.exploratorium.edu/cycling/aerodynamics1.html

Bernoulli vs. Newton—NASA webpage on the competing theories for lift forces in fluids.
  http://www.grc.nasa.gov/WWW/K-12/airplane/bernnew.html

ISBS Coaching Information Service—select swimming link.
  http://coachesinfo.com/