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

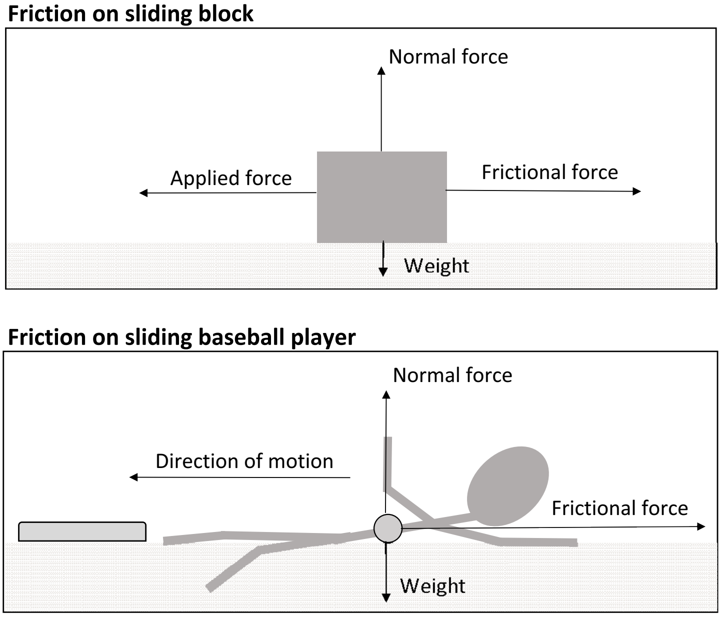

Figure 3.1. Forces acting on a block sliding along a surface and a baserunner sliding along the ground into a base.

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,

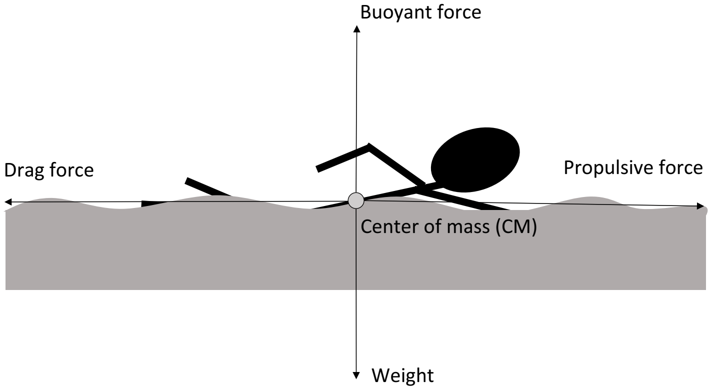

Figure 3.2. Force diagram for a swimmer, indicating propulsive, drag, gravitational, and buoyant forces.

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 $\mathrm{m\ s^{-1}}$, as compared with Olympic sprinters in track and field who attain top speeds in excess of $11\ \mathrm{m\ s^{-1}}$. 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:

$F_D = 0.5C_D\rho Av^2$. 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.