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Science in the Arena

Explanations and analyses of performances and phenomena in sport

Blane Baker

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Blane Baker
William Jewell College, Liberty, Missouri, USA

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To my family and my students.

Contents

Preface

Science in the Arena has emerged from a lifelong love of sport and fascination with all things connected to nature. Nearly two decades ago, I was given the opportunity to develop a new classroom course, devoted to the study of science and sport. Experiences gained through teaching this course ultimately led to several students and friends encouraging me to pursue this writing project. Much of the content for *Science in the Arena* originated from students asking insightful questions and presenting new material in class.

Acknowledgements

I would like to thank my colleagues in the Physics Department at William Jewell College for valuable conversations and encouragement. In addition, I am grateful to all my students, who have motivated me with their perceptive questions and stimulating classroom discussions. Finally, I would like to extend my deepest appreciation to my family and friends for their love and support.

Author biography

Blane Baker is Professor of Physics at his alma mater William Jewell College where he returned to teach in 1999. Over his tenure, he has taught general physics, electronics, and quantum mechanics, along with a popular sport science course for non-science majors. Much of the material for Science in the Arena was developed for this course, entitled Sport Science and Ethical Issues. Baker is an active contributor to the American Association of Physics Teachers (AAPT) and serves on the National Council of Society of Physics Students (SPS). His areas of interest include electronics, sustainable energy, and materials science. He is also a member of the American Physical Society (APS), and Sigma Pi Sigma. He also holds the Wallace A. Hilton Chair at William Jewell College. Baker is an avid runner and baseball fan and enjoys traveling with family and friends.

Chapter 1

Introduction and 1-D and 2-D motion

What is science?

Much public debate continues as to the role and scope of science in modern society. Given this backdrop, the objective of our study here is to use principles of science to analyze and explain phenomena in the world of sport. We will begin with discussions of some of the fundamentals of science and how scientists solve problems.

The word for science originates from the Latin root *scientia* meaning knowledge. Thus, the goal of science is to gain understanding of our natural world through systematic study and development of coherent theories and universal laws. In the realm of science, theories and laws are always subject to change as experimental results prescribe, and so they evolve over time. Scientists, as practitioners, often focus on particular fields of study. Astronomers delve into the mysteries of systems such as galaxies, black holes, and quasars. In the arena of sport, sport scientists study how athletes in particular events undergo various motions or how implements (such as rackets, bats and clubs) and their use contribute to outstanding performances.

For purposes here, we will draw on the disciplines of physics, chemistry, and biology. Physics seeks to understand underlying principles of light and matter in the Universe. Chemistry focuses on elucidating mechanisms and reactions in nature that produce the myriad of compounds in the Universe. Biology seeks to enlighten us on processes that are common to all life forms and to understand how living organisms work.

As a human pursuit, the aim of science is to produce the most accurate theories possible with the available data. While no one scientific method works for every problem, a general approach may begin with a question or observation. From there, a working set of hypotheses is developed to explain tentatively what is happening. Then experiments are designed and run. After data are collected, analyzed, and interpreted, modifications to the present hypotheses may be required. Once refined, they are used to make predictions of subsequent experiments. If predictions are confirmed, the latest hypotheses are retained. Otherwise they are modified or

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discarded completely. In reality, investigations can begin at any point in the process and are ongoing.

In addition to how scientists approach their work, some discussion of what questions are appropriate for scientific investigations is useful for the sport scientist. Generally speaking, science is only equipped to address questions that are accessible by experimental methods. For example, if we want to know how a swimmer generates a certain motion, various experiments could be designed to answer this kind of question. On the other hand, if we want to know how an athlete should behave in a given situation, scientific experiments are not particularly helpful. In the latter case, other disciplines such as philosophy are needed to make ethical decisions.

When considering questions and topics for scientific studies, a couple of over-arching questions help us to determine applicability: can measurement of a scientific quantity answer the question? Can an experiment lead us to an answer? If the answer is 'yes' to either or both questions, then science will play a role in determining answers. If not, other disciplines must be utilized to acquire that knowledge. Examples of questions that require scientific investigations might be: how high can a world-class pole-vaulter jump? How far can a javelin be thrown? What maximum forces are produced during a tackle in football? These and other similar questions are at the heart of our investigations here, so let us begin.

1-D motion

Performance in sport often is associated with optimizing or perfecting a particular motion, as in the case of a sprinter in a 100 m dash or a gymnast in a floor exercise routine. Systems throughout the Universe exhibit a number of different kinds of motion, the simplest of which is described as a mass traveling from one point in space to another. This change in location or position, known as displacement, occurs over some interval of time. From these basic quantities of displacement and time, quantitative analyses of motion follow. (See below.)

The simplest of point-to-point motions occur along straight-line or linear paths. A drag racer sprinting along a straightaway, a base runner churning from third to home, and a hockey player skating directly across the rink are all examples of linear, or one-dimensional (1-D) motion, as illustrated with the runner in figure 1.1. To determine displacement along a 1-D path, the difference between the final and initial locations of a system is calculated. Displacement of a runner dashing along a 100 m straightaway is simply: 100 m − 0 m = 100 m.

Once displacement is known, its value can be divided by the interval of time to obtain the average velocity, or rate at which displacement occurs. Running the 100 m dash in 10 s produces an average velocity of 10 m s^{-1}, whereas covering 40 yards (36.6 m) in 4.23 s during a National Football League NFL tryout generates a value of 8.65 m s^{-1}. Knowing velocity allows for comparison of how rapidly objects are moving in a variety of settings.

Both displacement and average velocity involve numerical values and directions in which the motions occur. For example, average velocities often are expressed as +5.0 m s^{-1} or −5.0 m s^{-1}, where the + sign refers to motion to the right and

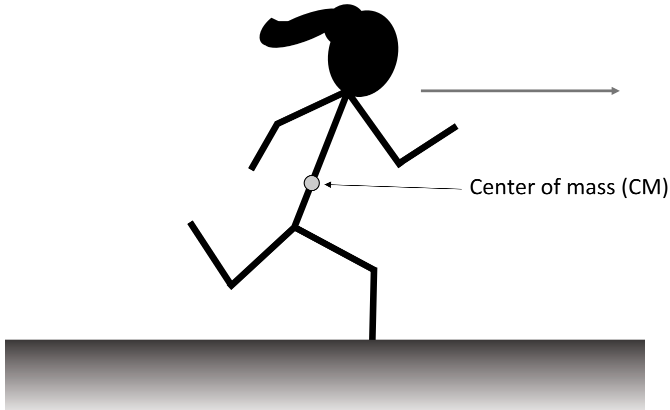

Figure 1.1. Depiction of a sprinter undergoing motion along a straightaway. Translation of the center of mass (CM) of the runner approximates one-dimensional motion.

the − sign refers to motion to the left. If one object is traveling at +10.0 m s^{-1} and another at +7.0 m s^{-1}, they are both moving in the same direction but the former is covering 3.0 additional meters each second, as compared with the latter.

As objects undergo variations in velocities, they experience what is known as acceleration. Acceleration is defined as the ratio of the change in velocity to the time interval over which that change occurs. Soccer balls have accelerations of order 250 m s^{-2} in scenarios in which they are launched from rest at velocities of 25 m s^{-1}, following collision times with the foot of 0.1 s. Elite sprinters can attain velocities of approximately 10 m s^{-1} during the first 2 s of a race, thus producing accelerations of 5.0 m s^{-2}. Acceleration experienced by objects falling in the Earth's gravitational field is constant at 9.8 m s^{-2} when effects such as air resistance are neglected.

Average speed and types of motion

In contrast to average velocity, average speed does not consider direction and is found simply by taking the ratio of the total distance covered to the total time elapsed. A baseball released from the hand of a Major League Baseball MLB pitcher takes approximately 0.38 s to travel a distance of 16.4 m, producing an average speed of 43 m s^{-1} (just a few miles per hour mph shy of 100 mph). Typical speeds in sport range from less than 1.0 m s^{-1} to over 140 m s^{-1}. Table 1.1 shows some common speeds associated with various sporting activities, along with other values from the natural world. As seen here, a fastball in baseball is about 40% faster than a cheetah running at top speed. The speed of light is approximately a million times greater than the speed of sound. Given this vast difference, fans in baseball stadiums see the ball make contact with the bat well before they hear the sound of impact.

Motion along a straight line or curved path is characterized as translation. A sprinter dashing along a straightaway and a soccer ball traveling along a field of play are both examples of translation. Two other kinds of motion—rotation and oscillation (vibration)—also occur in the natural world. Rotation involves an angular displacement of a system, characterized by motion about an axis of rotation.

Table 1.1. Typical speeds observed in sport and nature.

Source or system	Speed (m s^{-1})
Light	3.0×10^8
Sound	340
Tennis serve	58
Fastball	45
Cheetah (top speed)	31
Race horse	22
Elite sprinter	13

Depending upon the scenario, this axis can be fixed in space or moving itself. For example, a spinning soccer ball on its trajectory to the net exhibits motion about an axis, running through the center of the ball and undergoing translational motion itself. Oscillation, in contrast to the other motions, refers to repetitive back and forth changes in position about a point of equilibrium. A number of systems in sport including bats, rackets, and clubs exhibit oscillation when struck.

How many paths for the runner?

Given our treatment of point-to-point motions, one particularly fun problem to consider involves finding the number of possible paths taken by a runner traveling from point A to point B, along a series of short 1-D sprints. In the extreme case that the runner can cut along any direction, relative to the original direction, the number of possibilities is essentially endless. For more limited changes in direction, the number of possible paths is large but tractable.

Take, for example, a scenario in which a running back (RB) in American football is running downfield trying to avoid defenders. Suppose that the runner continues his forward motion during each encounter with a defender, and, assume that only 45° cuts or straight-line motion are possible. From these assumptions, the runner has three options: continuing along the original path, cutting to the left at 45°, or cutting to the right at 45°.

If only one defender is encountered during the run, the number of possible paths is simply 3^1 or 3: the runner can continue along a straight-line path or make either a 45° cut to the left or right. With each new defender in the runner's path, the number of possibilities increases by a factor of 3. If all 11 defenders are encountered once, the number of possible paths is extraordinarily large 3^{11}. For more reasonable estimates of 3–4 encounters during a typical run, an incredible 27–81 paths are possible. Such a large number of paths, together with the ability of elite RBs to make these cuts quickly, contribute to their elusive running styles.

2-D projectile motion and trajectories of baseballs

Motions along 1-D paths are fairly prevalent in sport especially considering the number of systems that exhibit translation along straight-line-paths. Examples of translation in one-dimension include short sprints in track and field, any of the drag racing events in motor sports, and ground balls struck in baseball. In reality, however, the vast majority of motions in sport occur along 2- or even 3-D paths. Players zigzagging around fields of play, implements such as javelins, shot puts, and discuses flying through the air, and cyclists racing around oval tracks are all examples of multi-dimensional motions.

One particular kind of 2-D motion in which an object travels through the air near the surface of the Earth is ubiquitous in sport. Objects moving in this fashion are the subject of much study and are referred to as projectiles. Ideal mathematical treatments of these motions neglect effects due to air resistance and assume that acceleration produced by gravity is constant. Under these conditions, motions of projectiles follow smooth, parabolic paths; moreover, positions and velocities associated with their motions can be predicted exactly using Newton's laws. Objects such as shot puts and javelins *approach* this ideal case so that their trajectories are nearly parabolic and their paths are predicted to within a few percent via theoretical calculations.

Motions of other projectiles like baseballs and softballs are affected more dramatically by air drag, sometimes reducing the horizontal distance (range) attained by as much as 50%, as depicted in figure 1.2. Range for an ideal projectile is the maximum horizontal distance traveled when the object is launched near the Earth and confined to a 2-D path. Range is computed using the following equation: $R = v_0^2 \sin(2\theta_0)/g$, where v_0 is launch speed, θ_0 is launch angle, and g is acceleration due to gravity (9.8 m s^{-2}).

On the Major League Baseball MLB level, well-struck balls leave the bat at 100–120 mph (45–54 m s^{-1}) and at angles between 20° and 37°. Inserting a launch speed of 49 m s^{-1} and a launch angle of 37° into the range equation predicts a value of 240 m (770 feet), well beyond distances attained by Major League hitters. Given this discrepancy, effects due to air resistance (drag force) on a batted ball must be considered to make accurate predictions of range.

To account for air resistance in analyzing trajectories, computations require an initial launch speed and an initial launch angle. Once launched, the ball's position and velocity are computed in a step-wise fashion using Newton's laws and basic kinematic relations. For each step along the path, the constant gravitational force and variable drag force are inserted into equations of motion, and, subsequently, velocities and positions are calculated. Step-wise computations are needed, because the drag force constantly varies due to its dependence on the speed of the projectile.

After the entire path of the batted ball is determined, the computed range in the presence of air resistance is compared with the ideal range assuming no air resistance. This ratio of range in air to range in vacuum is plotted as a function of launch angle for various launch speeds. These data are useful for determining how far a baseball will travel for various launch conditions, without the need to perform the sophisticated modeling described above. The required ratio is obtained simply by reading the graph.

For the launch conditions above, the ratio of the range in air to the range in vacuum is found to be 0.51. (As a result, the expected range is 51% of the ideal

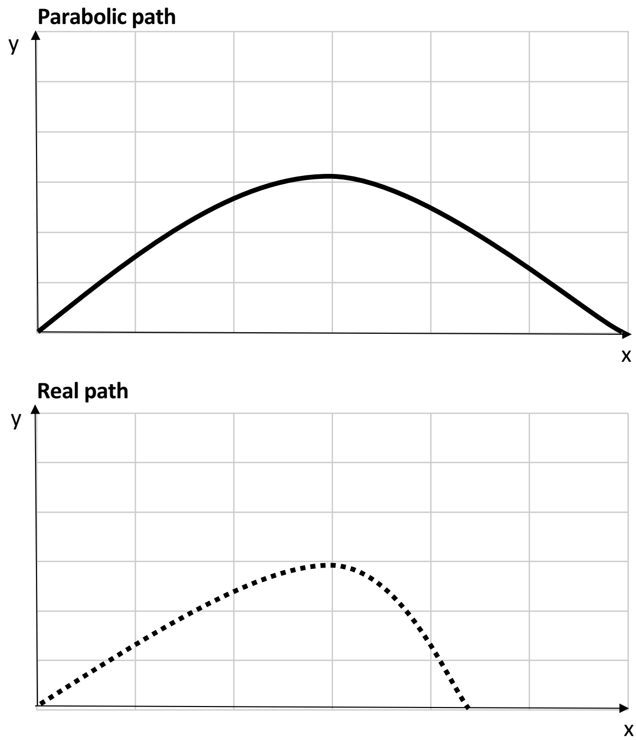

Figure 1.2. Ideal and real paths of projectiles, launched near the surface of the Earth.

range.) From this ratio and an ideal range of 240 m, the predicted range in the presence of air resistance is 120 m (390 feet), a much more reasonable value for an MLB batter. For perspective, many centerfield walls in MLB are located approximately 122 m (400 feet) from home plate, well within the capabilities of outstanding batters.

If atmospheric conditions change over time, drag forces are affected and the range attained by a struck ball will vary. For example, as air temperature increases, air density decreases and drag force is reduced. For Major League hitters, the range of a baseball is expected to increase by approximately 6–7 feet (1.8–2.1 m) for temperature increases from 70 °F to 90 °F (21 °C to 32 °C).

Chapter 2

Energy and conservation

At first glance, many scientific questions appear rather daunting to analyze and therefore beyond our abilities to find answers. Examples of such questions might include: how high can pole-vaulters jump? How much energy is required for swimming? Why do elite sprinters attain certain levels of speed more quickly than others? Indeed, from the standpoint of forces and Newton's laws, these intriguing questions usually require advanced study in physics to pursue. However, by learning some basic energy concepts and by developing a firm grasp of conservation of energy, these and many other questions are accessible to both fans and sport scientists alike.

Work and kinetic and potential energy

Energy in a conversational sense usually suggests activity level or effort. In scientific descriptions, however, more rigorous definitions are needed for accurate analyses and computations. As an alternative, energy often is described as the capacity of a system to do work. Work, as a physical quantity, requires both a force and a displacement such that the displacement occurs due to application of that force. Thus, a system is known to possess energy when it is capable of producing forces that result in movement of a mass from one point to another. If forces are applied and no displacement occurs, no work is done.

In practice, a soccer player moving her foot toward a ball at rest possesses energy as a result of the foot's motion. Once contact is made, the foot, possessing kinetic energy, exerts a force on the ball, causing displacement of the ball and production of a given amount of work. Many forms of energy such as mechanical, electrical, chemical, radiant, and nuclear are present across the Universe. For the moment, we will focus on two mechanical forms of energy—namely kinetic energy and gravitational potential energy.

Mechanical energy, associated with the motion of a particle or a system, is referred to as kinetic energy. (The word kinetic originates from the Greek word for

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motion.) Kinetic energy depends on both the speed v of an object and its mass m; kinetic energy (KE) in units of Joules is expressed mathematically as $0.5mv^2$, where v is in units of m s^{-1} and m is in units of kg. In the world of sport, kinetic energies typically range from 10^{-2} to 10^7 J. A slow rolling grounder in baseball has a relatively small KE of 0.08 J (0.5 × 0.15 kg) × (1.0 m $s^{-1})^2$; whereas, a top fuel dragster has a kinetic energy approaching 9.5×10^6 J at top speeds exceeding 300 mph (134 m s^{-1}).

In addition to objects attaining KE by virtue of their motions, they can acquire energy due to their positions relative to certain reference points within the Earth's gravitational field. When this energy involves interactions between an object and the Earth, this form of mechanical energy is known as gravitational potential energy PE and is given by the equation: PE = mgh, where m is the mass in kg, g is acceleration due to the Earth's gravitational field (9.8 m s^{-2}), and h (in m) is the height of the object relative to the surface of the Earth. As an everyday example, a book located on the top shelf of a bookcase has a greater potential energy than an identical book located on a lower shelf. For a book of mass 0.50 kg located at 2.3 m its potential energy (relative to ground level) is 11 J. A diver of mass 73 kg on a 3.0 m diving board has a potential energy of 2100 J. On a grander scale, our Sun produces about 384.6 yotta Joules (3.846×10^{26} J) of energy during each second of its life.

Conservation of energy

In many instances, potential energy can be converted into kinetic energy and vice versa. This interplay between the two forms of mechanical energy is a consequence of conservation of mechanical energy. Conservation of mechanical energy is a rule of nature that says that the mechanical energy of an isolated system is constant. That is, either form of mechanical energy may increase or decrease *but* a compensating decrease or increase in the other form of energy must occur to maintain this equality. Using a monetary analogy, a one dollar bill can be converted into four quarters and vice versa, *but* the overall amount of currency is fixed at one dollar.

In equation form, this energy equality is expressed as $KE_i + PE_i = KE_f + PE_f$, where i represents initial values and f represents final values. If three of the four energy quantities are known, the fourth can be found. Once that energy is known, other quantities such as height h or speed v can be determined from the calculated energy.

Energy conservation in pole vaulting

One of the most dramatic examples of conversion of kinetic energy into potential energy is the pole vault event in track and field. In this competition, the athlete begins from rest and develops kinetic energy by accelerating along a runway. Provided the jumper does not experience significant interactions except with the Earth's gravitational field, the jumper and Earth constitute an isolated system and conservation of mechanical energy applies.

Once the jumper reaches the end of the runway, she projects herself into the air using a vaulting pole that she carries during the run-up phase of the jump. As her height increases during the vault, she converts more and more of her initial KE energy into PE until she reaches a maximum height. At this point in the jump, her speed is nearly zero, because her initial KE has been converted nearly entirely into PE. During this conversion, the height attained by the jumper is determined by equating the initial KE to the final PE. Here the initial PE is zero because she begins at ground level, and the final KE is zero because her speed is nearly zero at the maximum height of the vault. Setting $KE_i = PE_f$ and solving for height h attained yields: $h = v^2/2g$, where v is speed of the jumper at the end of the runway just as she plants her pole.

To predict the total height attained by the jumper, conversion of kinetic into potential energy, along with re-orientation of the jumper as she clears the crossbar, must be considered. In nearly all cases, the jumper approaches the crossbar and jumping pit in a nearly upright (running) position; however, she clears the bar in a nearly horizontal position. This change in orientation is necessary in order to gain an additional vertical height equal to approximately the distance between the bottom of the jumper's feet and the center of mass of the body. The center of mass (CM) for the human body is located at approximately 55% along the length of the body from the bottom of the feet, as shown in figure 2.1. In reality, the jumper's CM may pass slightly below the crossbar as clearance occurs due to the bent orientation of the body. However, we will neglect these effects given that the exact body shape during clearance is dependent upon the individual jumper.

Using the model described, the total predicted height of a jump is determined from $(v^2/2g) + 0.55$ (height of the athlete). While values of speed attained along the runway vary from jump to jump and athlete to athlete, typical approach speeds for world-class women jumpers are in the range of 8.5–9.0 m s^{-1}. Using a speed of 8.7 m s^{-1} and a standing height of 1.74 m, gives a predicted jump height of 4.82 m, a value within 5% of the current world record WR of 5.06 m set in 2009 by the great jumper, Yelena Isinbayeva.

As seen here, world-class jumpers are able to convert a large fraction of their KE along the runway into PE at the maximum height attained. In reality, some of the

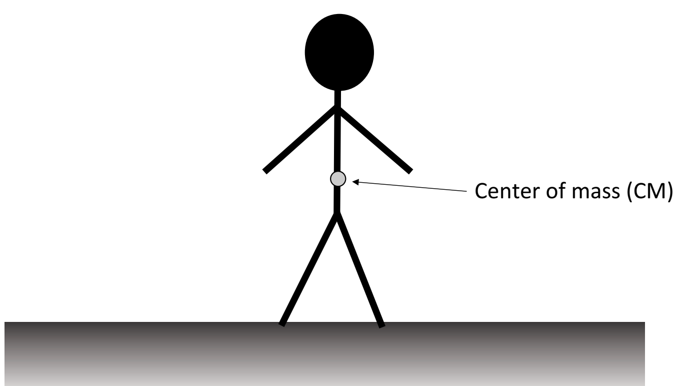

Figure 2.1. Approximate location of the CM of a human body.

initial KE is converted into thermal energy within the pole and some is transferred to the sea of air surrounding the jumper as she moves through the atmosphere. In spite of these energy transfers, many jumpers can vault to heights slightly greater than those predicted above. In effect, the jumper generates extra height by pushing on the pole when it is in its vertical position. Thus, work is done on the jumper's body, causing it to be raised even beyond what is predicted by conservation of energy. For most jumpers, this added height is in the range of 0.2–0.5 m.

Stored energy, energy for activities, and calories

Energy needed to support all life processes as well as to perform athletic and other activities is derived from the foods we eat. Foods typically contain fats, proteins, and carbohydrates, all of which contain energy stored within their chemical bonds. In certain cases, this energy can be released directly via chemical reactions for on-demand use or, alternatively, stored in various compounds within the body for later use. In a wide range of scenarios, the amount of energy needed for a specified activity can be determined from basic bodily requirements and then converted into equivalencies, based on calorie units.

In order to support the necessary functions of the body, a minimum quantity of energy is required during each second of our lives. This basic energy demand is known as the basal metabolic rate BMR and is equivalent to approximately 120 W (J s^{-1}) for an adult. The rate of energy consumption here corresponds to approximately 1.04×10^7 J during the course of a day given that there are 3600 s in 1 h and 24 h in a day: (120 J s^{-1})(3600 s h^{-1})(24 h day^{-1}) = 1.04×10^7 J. Such a quantity of energy is equivalent to approximately the kinetic energy of 69 000 baseballs, each traveling at 100 mph (44.7 m s^{-1}). For purposes of food intake and diet, 1.04×10^7 J translates to 2480 cal from the conversion of 4186 J = 1 food calorie. (For reference, this daily caloric requirement is typical for males between the ages of 20–25 with modest activity levels.)

Using the arguments above, other activities can be evaluated in view of caloric requirements. Metabolic studies of different kinds of athletes have been conducted to determine rates of energy consumption. Swimming, for example, has a typical power requirement of 600 W so that a swimmer exercising for 2 h per day requires 4.32×10^6 J or 1032 cal. This caloric requirement, together with the one to maintain basic processes (BMR), gives a total of 3512 cal. With these data in mind, a 2 h swimming workout can increase daily caloric requirements by nearly 42%. Results such as these are important for athletes when considering caloric intake and dietary needs, but also for more sedentary persons who are interested in reducing body weight through exercise.

Besides energy requirements addressed thus far, more recent studies strongly suggest that vigorous exercise can lead to increased energy demands even beyond the workout period. Such increases in energy consumption are referred to as afterburn effects, which typically occur for about 14 h after a person exercises at 70% or more of maximum oxygen uptake. (This rate of oxygen uptake is characterized by the inability to carry on a normal conversation.)

From quantitative measurements, the added power required during the afterburn period is approximately 16 W for up to 14 h after the exercise is complete. Converting this additional power to energy consumed over the 14 h is equivalent to approximately 190–200 cal. Details of this computation are as follows: (16 J s^{-1}) (3600 s h^{-1})(14 h) = 8.06×10^5 J or 190 cal. Given these extra energy demands, those who exercise at such levels should not feel guilty about eating an extra cookie or two (equivalent to about 200 cal). In addition, consideration of these effects is necessary for athletes when planning their diets and caloric intakes.

Energy rates and power

In many events in sport a certain amount of energy must be produced in the least amount of time possible. Given their specifications in particular events, racecars typically have comparable maximum speeds and kinetic energies. However, top racers can attain energy of motion (kinetic energy) more rapidly than those racers who do not finish near the top. In the language of physics, top racers are said to develop more power.

Power refers to the ratio of the work produced (or energy transferred) to the time interval over which that work is done. Average power is expressed as P_{avg} = work/time, where work W is given in units of Joules and time is given in units of seconds. Two athletes who can perform the same task such as lifting a mass over a given displacement will produce the same amount of work. However, the one who performs the given task in a shorter interval of time produces more power. Events in sport that require substantial amounts of power in order to achieve success include weightlifting, sprinting, and car racing.

One of the consequences of doing work is to generate energy changes within systems; therefore, the quantity known as power can be extended to include energy expended (or produced) per interval of time. Elite sprinters are able to achieve about 90% of top speed during the first two seconds of a 100 m sprint. For an athlete of mass 90 kg, the amount of kinetic energy produced during this time interval is 6200 J. (A top speed of 13 m s^{-1} is assumed so that 90% of this value is 11.7 m s^{-1}.) Here, the change in kinetic energy is equivalent to the work done by the athlete; the power generated is 6200 J/2 s, or 3100 W. For perspective, this power level is approximately 477 times that of a common 6.5 W LED bulb. The human body can only maintain these levels of power production for a few seconds. More typically, humans are capable of producing power levels in the range of 400–700 W for time intervals of an hour or so.

One of the most extreme examples of power production is found when racing a top fuel dragster along a straightaway. These particular racecars have mass of approximately 1050 kg and reach speeds over 100 mph (44.7 m s^{-1}) in less than 0.7 s. During these acceleration intervals, average power levels exceed 1.5×10^6 W, equivalent to the power developed by 484 elite sprinters in the first few seconds of a 100 m sprint.

Kinetic energy, collisions, and protective gear

In other contexts analyzing KE is crucial for protecting players during certain kinds of collisions. In baseball, for instance, catchers are particularly vulnerable to errant pitches or foul tips striking their bodies. Catchers typically wear facemasks and headgear along with chest protectors and shin guards to minimize forces transmitted to the body. Impact forces exceeding certain critical values can lead to concussions, broken bones, and damage to soft tissue.

From an energy standpoint, the most effective body protection should convert as much KE as possible into other forms of energy, which are dissipated within the protective material. To illustrate, assume an extreme case in which a catcher's upper body is protected by an ultra-thick pillow filled with layers and layers of foam beads. When struck by a fast-moving ball, numerous internal collisions occur amongst the beads. Collisions between soft bodies such as the foam beads are typically highly inelastic—that is, they do not conserve KE. As a result, a certain fraction of the ball's initial KE is converted easily to other forms of energy that are not transmitted to the player. Conversions occurring within the protective gear include generation of mechanical waves such as sound, increased thermal energy of the beads, and work done on the particles (beads) as they are displaced. If complete conversion of KE occurs, the ball becomes embedded in the protective gear with no transfer of KE to the player.

Unfortunately, extremely thick layers of protective gear are needed in order for particles in contact with the player's body to transfer zero KE. For illustration, imagine a sand pile with your hand embedded well below the surface. If a ball collides with the top of the pile and becomes embedded well above your hand, your hand feels no effects due to the fact that sand particles near your hand have no work done on them. As mentioned above, this extraordinary level of protection is not feasible due to the excessive amounts of protective gear required.

In the other extreme, if the protective gear is very thin, essentially all of the initial kinetic energy of the ball is transferred to the player's body. As the ball makes contact with the thin padding, nearly all particles in the path of the ball experience impact forces due to the ball. In turn, work is done on the particles so that they transfer energy to whatever is in contact with them. Unfortunately for the player, these transfers of energy are palpable.

In a more realistic case, some of the initial KE of the ball is transferred to the protective gear and some is transferred to the player's body. Researchers who study collisions in sport, along with equipment manufacturers, must consider carefully maximum transfers of energy to the body in order to minimize injury. At the same time, players demand a certain amount of freedom of motion so as to perform at their highest levels. Extensive research continues in order to provide sufficient protection for players, together with maximum maneuverability.

Chapter 3

What did Newton say about force?

For millennia humans have been intrigued by countless questions related to motion: how do objects move? What makes one faster than another? What causes them to come to rest? Virtually all motions in the Universe, and, particularly ones in sport, can be analyzed using basic concepts outlined within Newton's three laws of motion. Newton's laws describe the concept of force, explain how objects behave in the absence of net forces, and give insights into interactions between systems.

Force and Newton(s)

All motions in the Universe originate from actions on a body. Actions in the physical world generally refer to forces. Forces can be classified according to whether they act directly upon a body or through space. Those that act directly are called contact forces and thus require physical touch in order to manifest themselves. Contact forces allow us to move objects such as a carton of milk or to walk across the room. (Walking results from our feet exerting forces on the ground, and the ground, in turn, producing equal and opposite forces on our feet.) In the realm of sport, contact forces arise from a bat striking a baseball, a basketball player taking a charge, a hockey player checking an opposing player, and a soccer player heading the ball.

In addition to forces that act by direct contact, others act through space and, as a result, are called 'action-at-a-distance,' or field forces. Field forces include gravitational forces such as those between the Earth and a javelin thrown into the air and electrical forces such as those between a charged van de Graaf generator and human hair. One of the basic properties of gravitational fields, espoused by Einstein and others, is that they cause curvature of space and time. Thus, the javelin's parabolic path results from the implement responding to the curvature of space near the surface of the Earth. Experimental results have confirmed the curvature of space and time due to field sources so that Einstein's general theory of relativity is our best description of gravitational field forces in the Universe. For purposes here, however,

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we will simply say that the Earth exerts a downward gravitational force on the javelin.

With the concept of force now established, we are ready to discuss how forces impact motions in the natural world within the context of Newton's laws. Because a change in the state of motion is ultimately caused by an action known as a force, Newton's first law says that all objects in the Universe maintain their present state of motion unless acted upon by a net force.

The idea of a net force implies that, in many instances, several forces act upon a single body. If those forces balance one another, no change in motion occurs. (An example would be a runner moving at constant speed, so that forces propelling the runner are balanced by ones resisting the runner's forward motion.) In addition, the present state of motion of a body may be one of rest so that if forces remain balanced that state continues. With these descriptions in mind, Newton's first law (the law of inertia) often is summarized as 'a body at rest tends to stay at rest, and an object in motion tends to stay in motion unless acted upon by a net, external force.'

In order to address what happens when a net, external force is applied, Newton formulated a second law of motion stating that the force (in units of Newtons, N) is equivalent to the product of an object's mass in kg and its acceleration in m s^{-2}. From basic definitions, acceleration produces a change in velocity, and velocity produces a change in position (displacement). When an object undergoes displacement, motion occurs along a particular path. Thus, as implied above, a net force is the ultimate cause of a change in the state of motion of a system.

One classic example of how motion arises due to a net force is an Olympic sprinter leaving the blocks in a 100 m dash. As the gun sounds, the runner reacts by generating forces on the starting blocks; the blocks, in turn, generate reaction forces on the sprinter. Such reactions forces exceed any resistive-type forces (such as air drag, friction, or other dissipative forces) so that the net force on the athlete is forward and equivalent to around 500 N for a male sprinter. Given a typical mass of 90.0 kg, a 500 N net force produces an acceleration of 5.6 m s^{-2}. This value is approximately 60% of the acceleration produced by the Earth's gravitational field.

Another characteristic of forces is that they always occur in action–reaction pairs. That is, object A exerts a force on object B, and, in turn, object B exerts an equal and opposite force on object A. One of the subtleties of action–reaction is that each force acts on a different object in the pair of interacting bodies. Thus, action–reaction forces never cancel one another as is sometimes stated erroneously. The principle of action–reaction extends to all forces in nature—including field and contact forces—and is referred to as Newton's third law.

During direct body-on-body collisions, action–reaction forces are always contact forces. A linebacker (LB) in football exerting a force on a running back (RB) experiences an equal and opposite force, produced by the RB. Such forces are often apparent when two players collide and their subsequent velocities after collision are very nearly zero. As described by Newton's third law, the LB produces a force on the RB to reduce his velocity to zero and the same can be said for the reaction force produced by the RB. A basketball colliding with a wooden floor also illustrates action and reaction. The basketball striking the floor causes the floor to flex as a result of the force exerted by the ball. In turn, the floor exerts a reaction force on the ball that causes it to bounce.

Other contact forces in sport include those generated by actions of human muscle. When considering feats of strength we often ask: what determines how strong someone is? The ability of muscle fibers to generate forces for lifting certain loads is directly dependent upon their capacity to support those loads. To determine how much force a muscle can support, consider the analogous problem of a cylindrical rod experiencing a force along its length. Provided each bond within the rod provides a specified force, the total force keeping the rod from breaking depends on the number of bonds formed over the cross section of the rod. Thus, the ability of muscle fiber to generate force is directly proportional to its cross-sectional area. As an athlete builds muscle, both the mass of that muscle and its cross-sectional area increase. As a result, athletes gain strength due to the ability of muscle fibers to generate greater forces.

All that friction

The question of whether or not an athlete will maintain traction on a field of play is determined by analyzing frictional forces. These kinds of forces act whenever two surfaces in contact move relative to one another, or whenever the two exhibit impending motion. Impending motion refers to the condition in which forces are applied to one or both systems; however, these forces are not large enough to produce motion along the surface. To analyze slippage, we will consider the case of impending motion, often referred to as the static regime.

As an example of impending motion, push the palms of your hands together in front of you and then begin pushing one hand forward with increasing force. At first no motion occurs, but, eventually, as the applied force is increased, the hand exerting the forward force breaks free and moves along the surface of the other hand. This experience of the hands is a direct analogue to how slippage occurs on a field of play.

In the experiments with your hands you may have noticed that the harder you push your hands together, the more force you need to produce motion. Indeed, the frictional force depends on how much force a system experiences due to the other surface. (By action–reaction the two exert equal and opposite forces on each other.) Frictional force also depends on the materials in contact with one another. In mathematical language, static frictional force $F_{\mathrm{f}} = \mu N$, where μ is the coefficient of static friction, determined by the materials properties of the two surfaces in contact with one another, and N is the normal force. Normal force refers to the perpendicular force experienced by a system due to the surface on which it maintains contact.

From these dependences, the ability to maintain traction on a playing field can be determined. For the moment, consider an artificial turf field and an athlete making a series of cuts on that field. As the athlete attempts to change direction, the feet must exert forces on the turf (and, in turn, the turf exerts forces on the feet). To achieve the intended motion, the athlete must produce forces that have both vertical and horizontal parts, often referred to as the components of the force. Horizontal forces obviously produce changes of direction in the plane of the field, allowing the athlete to make dramatic cuts.

The vertical forces produced by the feet cause vertical reaction forces acting on the feet due to interactions with the field. These reaction forces contribute to frictional forces to keep the athlete from slipping. Provided the reaction forces are fairly constant for a particular athlete, values of frictional force then depend primarily on what the coefficient of friction is under the present playing conditions. Dry fields have static coefficients of friction of 0.6–0.8; whereas, wet fields usually have coefficients of 0.1 or less. Consequently, frictional forces can be reduced by as much as a factor of 6–8 when fields become soaked, thus prompting commentators to say, 'field conditions have deteriorated due to the wet conditions.'

Centripetal force

Acceleration of a body requires the presence of a net force as seen from Newton's second law. In many instances, forces are applied in order to either increase or decrease the magnitude of a system's velocity. A soccer ball at rest experiences acceleration when a net force is exerted on it, and, in response, the ball attains a velocity in the direction of the force. By contrast, a base runner sliding into second base reduces his velocity to zero just as he touches the bag. (Figure 3.1 depicts forces acting on two systems, a block and a base runner, both undergoing motion along a surface.) In the case of the runner, the frictional force due to the ground opposes the original motion, thereby reducing the velocity to zero during the slide. For both the

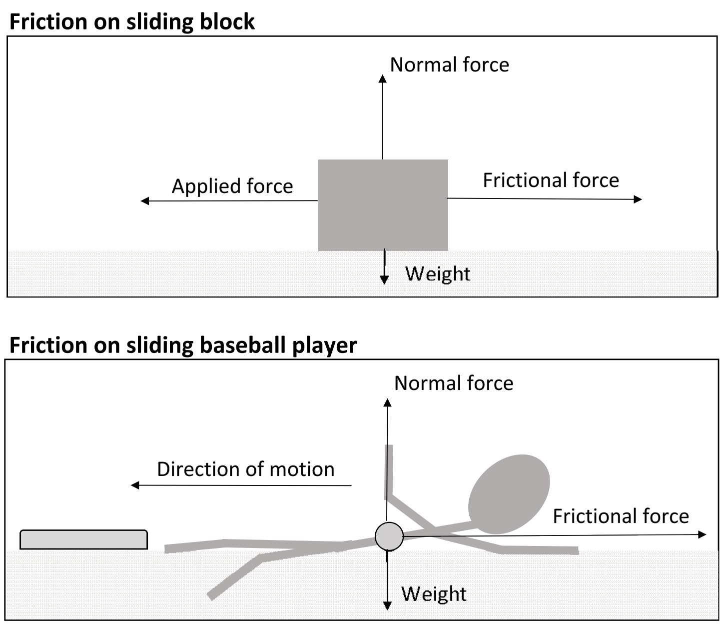

Figure 3.1. Forces acting on a block sliding along a surface and a baserunner sliding along the ground into a base.

soccer ball and base runner, acceleration is produced as a result of the magnitude (value) of the velocity changing with time.

Acceleration also occurs when an object experiences a change in its direction of motion (even when no change in magnitude occurs). To understand the significance here, recall that a vector quantity has both a magnitude and a direction associated with it. For acceleration to occur, there are three possibilities: the magnitude of the velocity vector can change, the direction of the velocity vector can change, or both the magnitude and direction can change simultaneously. We will consider the second case.

Imagine an object whose direction of motion changes continuously over time, but whose velocity magnitude is constant. Such motion is present when a particle is moving in a circular path with constant speed. A classic example is that of an ice skater cruising at a constant rate around a circular path. To maintain this state of motion, the skater must experience a force, directed toward the center of the circular path. This centripetal or 'center-seeking' force on the skater is supplied primarily by the ice surface.

When an object undergoes circular motion, the direction along which the particle travels is changing constantly. (For illustration, walk along a circular path at a constant pace and note your direction of travel. You should see that your direction of travel changes from moment to moment.) To produce this change in direction, a constant tug toward the center of the circular path must be exerted. This force constantly re-directs the particle's path so that it remains circular. To observe what happens when such a force is absent, swing a ball on the end of a string along a circular path. Once the ball is moving with constant speed, release the string. Once released, the centripetal force is no longer present so that the ball now moves along a path tangent to the original circular path.

In sport numerous systems undergo centripetal acceleration with accompanying centripetal forces. In track and field, hammers and discuses are set into circular motions by throwers who subsequently release the implements into the air. Base runners also experience centripetal forces along the base paths as they transition from linear to curved paths. Other events in sport that involve motion along curved paths are running, cycling, gymnastics, and car racing.

Given the ubiquity of centripetal forces in sport, several questions immediately come to mind. What factors determine centripetal force? How large are these forces? How might these forces change? Centripetal force (like any other force) is the product of mass and acceleration; thus, the magnitude of the centripetal force is dependent upon mass m. As mass increases, a larger centripetal force is necessary in order to maintain the present state of motion along a specified path. The basic argument here is that a larger mass requires a larger force to produce a given acceleration (Newton's second law). As a result, extremely large centripetal forces are required to keep a hammer moving in its circular path before release.

Another factor that determines centripetal force is the radius r of the circular path. As radius increases, the object in uniform circular motion requires less re-orientation during a given time interval to maintain its present state of motion. Because less re-orientation is necessary, the required centripetal force is reduced. From this dependence, centripetal force varies as the inverse of the radius.

The final factor that determines centripetal force is speed v. As speed increases, the object in motion travels farther along its circular path from one moment in time to the next so that more re-orientation is required. This increased re-orientation means that more force is required to maintain the present state of uniform circular motion. From these arguments and a little more mathematics, the magnitude of the centripetal force F_c is found to be proportional to the square of the speed and can be expressed as: $F_c = mv^2/r$.

Centripetal forces in sport

Analyses of various athletic events allow us to determine magnitudes of centripetal force. In the discus throw, athletes typically rotate their bodies several times within a well-defined ring before releasing the discus into the air. During this throwing action, the discus attains motion along a circular path whose radius is approximately equal to the length of the thrower's arm. To achieve this motion, the athlete must supply a centripetal force on the discus until release occurs. World-class throwers typically release the discus with speeds of around 25 m s^{-1}, corresponding to centripetal forces in the range of 1600 N (given a radius of 0.8 m and mass of 2.0 kg). Even larger forces of order 3500 N are needed to maintain circular motions in the hammer throw event where the implement has a mass of 7.3 kg.

In running events such as the 200 m dash, centripetal forces of up to 350 N are required for elite sprinters running in the inner track lane whose radius is approximately 36.5 m. For sprinters running in lane eight, centripetal forces are reduced by approximately 23% due to the larger radius (45 m) of the curved path. Presumably, if two runners exert the same forces during a race, the runner in lane eight would achieve greater speed due to the fact that less of the applied force is required to maintain motion along a curved path. Simple models suggest that the runner in lane eight would reduce elapsed time during the first 100 m of a race by about one second. In practice, elite runners are placed in the middle lanes during competitions, so there is little evidence available to verify if record times could be accomplished by careful choice of running lanes.

As seen from our discussions, centripetal forces are necessary to maintain uniform motions along circular paths. Various contact, and even field forces, can serve as the sources of these actions. For Olympic throwers centripetal forces are generated through muscular actions of the arms and shoulders. For stock car racers, friction between the tires and racetrack contribute to centripetal forces. In addition, racetracks are banked so that reaction forces on the tires due to the track provide additional forces directed toward the center of the circular path. Planets in circular orbits also experience centripetal forces due to the gravitational action of the central star. An interesting exercise is to identify the sources of centripetal forces in various sporting events.

What a drag

As seen in the example of a batted baseball, interactions between moving objects and fluids surrounding them often have dramatic effects. A baseball, for example,

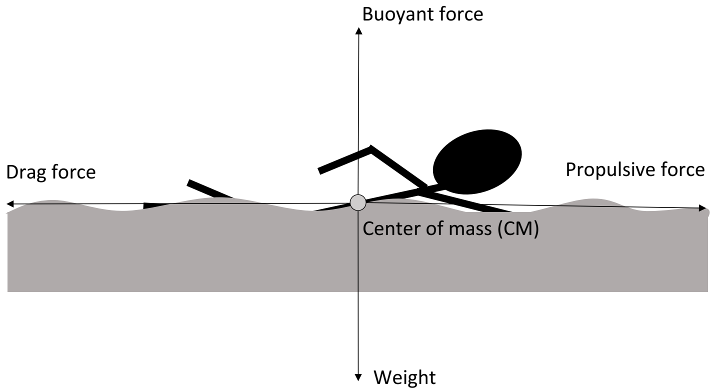

Figure 3.2. Force diagram for a swimmer, indicating propulsive, drag, gravitational, and buoyant forces.

experiences a reduction of roughly 50% in horizontal distance (range) traveled as a result of such effects. Aerodynamic drag also limits swimmers to top speeds of a few m s^{-1}, as compared with Olympic sprinters in track and field who attain top speeds in excess of 11 m s^{-1}. For reference, figure 3.2 depicts a swimmer with horizontal and vertical forces indicated.

As the name implies, drag force originates due to collisions between a moving object and the collection of molecules in which that object is immersed. As the object moves, it encounters fluid particles, thus generating collisions between the two. As a result, fluid particles experience forces due to interactions with the object. In turn, the molecules exert forces on the object that are opposite in direction to those experienced by the molecules. The multitude of collisions occurring during each small interval of time results in an aerodynamic drag force, which always opposes the motion of the object.

Drag force depends upon a number of factors, the most important of which is the object's speed v through the medium. As the object's speed increases, it encounters a greater number of fluid particles per unit time and thus experiences an increased number of collisions. As the number of collisions in a given amount of time increases, drag force increases as a consequence. This result is in close analogy with a person moving through a crowded room of people. As the person moves more rapidly, she encounters an increased number of bodies per unit time. This increased number of interactions leads to an increased force opposing the person's motion.

Given that drag force increases with the number of collisions occurring during an interval of time, it should scale with the density ρ of the fluid and the cross-sectional area A of the object, as confirmed by experiment. Each of these factors affects drag in a linear fashion and for similar reasons. When the density of the fluid surrounding the ball increases, the ball encounters a greater number of molecules during an increment of time, which, consequently, increases the number of collisions and the overall force. Similar arguments hold as the cross-sectional area of the ball increases. A final factor that determines drag force is the so-called drag coefficient C_D, which depends upon a number of quantities, including the shape and smoothness of the object. From these arguments aerodynamic drag force is expressed as:

$F_D = 0.5 C_D \rho A v^2$. For a baseball traveling at 100 mph (44.7 m s^{-1}), F_D is approximately 2.0 N, a value comparable to the weight of the ball itself. As seen earlier, such effects reduce the range of baseballs by approximately 50% of their ideal range.

As a result of atmospheric effects, drag forces can vary even for specified objects moving with constant speed. Such variations usually occur due to changes in air density with altitude or temperature. As air temperature increases, gas particles attain greater kinetic energies and, as a result, they move with greater speeds and occupy greater average volumes. Air density then decreases and the drag force decreases proportionally. Studies reveal that air density and drag force decrease by about 2% as temperatures increase from 20 °C to 25 °C. While these changes seem inconsequential, effects due to drag forces are cumulative. For example, reduced drag of 2% in a 4 km pursuit race in cycling decreases race times by 1–2 s, a significant difference given that a few hundredths of a second often separate racers at the finish line.

Chapter 4

Momentum, collisions, and sweet spot

Whenever two objects interact in time and space, they undergo what is known as a collision. In scientific studies, numerous theoretical treatments have been developed to analyze collisions of objects ranging from atomic nuclei to human bodies to galaxies. Collisions are prevalent in nearly every sport—even in ones classified as 'non-contact' such as golf and running in which, respectively, ball–club and foot–ground collisions occur rather frequently. In fact, it is difficult to imagine any sport or athletic contest in which no collisions occur. Given the ubiquity of collisions in sport, the treatments here will consider where along a bat a collision should occur for maximum effect and how to predict speeds of objects after collisions occur.

Sweet spot

Striking a ball with a bat produces a variety of effects, depending upon where the impact occurs. In the most painful cases, the batter's hands experience stinging sensations, often lasting for several seconds. During more optimal strikes, the collision produces no ill effects on the hands and the ball rebounds with maximum velocity. So what is different about the two strikes?

As an extended body, a bat or racket has a special point, known as a center of percussion (COP), associated with it. In physics language, a force acting through that location causes the rotational and translational motions of the bat to cancel at the pivot point, located near the hands. Given this lack of motion at the pivot, no reaction force is produced there, and the batter feels essentially no effects due to impact. If the (collision) force is applied between the hands and the center of percussion, the batter feels a force that tends to push the hands backwards (away from the pitched ball). If the force is applied between the center of percussion and the far end of the bat, the batter feels a force that tends to push the hands forwards (toward the pitched ball). See figure 4.1 for the approximate location of the center of percussion COP of a baseball bat.

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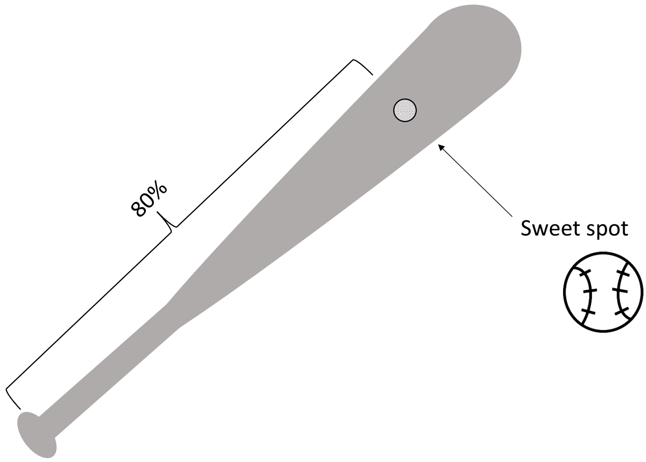

Figure 4.1. Depiction of baseball bat and the approximate location of its center of percussion COP or sweet spot.

Collisions at the COP then are desirable from the standpoint of the batter's comfort, but also from the point of view of producing longer hits. Impacts at the COP produce no overall motion of the pivot point, thus no work is done at that location. In turn, more of the initial kinetic energy of the ball is returned after collision. Greater return of kinetic energy (KE) causes the ball to travel farther given that distance traveled for a projectile is dependent upon launch speed.

The COP is closely associated with another optimal point of impact along an implement known as a node of vibration. When objects such as bats, rackets, and clubs are struck, they tend to vibrate along directions perpendicular to their lengths. These oscillations cause transverse waves, and, when combined with the fact that these waves travel in both directions along the implement, produce what are known as standing waves.

Standing waves result from the combination of waves traveling in opposite directions and are characterized by regions of maximum oscillation called antinodes and regions of minimum oscillation called nodes. To best observe these regions, tie a rope to a fixed location and shake the other end at higher and higher frequencies until a series of antinodes and nodes is observed. This kind of pattern is what is created along an extended body such as a bat. (Standing waves also occur within a pipe organ or along a guitar string when a particular note is played.) A bat held at one end generally oscillates in one of two natural modes—one with a single node near the handle end of the bat and another with one node near the handle and second one about 80% along the length of the bat. The second node is where the batter should strike a pitched ball to avoid unwanted vibrations.

Collisions at nodes and antinodes determine hit distance following impacts between a ball and a bat. When a bat is struck at one of its natural antinodes some of the initial kinetic energy KE associated with the object colliding with the bat is converted into vibrational energy of the bat. By contrast, when a bat is struck at one of its natural nodes, little or no KE is converted into vibrational energy of the bat. As a result, nearly all the KE of the object (ball) colliding with the bat is returned to that object. This greater return of KE causes the object to attain a greater speed after collision. As a result, striking a ball at or near the COP or a closely associated node of oscillation produces the most optimal conditions for a batter—minimal reaction forces, reduced vibrations, and greater hit distances.

Conservation of linear momentum

In the absence of forces other than those acting between colliding bodies, a system of bodies is said to be isolated. Under these conditions, application of Newton's laws of motion proves that the physical quantity known as linear momentum is the same before and after collision. Linear momentum by definition is the product of mass and velocity; conservation in the realm of science refers to the fact that the conserved quantity maintains the same magnitude and direction.

A simple example of conservation of linear momentum involves the head-on collision between two billiard balls—one that is initially at rest and another one moving with initial velocity v. In this scenario, the first ball has zero initial linear momentum, and the second one has linear momentum given by its mass times velocity. Upon collision, the first ball usually comes to rest quickly while the second one moves in the forward direction with essentially the same velocity as the first one had initially. Thus, the linear momentum of the first ball is transferred to the second, resulting in no change in either the magnitude or direction of the linear momentum of the system—a clear demonstration of conservation. These arguments, of course, assume that only interactions between the two billiard balls occur during collision. In addition, only translational motions are considered for these analyses.

Conservation of momentum—it's the law

The mathematics of conservation of linear momentum is based on the fact that the conserved quantity must have the same magnitude and direction before and after a collision occurs. Magnitude here refers to the numerical value associated with the quantity; direction refers to the orientation of the quantity in space. For head-on collisions, application of conservation of linear momentum is reduced to one dimension and the mathematics describing a system of two colliding bodies becomes $m_1v_{1\mathrm{i}} + m_2v_{2\mathrm{i}} = m_1v_{1\mathrm{f}} + m_2v_{2\mathrm{f}}$, where m_1 is the mass of the first object, m_2 is the mass of the second object, $v_{1\mathrm{i}}$ is the initial velocity of the first mass, $v_{2\mathrm{i}}$ is the initial velocity of the second mass, $v_{1\mathrm{f}}$ is the final velocity of the first mass, and $v_{2\mathrm{f}}$ is the final velocity of the second mass. For reference, a direct collision between a baseball and a bat with initial and final velocities shown is depicted in figure 4.2.

Numerous examples of head-on collisions occur in sport; all of them can be analyzed using the expression above. One of the most dramatic is a quarterback sack in football. Suppose that an NFL quarterback (QB) of mass 98.0 kg is set up in the pocket, ready to deliver a pass downfield to an open receiver. In this scenario the QB often is unaware of an oncoming rusher, so he is essentially motionless at the time of collision. As a result, all the initial linear momentum is due to the pass rusher. If such a rusher has a mass of 130 kg and a velocity of 5.0 m s^{-1}, the initial momentum is

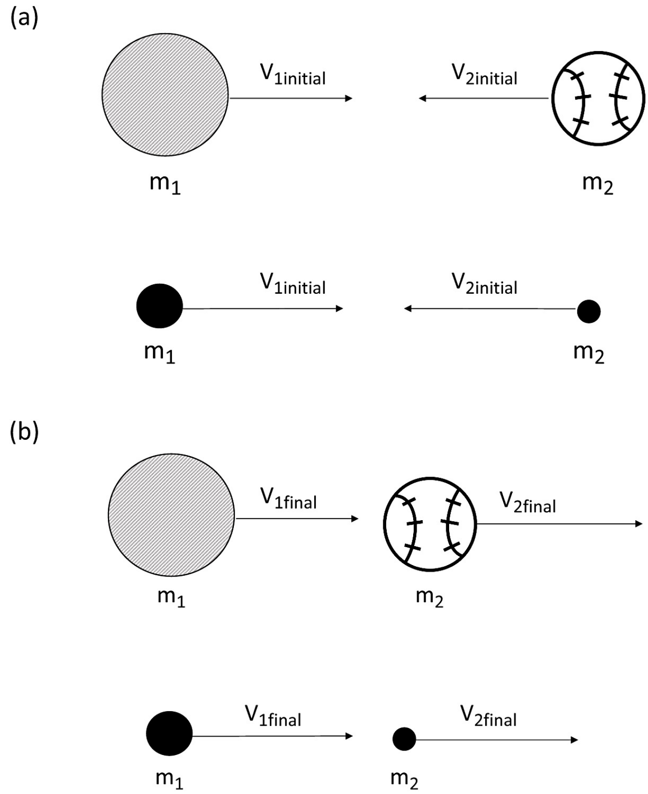

Figure 4.2. (a) Schematic of a baseball bat and ball moving toward each other before collision. (b) Schematic of a baseball bat and ball after collision. The smaller filled circles depict how extended bodies can be treated as point masses for computations in which rotation is neglected.

650 kg m s^{-1}. The goal of the pass rusher is to take the QB to the ground, so, upon collision, the pass rusher grabs the QB and the two move as one system with a common velocity. Setting the initial momentum of the rusher equal to the mass of the combined players times the final velocity of the combination, yields a final velocity of 2.9 m s^{-1}. Speeds of this magnitude, combined with falling to the ground during the tackle, can lead to severe injuries to the shoulders, legs, neck, and back. Quarterbacks beware.

Basketball is another sport in which body-on-body collisions occur. In many instances, a player drives to the basket and an opposing player moves into position to prevent the drive. An ensuing collision occurs that can be analyzed using the principle of conservation. To illustrate, assume the player driving to the basket has a mass of 91 kg and a velocity of 5.0 m s^{-1}, and, after collision, that same player has a velocity of 2.5 m s^{-1}. A second player has a mass of 88 kg and an initial velocity of zero. Inserting these numerical values into the equation for conservation of linear momentum yields a final velocity for the second player of -2.6 m s^{-1}, indicating that the second player is moving backwards at a rate of 2.6 m s^{-1}. These motions are expected given that players taking charges generally move backwards following collisions with players driving to the hoop.

Chapter 5

All that spin: angular motions and angular momentum

Rotational motions in sport both intrigue us and motivate us to ask questions such as: will the gymnast land on her feet during a dismount from the balance beam? How much will the slider break on its way to home plate? How many rotations can the skater perform on a particular jump? Discussions below begin with a few definitions related to angular motions and then introduce one of the most robust laws in physics—conservation of angular momentum. With this powerful tool in hand angular motions of systems ranging from atoms to galaxies and everything in between can be analyzed with surprisingly simple mathematics.

Angular speed

The concept of (average) speed is based on the rate at which an object moves from point to point in space. Angular speed, by contrast, refers to the rate at which an object rotates about an axis. Many systems in sport including divers tumbling in the air, ice skaters twirling during a jump, and baseballs spinning during their movement to home plate exhibit rotation. To determine how fast these rotations occur, the quantity, average angular speed, is defined as $\Delta\theta/\Delta t$, where $\Delta\theta$ refers to a change in the angular position of the system and Δt refers to the interval of time to undergo the given rotation.

In the commercial world, rates of rotation often are expressed in terms of number of revolutions per minute. Fan motors, for example, have operating rates of rotation of around 1000–1800 revolutions per minute (rpm). In the scientific world, angular speeds are expressed in radians per second. (For reference, there are 2π radians in one revolution.) Angular speeds in sport range from curveballs in baseball (188 rad s^{-1}) to penalty kicks in soccer (60 rad s^{-1}) to slowly rotating gymnasts (6 rad s^{-1}). Quantifying angular speeds is crucial for analyzing maneuvers of ice skaters and

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gymnasts, determining curvature of soccer balls, and specifying forces necessary for racecars to maintain their paths along circular paths.

Angular acceleration—all that change in angular velocity

As seen from motions in one and two dimensions, velocity arises due to intervals of acceleration. Acceleration, in turn, depends on generation of forces such that acceleration is proportional to the net force applied. For rotational motion to occur, a system must experience a change in angular velocity, which is characterized by angular acceleration. Angular acceleration is generated as a result of a net torque applied to a system.

Torque has many nuances and complications but can be understood by thinking about the operation of a wind turbine. Air passing over the blades of a turbine produces forces at right angles to the blades and at nonzero distances from the axis, causing the blades to turn. In a similar fashion, actions of the hands and fingers generate forces at the outer edges of a basketball, thus producing rotation (backspin) upon release of a jump shot. From these examples, systems undergo angular motion when a net force is applied at a nonzero distance from the axis about which the system rotates. In the language of physics, angular motion is generated by a net torque, which requires the product of two physical quantities—an applied force and a lever arm. A lever arm for a rotating body refers to the perpendicular distance between the pivot point (axis) and the line of action of the force.

As a final everyday example of angular motion, consider operation of a hinged door. By design the handle of the door is located at nearly the width of the door away from the axis of rotation running through the set of hinges. When a force is applied at the location of the handle, a torque is generated to cause the door to rotate. If a force is applied halfway between the hinges and the handle, the force must be doubled in order to produce the same torque. For a fixed value of force, the torque depends directly on the value of the lever arm. Often we talk about increasing leverage, which basically translates to increasing the lever arm.

Triple axel

Competitive singles' ice-skating is a splendid event consisting of compulsory routines as well as free programs, emphasizing thrilling jumps and spins. Olympic singles' ice-skating first appeared in the 1908 Games in London and has continued until the current day. Extraordinary athletes who have become Olympic ice-skating champions include American men Dick Button, Hayes Alan Jenkins, David Jenkins, Scott Hamilton, Brian Boitano, and Evan Lysacek and American women Tenley Albright, Carol Heiss, Peggy Fleming, Dorothy Hamill, Kristi Yamaguchi, Tara Lipinski, and Sarah Hughes. Historically, Americans have performed well on the world stage; however, more recently, skaters from Russia and Japan have dominated international and Olympic competitions.

One of the most exciting personal moments in the 2018 Winter Olympics in Pyeongchang (South Korea) occurred when Mirai Nagusa became the first American woman to land a triple axel in Olympic competition. The triple axel is a particularly difficult jump to execute given that the skater takes off in a forward position and lands in a backward position. Prior to launch, skaters like Nagusa approach the takeoff point at close to 20 mph (8.9 m s^{-1}) so that exquisite timing is crucial. Upon landing the body experiences forces up to five times the skater's body weight, distributed over a single skate whose blade width is only 4 mm. The entire jumping maneuver requires 3.5 rotations in less than a second. Average angular speeds developed during rotation in the air are approximately 22 rad s^{-1}, or close to 40% of angular speeds attained by soccer balls during penalty kicks.

Rotation and conservation of angular momentum

An Olympic diver walking toward the end of a springboard takes a final hop-step causing the end of the board to bend downward. As the board returns to its natural position, the diver uses the action of the board to propel herself upward in preparation for a dive. As she returns to the board, it flexes further this time so that when she leans slightly forward, the board's upward motion causes her to vault into the air. During flight, her body's motion is upward and forward, ultimately causing her to reach a maximum height before continuing her descent along a curved path toward the pool. This trajectory through the air takes only a few seconds but dramatically determines the outcome of what is often a once-in-a-lifetime competition.

As seen from slow motion replays, the path of a diver follows a familiar parabolic shape, much like that of a basketball or shot put projected into the air. This trajectory is predicted by Newton's laws of motion for an object undergoing 2-D motion with constant acceleration along one of those directions. This so-called projectile motion is what causes the diver to go from the board to the water, along a relatively smooth path.

During her trajectory through the air the diver experiences both translational and rotational motions. The quantity characterizing how fast she is rotating, called angular speed, remains relatively small, as she leaves the board in an extended body position. So subtle is this motion in the extended position that it is sometimes imperceptible to the eye.

However, as she tucks her body into a fetal position during the dive, her angular speed increases, thus allowing her to negotiate several rotations in the air. Before entering the water the diver often returns to an extended position, reducing her angular speed prior to entry. Such a maneuver allows her to enter the water in a nearly vertical position so as to prevent excessive splash that would lead to deductions in scoring. Given this interplay between angular speed and body position, an observer might ask: why do these changes in angular speed occur?

The basic physical principle, describing the changes observed during the dive, is referred to as conservation of angular momentum. Angular momentum by definition is the product of two quantities—the moment of inertia I of a body and its angular speed ω. Angular speed, as described previously, refers to the rate of rotation of an object in special units of radians per second. Moment of inertia is a physical quantity that describes quantitatively how the mass of a system is distributed about its axis of rotation.

For a given mass, a larger moment of inertia indicates that a larger portion of that mass is distributed farther away from the rotation axis. As an example, consider a solid disk and a ring, each with the same mass m and radius r, free to rotate about axes perpendicular to the planes in which they lie and through their geometric centers. Under these conditions, the ring has a moment of inertia that is twice that of the disk, leading to noticeable differences in their motions. When a disk and a ring, both of equal mass and radius, are released from rest at the top of a ramp, the disk reaches the bottom first.

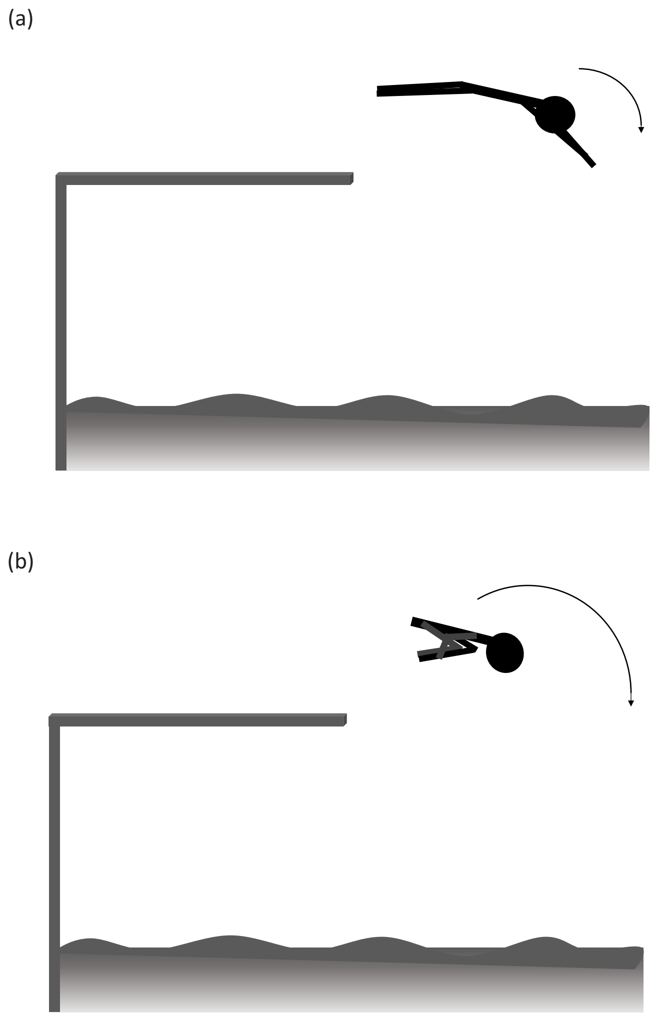

Figure 5.1. (a) Diver undergoing rotational motion in an extended position. (b) Diver undergoing rotational motion in a tucked position.

The physical reasoning is that the disk has a lower moment of inertia and, as a result, less resistance to a change in its rotational state of motion. Because this resistance is reduced, the disk attains angular speed more quickly. Such effects are akin to a smaller mass, experiencing an equivalent force to that of a larger mass, attaining a greater speed in a given amount of time.

Returning now to conservation of angular momentum, motions of the diver will become more apparent. Conservation laws in physics arise whenever conditions are just right so that a particular quantity remains constant. Angular momentum is a conserved quantity whenever a rotating body is isolated—that is, the body is not interacting with its environment. Once airborne, the diver essentially becomes an isolated body in terms of its rotational motion, provided small effects such as air resistance are neglected. As an isolated body, the product of the diver's moment of inertia and angular velocity has a fixed value and direction. If the diver extends, the moment of inertia increases and the angular velocity decreases so that the diver does not rotate as rapidly. Conversely, if the diver tucks the moment of inertia decreases and the angular velocity increases so that the diver rotates more rapidly. See figures 5.1(a) and (b) for both scenarios.

As a quantitative example, consider a diver who leaves the board in an extended position such that her moment of inertia is 12.0 kgm^2 while rotating at 1.2 revolutions/second (7.5 rad s^{-1}). Suppose that as she tucks, her moment of inertia is reduced to 4.2 kgm^2 causing her angular speed to increase to 21.4 rad s^{-1}. (This angular speed translates to over 3 revolutions/second.) With this example in mind, it is interesting to observe changes in angular speed during diving events in the Olympics and international competitions. Other athletes who make use of conservation of angular momentum to control their rates of rotation (angular speed) include ice skaters, gymnasts, and acrobats.

Chapter 6

Effects of fluids in sport

Many effects in sport are the result of a system—such as a soccer ball or the body of an athlete—interacting with matter in the form of a fluid. Fluids such as air and water often are described as systems whose constituent particles interact weakly with one another. In response, bulk fluids usually take the shape of the containers in which they are confined. While interactions among fluid particles are weak, the collective action of billions and billions of fluid particles, moving randomly or along streams of flow, produce forces whose effects are visible. Such effects provide the buoyancy that cause swimmers and water polo players to float and generate forces that produce deflections of soccer balls, baseballs, and volleyballs.

Buoyancy

One of the most fundamental interactions between an extended body and a fluid involves the effect of buoyancy. By definition buoyancy refers to an upward force generated on a body due to the fact that the body partially or fully displaces a fluid. A toy boat floating on water is a familiar example of a system experiencing buoyancy. The fact that the boat does not sink is due to a buoyant force produced by the water on the boat. When the boat is placed on water, a portion of the boat sinks below the surface level. That portion of the boat displaces a volume of water equal to the volume of the boat below the water level, and an accompanying buoyant force is exerted on the boat. This force is common to all objects that displace water or other fluids.

The origin of the buoyant force is best understood by thinking about a fluid at rest within a container. Consider a thin slice of water whose top edge aligns with the surface level of water within a container. Provided the thin slice remains at rest, all forces on it must balance. For any net downward force acting on the slice there must be a compensating upward force.

Near the surface of the Earth the thin slice of fluid experiences a gravitational force directed downward. For equilibrium to be maintained, an upward force must

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be exerted on the slice, and further that force must be exerted by the water itself. In this scenario, a fluid can only exert an upward force that is equal to the weight of the fluid displaced. If such a force were larger than the weight of the fluid displaced, the slice of fluid at the surface would accelerate upward. If such a force were smaller, a similar slice of fluid would sink. These arguments can be summarized as follows: a fluid exerts an upward (buoyant) force on an object either partially or completely submerged within it. That upward force is equal to the weight of the fluid displaced.

All objects on the surface of the Earth experience buoyant forces due to immersion within the atmosphere. In most cases, buoyancy due to air is so small compared to gravitational forces that no significant effects are observed. However, when objects are immersed in water, substantial buoyant forces are present. Given that the ratio of the density of a human body to that of water is approximately 98%, Archimedes' principle predicts that 98% of the human body will be below water level, and 2% of the volume of the body will be above water level at equilibrium. Buoyancy effects are observed most commonly in water sports such as water polo, diving, and swimming.

The curveball and a bender in soccer

Watch any soccer match or baseball game and you will see countless examples of balls experiencing sideways forces as they travel through air. Sideways forces produce curvature, which adds to the drama and challenge of competitions. As examples, a goalie in soccer must be able to react to a shot in which the ball experiences up to a meter or more of deflection, and a baseball batter must be able to make contact with a ball traveling over 90 mph (40 m s^{-1}) while also exhibiting curvature of 0.4 m or more. Given such dramatic effects, several questions emerge. What is the origin of these forces? How large are they? Can they change under certain circumstances?

Investigations of these questions require consideration of motions of air molecules relative to a spinning ball. Upon release a curveball rotates very rapidly (typically over 2000 revolutions/second) but also travels along a path through the air surrounding it. For the discussion here, this forward motion can be treated as if the ball remains at rest while the air moves in a direction opposite to the ball's motion. (This scenario is similar to wind tunnel studies in which objects are held at rest while air at a specified speed is directed at those objects. It also provides a more accessible way to address interactions between the ball and air.)

Fluid layers near the ball's surface are known as airstreams. A single airstream is essentially a string of particles, moving along a path that exhibits no rotational motion. Smooth airflow consists of a multitude of moving airstreams, each one parallel to its neighboring airstreams. In addition to the air's motion past the ball, figure 6.1 depicts a region on the side of the ball opposite to the origin of the airstreams known as the wake. In this region, airstreams interacting with the ball deviate from their smooth paths, thus leading to rotational motion and accompanying turbulent flow in the wake.

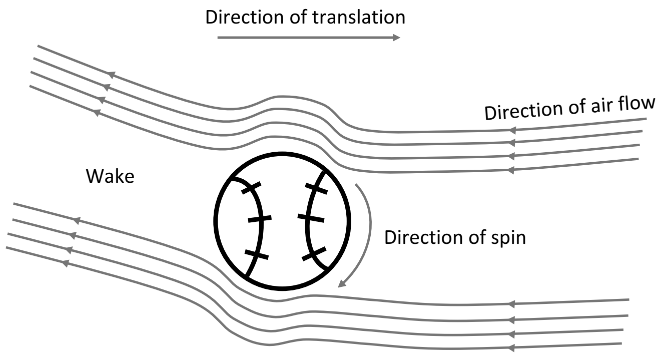

Figure 6.1. A baseball traveling to the right on the page and spinning in a clockwise fashion. In this scenario, the wake is deflected upward, resulting in downward deflection of the ball.

Sideways forces on balls in airstreams arise from deflections of the wake due to action–reaction forces between the wake and the ball. For a smooth, non-spinning ball the wake lies directly behind the ball and no accompanying sideways forces occur. For a spinning ball, airstreams moving in the same direction as the surface of the ball tend to stay in contact with the surface, causing the streams to bend around the ball before separating. By contrast, airstreams moving in the opposite direction as the surface of the spinning ball tend to bend around the ball less so before separating. The wake then is deflected toward that region where less bending occurs, and the ball is deflected in the opposite direction, in accordance with Newton's third law of motion.

In the scenario shown in figure 6.1, the upper part of the ball is traveling in the opposite direction to the motion of the airstreams. Thus, the wake is deflected upward, and the ball is deflected downward. Indeed, a ball rotating clockwise and moving to the right in the plane of the page is expected to experience a downward force, leading to bending or curvature of the ball's path. The degree to which a ball curves on its trajectory basically depends on how large the force is and over what time interval such a force acts. For a baseball traveling from the pitcher's hand to home plate, this time interval corresponds to how long the ball is in the air during its flight.

The bending force on a spinning ball depends upon a number of factors: a constant called the lift coefficient, density of the fluid, speed of the object, its diameter, and its rotation rate. Standard calculations predict typical forces on a Major League curveball in the range of 2–3 N. Forces of this magnitude acting over time intervals equivalent to the time of the ball's trajectory produce sideways deflections of order 1 m. Such deflections are approximately equal to the distance between the batter and the outer edge of home plate—so that a curveball directed at the batter will cross over the opposite side upon arrival. (This scenario assumes that the pitcher and batter have the same handedness.)

The knuckleball

Under certain conditions, objects such as baseballs, softballs, and volleyballs can exhibit sideways (or downward) motions even when no substantial rotation occurs.

In the parlance of sport, such motions are said to result from knuckling action of the ball. Pitchers in baseball sometimes throw non-spinning pitches to generate unpredictable deflections so as to deceive the batter. In other cases, knuckling effects result from certain playing conditions and are totally unintentional.

In order to understand how these motions arise, consider a non-spinning sphere interacting with a system of airstreams. As before, the ball's translational motion through air is equivalent to the ball remaining at rest and airstreams moving around the ball in a direction opposite to the ball's motion. As in the case of the curveball, a region called the wake develops behind the ball such that interactions between the ball and the wake produce knuckling effects.

For a non-spinning object in an airstream, deflections of the wake occur as a result of small asymmetries on the object. Asymmetries usually refer to regions that have different smoothness or surface features. For instance, a small scratch on one side of an otherwise perfectly smooth sphere provides an asymmetry. For a baseball or softball, the seams can create asymmetries from the perspective of airstreams passing over the ball. To visualize these effects, hold a baseball in front of you so that airstreams passing over the right side of the ball encounter two closely spaced seams at right angles to the airstream. On the other side of the ball, directly across from the seams, airstreams encounter the smoother covering of the ball. These differences in smoothness provide asymmetries necessary to cause deflection.

To illustrate these effects, consider a non-spinning ball with asymmetries, resulting from smooth and rough regions on opposite sides of the ball. As shown from wind tunnel experiments, airstreams interacting with the rough region of the ball tend to bend around the ball more so before separating. By contrast, airstreams interacting with the smoother region of the ball tend to bend around the ball less so before separating. Given that the rough side of the ball tends to maintain the airstream, the wake is deflected away from the rough side, and the ball, in turn, is deflected toward the rough side. In the description here, the deflection is sideways, but different orientations of the ball on its path to the plate can result in downward deflections. Claims of upward deflections have been made but would require extraordinary conditions not usually present in baseball stadiums. More likely, these observations can be explained by the fact that upward lift forces produce less overall drop in the ball than expected due to gravity alone. When the eye detects less overall drop, the brain perceives upward motion.

In addition, deflections can vary from moment to moment as the ball travels from the pitcher's hand to home plate. As a quick example, imagine that a ball is thrown with very little rotational motion, but with just enough to undergo a ¼ to ½ rotation during its trajectory. Returning to the situation where the right side of the ball has enhanced roughness, the ball initially undergoes deflection toward that side. Suppose now that the ball undergoes a ¼ rotation before reaching the batter.

During re-orientation, the asymmetry of the ball shifts from the right to the left side so that the deflection is now in the opposite direction to the original one. Analyses of outstanding knuckleball pitchers indeed show that multiple deflections are possible as the ball travels to home plate. These motions are inherently unpredictable due to the fact that trajectories are dependent upon details of ball orientation, rotation, and speed. Often batters experience confusion when trying to hit the knuckleball, but catchers also experience difficulties in handling the knuckleball. In fact, catchers often use over-sized gloves when catching knuckleball pitchers. Typical forces associated with knuckleballs are slightly less than those associated with curveballs so that deflections of 0.1–0.4 m are common.

Unexpectedly large knuckling action in sports can cause confusion among competitors, and, ultimately, affect outcomes of games. Prior to the 2010 FIFA World Cup the organizing body approved the new Jabulani football for competition. The officially sanctioned ball was designed with 8 instead of 32 panels, making it susceptible to enhanced knuckling, presumably due to a precipitous drop in its drag force at certain speeds. Decreases in drag force effectively enhance effects due to side-to-side (lift) forces generated by interactions between the wake and asymmetries on the ball. Before and during the World Cup, players and coaches complained that the ball's path was unpredictable, especially at intermediate speeds under slow rotation. Wind tunnel experiments confirmed that the Jabulani ball exhibits increased knuckling at intermediate speeds of 30–55 mph. This controversy in the soccer world led to development of the Adidas Tango 12 series of balls.

Tom Brady and Deflategate

Love them or hate them the New England Patriots since 2001 have appeared in eight Super Bowls winning five of them. One of the stalwarts of the team during this era of domination is quarterback (QB) Tom Brady. While the Patriots have been extraordinarily successful over these years, their winning ways are not without controversy.

Before a playoff game against the Colts in 2015, Brady was suspected of instructing ball handlers to underinflate game balls below legal limits set by the NFL. After finding that some of the footballs used in the 2015 playoff game were underinflated by 2–3 psig, NFL officials launched an investigation. Brady ultimately served a four game suspension, following an initial ruling and lengthy appeals process. For their role in the scandal, the Patriots were fined 1 million dollars and lost two draft picks.

Due to the protracted legal battle and public dispute stemming from the so-called Deflategate controversy, the NFL changed its rules concerning inspection, handling, and preparation of game balls. Now before each game two Game Officials, in the presence of a League Security Representative, obtain 12 footballs from each team, measure their air pressures, and, if needed, adjust pressures to allowable values between 12.5 and 13.5 psig. Once this process is complete, game-ready balls are numbered 1–12 for each team, and no further alterations are permitted.

Given the serious consequences to Brady and the Patriots and, at least, circumstantial evidence of cheating, does underinflation of a football provide substantial advantages? Laboratory measurements of mass loss due to underinflation by 2–3 psig indicate reductions in mass of about 0.8 g. Changes of this magnitude are less than the mass of a paper clip, and, in fact, may be smaller than inherent manufacturing variations for NFL footballs. Players would not notice these slight mass changes, and from physical analyses, a ball underinflated by 2–3 psig would travel through the air in essentially the same fashion as a fully inflated ball.

Underinflation, however, does allow for better grip so that a QB is able to perform throwing actions more seamlessly and is less likely to fumble the ball when under duress. Simple models predict that increases of at least 15% in grip forces are produced when a ball is underinflated by 2–3 psig. Better grip also helps receivers and running backs by reducing their chances of fumbling and aiding in catching the ball. While Tom Brady and his teammates, most likely, benefitted from use of underinflated footballs, the Patriots thoroughly defeated the Colts in the 2015 playoff game in question, dominating them in every aspect of the game. Several Colts' players later acknowledged that their loss had nothing to do with possible cheating by the Patriots.

In another twist, Brady led his team to a Super Bowl victory and was voted Super Bowl Most Valuable Player MVP during a season (2016–17) in which stricter rules for game ball preparations were in place. Brady served a four game suspension during the first four games of that season but performed brilliantly once he returned. Many have questioned why a team would risk sanctions and penalties for advantages that are seemingly unnecessary. By all accounts, Brady is a superior QB and performed just as well, or even better, following implementation of stricter rules for ball handling. Moreover, stricter rules did not lead to dramatically more fumbles or dropped balls by Patriots' running backs and receivers. The motivation behind the cheating scandal remains a mystery, but may lie in Coach Bill Belichick's obsession with gaining every possible advantage—even if that means risking getting caught and suffering significant penalties. You be the judge.

Chapter 7

Wave action

Disturbances in nature—when produced at regular intervals of time—often generate periodic oscillations that move outward from sources in the form of traveling waves. Waves are the primary mechanism for transmitting energy across vast expanses of our galaxy. Moreover, they are responsible for communication between players shouting instructions on a field of play. When wave energy is delivered at sufficiently high levels over space and time, high intensities result. Extreme levels of sound intensity in raucous stadiums can alter game play and ultimately lead to hearing loss. Within the electromagnetic spectrum of waves, certain properties of light also affect the ability of athletes to see and react to objects during competition.

Wave action

Swaying of branches in the wind, vibrations of stringed instruments, and sunlight felt on your face, all depend upon generation and propagation of waves. Prevalence of waves in everyday life have motivated scientists such as Galileo, Newton, and Einstein to study their origins, properties, and interactions with matter. In the arena of sport, actions of waves produce the deafening roar within stadiums, oscillations felt after a bat is struck by a baseball, and images formed by the eye as competitors scan a playing field. Generally speaking, waves can be divided into two major classifications: transverse and longitudinal. A transverse wave is generated by particles (or fields in some cases) oscillating along directions perpendicular to the direction in which the wave is traveling. These kinds of waves can be observed by securing one end of a rope and shaking the other end in an up-and-down fashion. Sections of the rope move up and down but the wave (disturbance) moves along the length of the rope itself.

In contrast with a transverse wave, a longitudinal wave is generated by particles oscillating parallel to the direction of travel. These waves can be demonstrated with a light spring (Slinky): first hold the ends of the spring, compress a section of the spring at one end, and then release that section. Particles within this section will

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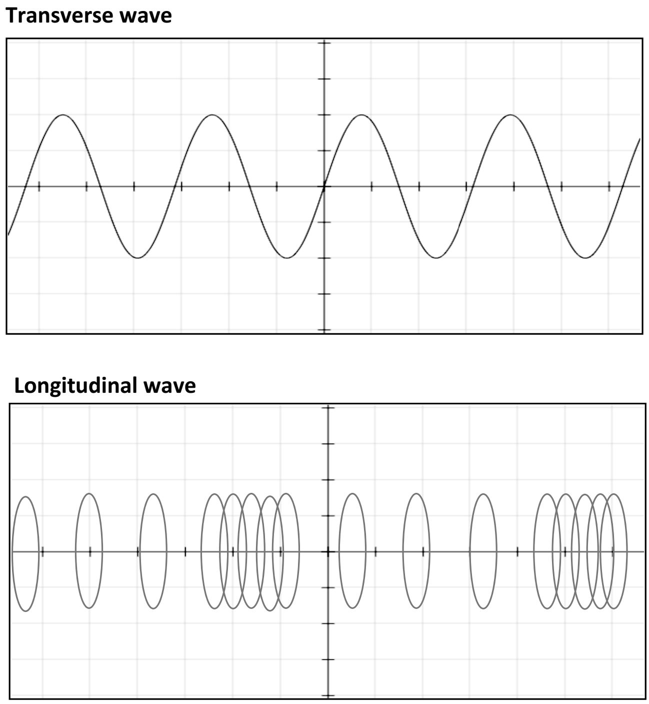

Figure 7.1. Transverse and longitudinal waves indicating oscillations perpendicular and parallel, respectively, to the direction of travel.

begin to oscillate about their original positions before the spring was compressed. Because sections of the spring are connected to each other, particles within nearby sections subsequently move back and forth (oscillate) and the disturbance moves along the length of the spring. (See figure 7.1 for schematics of transverse and longitudinal waves.)

Sound is one of the most ubiquitous examples of a longitudinal wave and is produced by air molecules oscillating back and forth along the direction of travel. Regions where the average separation of molecules is less than usual exhibit compressions, or regions of higher pressure. Regions where the average separation of molecules is greater than usual exhibit rarefactions, or regions of lower pressure.

Hear the stadium roar

The cheers of roaring crowds motivate players to perform at their highest levels; they also provide thrilling environments for spectators. For opposing players, however, crowd noise often hampers performance, especially in sports such as American football in which players often rely on voice signals for communication. In recent years several football stadiums have registered sound intensity levels exceeding 130 dB. The current record of 142.2 dB was measured in Arrowhead Stadium (Kansas City) on September 29, 2014. On this particular evening, Kansas City fans were especially boisterous during the Chiefs' resounding victory over the Patriots by a score of 41–14. In the Patriots' loss, quarterback Tom Brady threw two interceptions, one of which was returned for a touchdown.

Other teams also have endured poor performances in Arrowhead, partly due to overwhelming crowd noise. On a previous record-setting day during which intensity levels reached 137.6 dB, the visiting Oakland Raiders were penalized 11 times. Several of those penalties were due to the visiting players' inability to communicate. Even Kansas City Chiefs' safety, Eric Berry, resorted to yelling in teammates' ears to relay defensive play calls. With all the fuss about the loudest sports venues and various claims to records, what exactly is the dB scale and how loud is 142.2 dB?

The dB scale is based on the principle that sound waves deliver energy as a result of particles within the medium (air molecules) moving back and forth. Oscillating particles possess kinetic energy and thus produce a certain amount of power. (You may recall that power in physics is work done or energy delivered over a unit of time, generally one second.) Because this energy per time is incident on a specified region of space, sound has an intensity associated with it. Intensity is defined as the power delivered divided by the area over which it is distributed; intensity is measured in units of Watts per m^2. Transport of energy is common to virtually all waves in nature, including those associated with sound, light, and mechanical oscillations. In fact, exposure to extreme sound intensities is responsible for ringing of ears and other physiological effects experienced by the body.

The dB scale compares measured intensities to standard intensities and is calculated on a logarithmic (base 10) scale. The formal mathematical expression is given by β (dB) = $10\log(I/I_0)$, where β is the intensity level in dB, I is the intensity of the sound source under consideration, and I_0 is the intensity of a reference sound source. Applying this expression simply requires inserting known values for the intensities and performing the computations. While this work is straightforward, knowing how dB levels relate to familiar sounds provides a sense of the range of human hearing.

On the standard dB scale, all sound levels are related to what is known as the threshold of hearing, which corresponds to an intensity of 10^{-12} W m^{-2}. A sound level exactly equal to the threshold produces an intensity level of 0 dB. For each factor-of-10 increase in intensity, the dB level increases by +10 dB. Thus, an intensity of 20 dB is 10 times more intense than an intensity of 10 dB, and an intensity of 10 dB is 10 times more intense than one of 0 dB. For perspective, table 7.1 shows various sound sources and their respective intensity levels in dB. Sound levels produced in Arrowhead Stadium are comparable to those of jet airplanes about 100 feet (30 m) away. Quantitatively, crowd noise there is 1.66×10^{14} (approximately 100 000 billion) times greater than the threshold of hearing. To avoid hearing loss, the Environmental Protection Agency EPA recommends that humans should limit sustained exposure to <70 dB.

Red, green, yellow, or blue?

Energy in our cosmos is transported by a variety of waves including ones falling within the electromagnetic spectrum. Electromagnetic waves, composed of oscillating

Table 7.1. Sound sources and their intensity levels in dB.

Source	dB
Jet airplane (nearby)	140
Jackhammer	130
Rock concert	120
Power mower	100
Busy traffic	80
Normal conversation	50
Mosquito buzzing	40
Whisper	30
Rustling leaves	10
Threshold of hearing	0

electric and magnetic fields, travel at the speed of light—the Universe's ultimate speed limit. EM waves range from very short wavelength (10^{-10} –10^{-14} m) gamma rays to very long wavelength (1 m or greater) radio waves. Within this broad spectrum, lies a narrow region of waves corresponding to what the human eye can detect. Known as the visible light spectrum, wavelengths range from 400 nm, corresponding to violet-colored light, to 700 nm, corresponding to red-colored light. (One nanometer, 1 nm = 10^{-9} m.)

A normal human eye can detect all wavelengths within the range 400–700 nm but is most sensitive to wavelengths corresponding to the green–yellow part of the spectrum. Our enhanced sensitivity in this region of the visible spectrum is at least partially due to evolution of the eye to match the maximum output of the Sun. The Sun—a G-2 star with surface temperatures of approximately 5800 K—produces maximum blackbody intensities at wavelengths in the yellow–green part of the spectrum.

Despite our innate ability to detect certain wavelengths of light with greater sensitivity, color specifications in sport are based more on tradition than scientific results. In American football, for example, leather panels used in ball construction are tanned to a natural brown. Other sports also specify construction materials so that by tradition baseballs are white, American footballs are brown, and hockey pucks are black. In a few sports such as tennis and softball, officially sanctioned balls are yellow in color, which allow athletes to detect and track them more easily. Some officials have proposed to change the color of implements to match the maximum sensitivity of the eye, but, so far, few leagues have considered such ideas. In many towns and cities today, however, fire trucks are now yellow instead of red, presumably to help motorists detect them more readily.

Chapter 8

Doping in sport

Doping in sport refers to the use of drugs or other foreign substances in order to enhance athletic performance. Throughout history athletes have sought to boost their performances with substances ranging from dried figs in the ancient Olympics to performance enhancing drugs PEDs in modern times. In recent days, some athletes have resorted to using muscle-building agents in an effort to increase their competitiveness.

A number of compounds are known to enhance muscle mass within the human body and, as a result, increase forces generated by muscular contractions. One class of substances that produces increased lean muscle mass is testosterone and its derivatives. These so-called anabolic substances promote the synthesis of proteins which, in turn, aid in production of muscle mass. Increases in muscle mass lead to greater applied forces, and, ultimately, more outstanding performances due to enhanced strength and speed.

Performance enhancement in baseball

Use of performance enhancers in sports such as baseball benefits athletes by increasing lean muscle mass and thereby increasing strength. One of the most visible aspects of baseball, requiring substantial strength, is homerun hitting. The arguments below will assume that a capable MLB hitter is able to increase strength due to the aid of performance enhancers. For an estimated or known increase in muscle mass, the amount by which the range of a batted ball is expected to increase can be determined from physical arguments.

As body mass is enhanced due to use of PEDs, cross-sectional areas of major muscles within the body also increase. When this occurs, muscles are able to produce increased force in proportion to their cross sectional areas. Greater generation of forces applied by muscle groups leads to increased accelerations and ultimately greater speeds. For batters in baseball, effects due to muscle enhancement typically result in greater bat speeds. If other conditions remain constant, increased bat speeds

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generate greater launch speeds for baseballs colliding with those bats, and, ultimately, greater range of batted balls. An obvious consequence of increased range is increased homerun production.

From previous discussions of how far a baseball can be hit, the range of a baseball is known to depend upon the square of its launch speed. To see how much farther a ball is expected to travel with use of PEDs, an estimated increase in muscle mass is needed. Without divulging names, several players are known to have increased their body weights from around 180 pounds to well over 200 pounds during the 'steroid era' in baseball. (Here, we will assume that this increase in weight is due to an increase in muscle mass only.) For a starting weight of 180 pounds, a 20 pound weight gain amounts to an 11% increase. Thus, increases in muscle mass of at least 10% due to PED use are quite plausible.

From this estimate of mass gain, the following physical arguments follow. Increases of 10% in muscle mass give rise to 10% increases in applied force and work done by such a force. As work done on a system increases, the kinetic energy (KE) of that system also increases. (For a batter, these changes result in increases in KE and speed of the bat.) Kinetic energy depends on the square of the speed so that a 10% increase in KE corresponds to a 5% increase in speed. From extended collision analyses, a 5% increase in bat speed produces a 4% increase in launch speed of the ball off the bat. As observed earlier, the range of a projectile depends on the square of the launch speed, so here the range is expected to increase by 8%.

Suppose that a batted ball originally travels 350 feet (110 m) when hit from the bat of a player who is not using PEDs. If that same player, now with increased muscle mass of 10%, hits a ball under otherwise the same conditions it is expected to travel (350 + 0.08(350)) or 378 feet. Such an increase of 20–30 feet in the range of a batted ball in many ballparks is the difference between a 'warning-track out' and a homerun.

From casual observations, homerun hitters in baseball often hit one 'warning-track flyball' for every one or two homeruns produced. If each 'warning-track flyball' now becomes a homerun due to use of PEDs, homerun production would increase by 50–100%. Thus, a hitter who previously clobbered 40 homeruns during a season would increase that production to 60–80 homeruns. These estimates are certainly within the realm of possibility given that two players hit 70 or more homeruns in a single season during the 'steroid era' in baseball.

Not your grandparents' football

In sports such as American football in which both size and speed dramatically affect players' abilities, performance enhancement due to use of PEDs has the potential to lead to dangerous playing conditions. As discussed previously, the main outcome of PED use in conjunction with vigorous workouts is to increase lean muscle mass. Such increases in muscle mass lead to generation of increased forces and accelerations. In sports like football, increased accelerations often contribute to increases in running speeds. When players possessing greater running speeds undergo collisions, larger impact forces are delivered. To evaluate more quantitatively the effects of PED use in contact sports, two scenarios are considered.

Suppose a player, who is using PEDs and working out, experiences a 10% increase in lean muscle mass without a change in overall body mass. (This could occur if an increase in muscle mass is compensated by a decrease in body fat.) From arguments above, a 10% increase in lean muscle mass generates enhancements of 10% in applied force, acceleration, and, ultimately, maximum running velocity. As a result, 10% more linear momentum (mass times velocity) is present as this player collides with another player on a field of play. Assuming that the time interval for collision is comparable to ones before muscle enhancement, the impact force during collision will increase by 10%. If both players undergoing collision have enhanced muscle mass due to doping, forces increase even more.

In a more practical scenario, assume that lean muscle mass increases by 10%, whereas the player's total mass increases by 5%. Overall, the physical arguments produce the same result as above. The speed will increase by 5% and with the stated mass increase of 5%, the linear momentum (the product of the two) and force increase by 10%. Increased muscle mass leads to increased forces, particularly during player-on-player collisions. Enhanced forces often exceed limits of what athletes can tolerate without injury. In response, many leagues have strictly banned the use of PEDs and have begun making rule changes to improve player safety.

Chapter 9

Chronic traumatic encephalopathy, concussions, and knee injuries

Injuries in sport generally occur due to parts of the body experiencing forces beyond what they can withstand. Severe blows to the head, for example, initiate chemical and ion imbalances, leading to concussion and accompanying symptoms such as nausea, dizziness, confusion, and headache. Repeated injuries to the head now are linked to the condition known as chronic traumatic encephalopathy (CTE), which is characterized by accumulation of tau protein in various parts of the brain. Other injuries in sport, particularly ones to the joints, usually occur due to failure of ligaments, tendons, or other soft tissue. Fortunately, through modern surgery and extensive rehabilitation, athletes suffering these kinds of injuries often experience full recovery.

CTE

Many sports injuries such as broken bones are evident almost immediately; however, others such as CTE may take years to manifest themselves. While CTE is now a major health concern, even as recently as a decade ago, many experts did not believe that any long-term brain injuries such as CTE existed. Following extensive research, however, CTE now is recognized as a neurodegenerative disease, associated with repeated blows to the head and characterized by aggregation of tau proteins in various parts of the human brain. Aggregates form when hyperphosphorylation of the tau protein occurs, causing the protein to become insoluble. Once this happens the insoluble tau forms what are known as tangles or paired helical filaments. To date, not much is known about the role of tangles in manifestations of CTE.

As CTE advances, the brain is reduced in weight due to atrophy of several important brain centers including: the frontal cortex, temporal cortex, medial temporal lobe, and even brainstem. In addition, neuronal loss, TAR DNA-binding Protein 43 deposition, and white matter changes occur. Symptoms of CTE begin with confusion and disorientation and may lead ultimately to explosive behavior and dementia. Scientists

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originally believed that CTE occurred in athletes who were traumatized by repeated head injuries, usually over the course of several years. More recent evidence suggests that even moderate but repetitive impacts, experienced over only a few seasons, can produce tau deposition within the brain. Such evidence comes from limited studies of deceased teenagers, who had played football and other contact sports. While correlations between head injuries in sport and CTE have been established, more extensive research is needed to determine precisely what conditions lead to CTE.

Iron Mike

Known as Iron Mike, Mike Webster was the epitome of the Pittsburgh Steelers of the 1970's—a hard-nosed NFL football player who loved battling defensive lineman in 'the trenches.' Webster especially enjoyed playing on bitter cold days in Three Rivers Stadium in Pittsburgh where the Steelers were nearly unstoppable during their Super Bowl winning years of 1974, 1975, 1978, and 1979. Beyond contributing to team success, Webster was chosen as first team All Pro seven times during his playing days and was voted to the NFL 75th Anniversary All-Time Team to honor the greatest players of the first 75 years of the League. Many experts consider Mike Webster to be the best offensive center who has ever played the game. Following his playing career, Webster was elected to the Pro Football Hall of Fame and enshrined in 1997.

As Webster's career came to an end, he appeared to have everything he needed for a successful retirement—a supportive family, the adulation of a multitude of fans across Steeler Nation, and many contacts developed through years of playing in the NFL. In retirement, however, Iron Mike became increasingly confused and sometimes even violent. His family and others tried repeatedly to help him, but Webster grew even more disoriented and despondent. Eventually, he resorted to living in his truck where he was found dead from a heart attack at the age of 50.

Following Webster's death Pittsburgh medical examiner, Bennet Omalu, ordered a full autopsy of the body, including examination of dissections of the brain. On a global scale, the brain appeared normal, but, upon closer examination, dissections revealed substantial tau deposits—classic signs of CTE. Webster also suffered from multiple herniated discs, varicose veins, and a torn rotator cuff.

Omalu's findings and his conclusions that head injuries, suffered from playing professional football, contributed to development of CTE caused a major stir in the football community. Omalu endured retaliation for his bold claims, but later was vindicated through overwhelming scientific evidence. Many subsequent studies of deceased players' brains have confirmed that CTE is prevalent among former professional football players.

Torn ligaments

Human motions rely on the ability of the body to undergo bending at certain joints in order to generate forces along particular directions and to produce leverage. Leg and arm joints in the body are held together by one or more fibrous structures, known as ligaments. Ligaments not only hold bones together across the joint but also allow motions in particular directions. The human knee is a classic example of a hinged

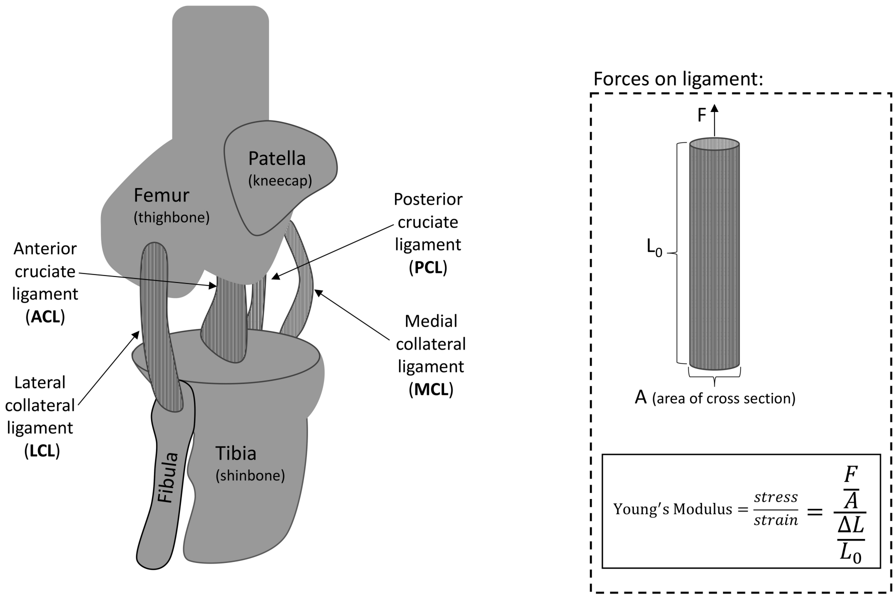

Figure 9.1. Human knee with the four main ligaments shown. The inset shows a section of a fiber in which a force is applied to a ligament of length L_0 and cross-sectional area A.

joint held together by four main ligaments—one on each side of the knee joint and two others in the back of the joint as shown in figure 9.1. Ligaments on the sides of the knee are known as the lateral collateral and medial collateral ligaments; they provide side-to-side stability of the joint. The other ligaments connecting the femur and the tibia are known as the anterior and posterior cruciate ligaments.

Torn ligaments often occur when an athlete makes a dramatic cut on a field of play or when the knee joint is struck during collision. In either case, the applied forces exceed what the ligaments can withstand without tearing. Ligaments tear due to forces tending to stretch them along their lengths. Such applied forces produce tensile stress and the resulting displacements produce tensile strain. To understand tensile stress and strain, consider a long bar with one end clamped in place while the other end is displaced by an amount ΔL due to an applied force F exerted on it. The tensile stress on this system is the ratio of the force F to the cross-sectional area A of the bar: F/A; the tensile strain is the ratio of the displacement (deformation) ΔL of the bar to its original length L_0:$\Delta L/L_0$.

When analyzing systems, scientists often examine the ratio of the tensile stress to tensile strain as a way to determine relative deformation, occurring for a given force per unit cross-sectional area. The ratio of tensile stress to tensile strain is known as Young's modulus: the greater the modulus the less the material deforms as a result of an applied tensile force. Liquids, such as water and alcohol, do not support tensile forces, thus their moduli are zero. Most solid materials have moduli in the range of 5×10^{10} to 35×10^{10} Pa. By contrast, ligaments have moduli about 20 times less than materials such as aluminum. As a result, ligaments are somewhat less resistant to tensile stress than solid materials but allow substantial range of motions so as to keep us mobile.

Chapter 10

Special topics

Novel questions arise every day in sport, often as a result of technological advances and emergence of new generations of extraordinary athletes. Many of the questions that stimulate our curiosity require scientific approaches to find suitable answers. Using the principles and habits of mind developed thus far give us the framework for answering contemporary scientific questions in the wide world of sport.

Need for speed

Our fascination with fast motions probably dates to prehistoric eras when sprinting and launching various weapons with great speed and accuracy were necessary for survival. Moreover, since ancient times, we have celebrated the ability of athletes to run quickly by declaring winners of particular races as 'the fastest runners in the world.'

Given our natural curiosity and awe of great sprinters, we, as observers, might ask: what makes them unique? In order to pursue this question, a quick glance back at the concept of speed is useful. Average speed is defined as the ratio of the distance covered to the time interval, required to travel that distance. In a particular competition, a sprinter who runs a given distance in the least amount of time wins the race—and generates the greatest average speed. With a view toward generating maximum speed, we will address what physical attributes make certain athletes extraordinarily fast.

One of the first studies to examine how human speed depends on the anatomy of an athlete was conducted in the 1970s by Hoffmann and co-workers [1]. Their work examined the stride lengths of 56 male athletes and 23 female athletes and revealed a linear correlation between average stride length L and a sprinter's height H. Linear relations take the form $y = mx$, so that $L = cH$, where c represents a constant of proportionality. In addition to showing this linear correlation, Hoffmann's studies found constants of proportionality of 1.14 for female sprinters and 1.13 for male sprinters. Recent analyses of modern, elite sprinters by the present author also have

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found linear correlations between L and H—but with slightly higher proportionality constants [2].

To extend the results of Hoffmann and to show the unique abilities of elite sprinters, two basic quantities are required—average stride length and average stride frequency. Average stride length refers to the average length of a stride during a race and is found by dividing the race distance by the number of strides taken during the race. Average stride frequency refers to the average number of strides taken per time interval and is found by dividing the number of strides taken during a race by the race time. Clearly, both quantities depend upon the number of strides taken, so the two are not independent of one another; nevertheless, their product is equivalent to the average speed. In order to develop significant speed, an elite sprinter must have both a sufficiently long stride, together with sufficiently rapid 'turnover' of the legs.

To examine numerical values of these quantities, a complete analysis of Usain Bolt's stride characteristics is undertaken, using data from his world record performance during the 2008 Olympics in Beijing. In these games, Bolt, whose standing height is 1.96 m, sprinted to victory in the 100 m dash in a time of 9.69 s while taking 41 strides to complete the race. With these numbers in hand, average stride length, average stride frequency, and the proportionality constant relating average stride length and standing height can be calculated quite readily.

Average stride length L is determined by dividing distance covered by the total number of strides, so in Bolt's case average stride length is 2.44 m (100 m/41 strides). Average stride frequency is found by dividing the number of strides by the race time; average stride frequency for Bolt is 4.23 strides per second (41 strides/9.69 s). Amazingly, Bolt's strides are slightly greater than 2.4 m (7.9 feet) each and occur at rates over 4 (strides) per second.

For completeness, the constant of proportionality relating average stride length and standing height H is found using the relation $L = cH$; c for Bolt is $L/H = 1.24$. For comparison, constants for other elite, modern-day sprinters have been determined to be in the range of 1.24–1.27. Knowing these constants and how they vary over time and from sprinter to sprinter are important for developing training regimens and modeling sprinters' improvement. The relation between L and H, determined for Bolt and other modern-day sprinters, agrees with previous work and confirms what might be expected: a taller sprinter takes longer strides when sprinting along a track.

So what makes an elite sprinter unique? The answer depends on the individual sprinter's physical characteristics and abilities. In Bolt's case, his stride length surpasses those of other elite sprinters by about 10% due to his tall stature (1.96 m or 6 feet, 5 inches). His average stride frequency, however, is somewhat less than other outstanding sprinters but still in the range of elite sprinters. Other sprinters like Maurice Greene who are of shorter stature rely more on stride frequency to generate substantial speeds. Extraordinary sprinters need both sufficiently long stride lengths and sufficiently rapid stride frequencies in order to compete on the world stage—yet no two sprinters are exactly alike.

The irony of Bolt's extraordinary sprinting performances is that his sprinting times could have been reduced even further—not by running any faster but by coming out of the blocks more quickly. In his 2008 Olympic race, for example, his reaction time was 0.165 s, as compared to 0.13 s for the next-worst sprinter. (Reaction time refers to the delay between the sound of the gun and the first motion of the sprinter.) By reducing his reaction time to 0.13 s, he could have decreased his 100 m race time to 9.655 s.

Beyond starting more quickly, Bolt could have reduced his race time by an additional 0.1 s in the 2008 Olympics by continuing to sprint through the finish line rather than reducing his speed while showboating. Finally, in a scenario in which he could take full advantage of maximum tail winds of 2.0 m s^{-1} in a particular race, he would reduce his time by an additional 0.1 s. Under such ideal conditions, his ultimate 100 m time would be lowered to 9.455 s—an achievement thought impossible only 20 years ago. While fascinating to consider, our speculation here is now hindsight in light of Bolt's retirement after the 2016 Olympics in Rio de Janeiro.

Extreme, extreme sports

On June 3, 2017, Alex Honnold reached the apex of pure rock climbing by scaling El Capitan, a nearly 3000 foot granite wall in Yosemite National Park, without the aid of ropes or other safety gear. He completed this historic free solo climb in less than four hours with no spectators present, except for a small team of filmmakers who documented his feat for National Geographic. Honnold had trained for this breathtaking climb for more than a year in venues across the United States, China, Europe, and Morocco. He had attempted the free solo climb the previous November but stopped after less than an hour when conditions were deemed unfavorable. The climbing world responded to Honnold's extraordinary achievement by comparing the free soloing of El Capitan to landing on the Moon. To appreciate his feat, it is worth noting that other climbers who have ascended El Capitan along the same Freerider route as Honnold have received significant acclaim and media coverage. The difference of course is that those climbers used ropes for safety and generally climbed with partners.

Free soloing of a rock face is remarkable both for the physical and mental challenges it presents. From a physical perspective, the ascent requires essentially lifting the body from the base of the rock face to the summit in a series of climbing maneuvers. During these maneuvers the climber performs work, leading to an increase in potential energy PE. For Honnold the potential energy *mgh* attained is 6.5×10^5 J, where $m = 73$ kg, $g = 9.8$ m s^{-2}, and $h = 914$ m; this PE change is equivalent to 4300 baseballs traveling at 100 mph (44.7 m s^{-1}). Beyond the large energy demand, the climb also requires some extremely difficult feats including balancing on a matchbox-wide ledge and dangling in the air with only a fingertip hold. In preparation for such extreme climbs, Honnold follows a rigorous training regimen, which includes hanging for an hour each day using only a fingertip hold.

As evidence of Honnold's thirst for new challenges, he and climbing partner, Tommy Caldwell, set a new record for speed climbing El Capitan on June 7, 2018. Using ropes the pair scaled the rock face along the Nose in 1 h, 58 min, and 7 s. Even before their latest record-setting climb, the pair had broken the previous record of 2 h and 19 min twice in the preceding two weeks. One of the former record-holders, Brad Gobright, was quoted in Outside Magazine, 'It's the proudest speed climbing ascent to have happened in the history of U.S. rock climbing.' The pair has not said whether or not they will attempt to break their own record, but Honnold has indicated that he thinks the limit of human potential for this climb is in the range of an hour and a half.

References

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