PART I

The Whole Body Level

Lesson 2  Describing Motion: Linear Kinematics in One Dimension
Lesson 3  Describing Motion: Linear Kinematics in Two Dimensions
Lesson 4  Describing Motion: Angular Kinematics
Lesson 5  Describing Motion: Inertia and Momentum
Lesson 6  Explaining Motion I: Linear Kinetics
Lesson 7  Explaining Motion II: Angular Kinetics
Lesson 8  Work–Energy
Lesson 9  Collisions, Impacts, and the Conservation Laws
Describing Motion: Linear Kinematics in One Dimension

LEARNING OBJECTIVES

After finishing this lesson, you should be able to:

- Define the following terms: abscissa, absolute value, acceleration, average value, axis, body, cadence, direction, displacement, distance, frame of reference, gait, instantaneous value, kinematics, net value, ordinate, orientation, origin, point, position, relative speed, sense, scalar, slope, speed, step, stride, system, vector, and velocity.
- Explain the difference between speed and velocity.
- Write equations for the following concepts: distance, displacement, speed, velocity, and acceleration.
- Identify speed on a position–time curve.
- Identify velocity on a position–time curve.
- Identify acceleration on a velocity–time curve.
- Explain the difference between instantaneous and average kinematic measures.
- Describe situations in which velocity is more important than acceleration.
- Describe situations in which acceleration is more important than velocity.
- List the determinants of gait velocity.

The first key in unlocking the code to how we move in the world is to be able to describe the motion itself. This is the branch of mechanics called **kinematics**, which is the study of motion without consideration of the causes of that motion. It involves both spatial and temporal characteristics of motion. In this lesson, we will begin by discussing the simplest case of motion: motion in a straight line going in one direction. The next section will examine motion in a more complex scenario—motion in two directions (but the same dimension). Throughout this lesson, examples from walking and running will be used to highlight these concepts, beginning with a familiar example from sport, then a test often used in physical education, and ending with issues involving gait and the elderly. You cannot adequately explain motion without first being able to describe it in detail, so it is very important that you master these fundamental ideas.

### 2.1 LINEAR KINEMATICS IN ONE DIRECTION

#### Section Question

Three men race the 100-meter sprint (Figure 2.1). Runner A finishes first with a time of 9.83 seconds, followed by Runner B with a time of 9.93 seconds. It took Runner C 11.12 seconds to complete the race. Why did Runner A win the race? What would Runners B and C have to do to beat Runner A?

The logical answers are, “Runner A ran faster than Runners B and C” and “Runners B and C need to run faster.” But what exactly does that mean? And is it very useful?

#### 2.1.1 Preliminary Considerations: Representing Bodies of Interest and Establishing Reference Frames

Before you can analyze any movement, you must first ask two basic questions:

1. What is moving?
2. What is it moving in relation to?
You first need a way to represent the thing you are interested in analyzing. In the case of the runners, you are currently interested in the whole persons. Later, you may also want to analyze just the hand or foot, or even an inanimate object like a ball or racquet. In these cases, you are interested in a single entity, which is a **body**, even if it is not a person’s entire body. (Conversely, a **system** is more than one body.) How should you represent the thing of interest? To paraphrase Albert Einstein, “Keep things as simple as possible, but not simpler.” Use the simplest representation that will answer your question adequately; more complex questions may require more complex representations. In the simplest case, you would represent the body as a **point** (a way to represent something without dimensions). More complicated representations of a body will be presented throughout the course of this book. But for now, representing the runners as points will suffice.

Second, movement must always be described in relation to something. That something is called a **frame of reference**. For example, it does not make any sense to say that your school is located 5 miles away, unless you also state that it is 5 miles away from a particular place (such as your current location or your house). The finish line of the 100 m sprint is 100 m away from the starting line. You would not tell somebody to go 5 blocks east, unless you had a mutually agreed-upon direction of east. So to set up your frame of reference you need to establish a location (called the **origin**) and directions from that origin.

The origin is where your frame of reference begins. The origin can be anywhere, but if the laws described in this book are going to “work” without some complicated mathematics, the origin has to be fixed (that is, not moving). Usually, the origin is placed someplace physically meaningful, although sometimes it is placed where it will make the calculations easier. For example, when analyzing the 100-meter sprint, you would probably fix your frame of reference to Earth and put the origin at the starting line, although you could just as easily put the origin at the finish line. Technically, you could place it anywhere along the race course. It just would not be very meaningful.

After defining an origin, it is necessary to determine directions so that the frame of reference is complete. Directions are specified by **axes**, which pass through the origin and extend indefinitely on both sides of it. Directions have both an **orientation** and a **sense**. The orientation is specified in terms of particular reference lines (such as horizontal, vertical, north, south, east, or west), and the sense is specified by two points on that reference line. The concept of sense is best illustrated by an example. In Figure 2.2, a horizontal axis has two points, A and B. Going from point A to point B is one sense, and from B to A is the opposite sense. Because the sense
To establish a frame of reference:
1. Locate an origin that is fixed and meaningful.
2. Define an axis, usually the horizontal and/or vertical along the lines of travel.
3. Specify a positive and a negative direction. The initial direction of travel and "up" is usually designated as positive.

**2.1 Linear Kinematics in One Direction**

Once you have a reference frame and a way to represent what it is that you wish to examine, you can begin your analysis.

**COMPETENCY CHECK**

Remember:
1. Define the following terms: body, direction, frame of reference, kinematics, orientation, origin, point, sense, and system.
2. What two things make up a frame of reference?
3. What does the positive or negative sign of an axis tell you?

Understand:
1. Why is it important to have a frame of reference?

Apply:
1. Pick an activity that only requires movement in one direction. Choose a reference frame. Why did you choose the reference frame you did?

**2.1.2 Position**

The next step is to determine a body’s position \( (p) \) that is, its location in the frame of reference. Position is the body’s physical location in space. Because your current frame of reference consists of a single axis, mathematically the position is the location of that body on the axis. When describing a body’s position, you have to state how far away it is located along the axis (magnitude) and on which side of the origin (direction). If body A is located 10 m to the right of the origin on the x-axis, it is \(+10\) in the x direction. (Note that usually the “+” sign is omitted, and it is understood that if there is no “−” sign, it is a positive number.) If body B is located 10 m to the left of the origin on the x-axis, \( p = -10 \) m. Note that both are equidistant from the axis: 10 m. So unlike algebra, \(-10\) is not less than \(+10\), it just happens to be in the opposite direction.

**Important Point!**

1. A positive or negative sign establishes direction. Unlike algebra, a negative number is not less than a positive number.
2. If the sign is not specified, assume it is positive.

Oftentimes, you would like to look at a "picture" of a body's location, so you would construct a graph. You can
2.1.2.1 Changing Position: Displacement and Distance

In biomechanics, you are usually interested in how things are changing. Kinesiology is the study of human movement, and movement implies change. Physically, change means that something is somehow different than how it was previously. Quantities that only have a magnitude are known as **scalars**; quantities that have both a magnitude and a direction are known as **vectors**. Do not confuse a change in magnitude of a scalar with a spatial direction. For example, temperature is a scalar quantity. You can talk about the temperature going up (increasing) or down (decreasing); temperature can even be a negative number. But temperature does not have a spatial direction.

As mentioned in the preceding section, position is denoted by the symbol \( p \). A prime (') after the \( p \) denotes the position of the body at some other point in time (denote by a corresponding prime after the “t” symbol for time) because things change over time. A change in position is known as **displacement** (\( \Delta p \)). Mathematically, it is the difference in position (measured as a length) between two instances in time:

\[
\Delta p = p' - p
\]  

(2.1)

where the symbol \( \Delta \), delta, means “change in.” So Equation 2.1 simply states the displacement (or change in position), \( \Delta p \), is equal to the position at data point “1” minus the position at data point “0.” The magnitude is simply how large the change is: A large number means a bigger change. Displacement is a measure of length, and so the units are in meters for the metric system. In the imperial system, the units are typically feet, yards, or miles.

Displacement is a vector quantity. This is not to be confused with **distance** \( (d) \), or the actual length of the route the body took to change its position, which is a scalar quantity. In the simplest case of a body moving in a straight line, the two are the same. From the start to finish of the sprint example, both the distance and displacement are 100 m. But if you ran a circuitous route, the distance could be over three times larger than the displacement (Figure 2.5). So if there is a large time difference between when you examine \( p \) and when you examine \( p' \), you may miss some valuable information.

If you wanted to construct a graph of how something is changing over time, one axis will no longer be adequate because you are now dealing with two dimensions (one being the direction of movement, the other being time). Your graph would have to have two axes to represent both of these dimensions (because you always need one axis per dimension on a graph). A typical 2-D graph will have a horizontal axis...
2.1 Linear Kinematics in One Direction

COMPETENCY CHECK

Remember:
1. Define the following terms: abscissa, distance, displacement, ordinate, position, scalar, and vector.

Understand:
1. Give an example of a movement or activity when distance and displacement would be the same.
2. Give an example of a movement or activity when distance and displacement would be different.
3. Can the final position be negative but the displacement be positive? Why?
4. Calculate the change in position for the following:

<table>
<thead>
<tr>
<th>Start (m)</th>
<th>End (m)</th>
<th>Δp (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>85</td>
</tr>
</tbody>
</table>

Apply:
1. When would you be interested in distance instead of displacement?
2. When would you be interested in displacement instead of distance?

2.1.3 Rates of Change

Simply knowing that something is changing is oftentimes not enough. Intuitively, you probably understand that something is different if two bodies change the same amount, but over a different time period. In the case of the sprinters, you know that each one covered a distance of 100 meters between the start and the end of the race but you are no closer to understanding why Runner A won the race. What is missing is how the change occurred with respect to time. This is called a rate.

Rate How quickly a value is increasing or decreasing with time.

2.1.3.1 Speed and Velocity

Speed and velocity are often used interchangeably in everyday language, and in fact, they can be used interchangeably if you are talking about bodies only moving in one direction. You
Speed is a scalar quantity. Suppose you were to create a reference frame where north on the freeway is positive and south is negative. Regardless if you were going north or south, your car’s speedometer would only give you a magnitude (55 mph), not a direction (positive or negative).

Speed is a scalar quantity that is the time rate of change of the distance, another scalar quantity. In the last section, you learned that displacement was the vector change in position. Velocity is the vector quantity that is the time rate of change in position. If you substitute displacement for distance in Equation 2.3, you get

\[ v(t) = \frac{\Delta p}{\Delta t} = \frac{p' - p}{t' - t} \]  

And if speed is how fast something is moving, velocity (being a vector) is how fast something is moving in a particular direction. The units are m/sec in the metric system and ft/sec in the imperial system.

In this relatively simple example of things moving in only one direction, displacement and distance are always the same, and thus velocity and speed will always have the same value. Biomechanicians are usually more concerned with vector quantities like displacement and velocity, and not distance and speed. As a scalar, speed is the magnitude of the velocity vector. If you are just comparing magnitudes (directions are not changing), it is acceptable to say “speed.” Otherwise, you should get into the habit of using displacement and velocity when appropriate.

Returning to the 100-meter sprint example, you know the (and distance traveled) was 100 meters (the length of the race). The times were recorded: 9.83, 9.93, and 11.12 seconds. Now calculate the velocity of each runner:

- Runner A: \( \frac{100 \text{ meters}}{9.83 \text{ seconds}} = 10.17 \text{ m/sec} \)
- Runner B: \( \frac{100 \text{ meters}}{9.93 \text{ seconds}} = 10.07 \text{ m/sec} \)
- Runner C: \( \frac{100 \text{ meters}}{11.12 \text{ seconds}} = 8.99 \text{ m/sec} \)

It is no surprise that Runner A ran faster than Runner B, who ran faster than Runner C. This was the obvious answer from the beginning of the lesson. It does illustrate an important point about ratios, though: If you want to increase velocity, and the numerator (top number, displacement) is fixed, you have to decrease the denominator (bottom number, time).

<table>
<thead>
<tr>
<th>Box 2.1</th>
<th>Essential Math: Ratios and Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>A <strong>ratio</strong> is simply one number divided by another number:</td>
<td></td>
</tr>
<tr>
<td>[ \text{ratio} = \frac{\text{one quantity}}{\text{another quantity}} ]</td>
<td></td>
</tr>
<tr>
<td>A <strong>rate</strong> is a ratio between the change in one quantity and the change in time:</td>
<td></td>
</tr>
<tr>
<td>[ \text{rate} = \frac{\Delta \text{one quantity}}{\Delta \text{time}} ]</td>
<td></td>
</tr>
<tr>
<td>The delta symbol (( \Delta )) is shorthand for “change in.” Think of the dividing line as “per,” so we can think of a rate as a change in one quantity (position, velocity, force, work) per a change in a unit of time (seconds, minutes, hours). Rates are going to be very important in biomechanics. From algebra, you should be able to recognize that the rate will be larger if the change in the quantity is increased and/or the change in time is decreased.</td>
<td></td>
</tr>
</tbody>
</table>

\[ \frac{\Delta \text{one quantity}}{\Delta \text{time}} = \text{Larger ratio} \]

| Increase this or Decrease this |

Probably already have a notion about speed. So that would be a good place to start, and then you will learn about velocity.

**Speed** is how fast something is going. If you cover a greater distance in the same amount of time, or the same distance in a smaller amount of time, you have a greater speed. You are probably familiar with the concept every time you get into a car: the speedometer, or “speed meter,” measures the speed of the car. What values does the car’s speedometer give you? Miles per hour (or kilometers per hour). That gives you a clue that speed is a rate at which something is changing:

\[ \text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\text{miles (kilometers)}}{\text{hour}} \]  

(2.2)

But that is a very specific case. To make it useful in a greater number of situations, you need a more general form. Miles (kilometers) is a measure of distance covered, how far a thing traveled. Hour is a measure of how much time has elapsed (60 minutes). So, in the general form:

\[ \text{speed} = \frac{\text{distance}}{\text{change in time}} = \frac{d}{\Delta t} \]  

(2.3)

Speed is the rate of change of distance.
Recall that the equations give an output for a series of inputs. If the output was the time to finish the race, Equation 2.4 could be rearranged to put the time on the left-hand side and the other variables on the right:

$$\Delta t = \frac{\Delta p}{v} \tag{2.5}$$

Thus far, the concept of velocity was discussed physically and mathematically. A graph is a picture, and as the old saying goes, a picture is worth a thousand words. Graphically, you would “connect the dots” on Figure 2.6. The results are presented in Figure 2.7.

Notice that the slope of the position–time curve gives you the velocity: The steeper the slope, the greater the velocity (and in this case, speed; see Box 2.2). If you look at the slopes of the three runners’ curves, you will note that Runner A has a steeper slope (and greater velocity) than Runner B, who has a steeper slope (and greater velocity) than Runner C. If a picture is worth a thousand words, then why is that not telling you much (certainly nothing you did not already know at this point)? It is because the resolution of your picture was too low to see all the details. For a higher resolution, you need more pixels. In this case, pixels are data points.

Slope  The incline of a line on a graph from the horizontal axis

If you have ever walked up a hill, then you have an intuitive appreciation for what a slope is. In the case of the hill, the slope is the ratio between the change in vertical distance and the change in horizontal distance. If you plot the horizontal distance along the horizontal axis and the vertical distance along the vertical axis, you get a visual of what the slope looks like. Technically, the horizontal axis is known as the abscissa, and the vertical axes is known as the ordinate. It is helpful to think of them in those terms because you will not always be plotting the horizontal distance on the horizontal axis. Many times, you will want to know how something is changing over time, and by convention you always plot time on the abscissa (horizontal) and the variable of interest on the ordinate (vertical). In the race example, you are interested in how the (horizontal) distance is changing with time. In this case, time will be on the abscissa, and distance is on the ordinate.

Mathematically, the slope is

$$\text{slope} = \frac{\Delta \text{ordinate}}{\Delta \text{abscissa}}$$

Where, once again, the delta symbol ($\Delta$) means “change in.” If the abscissa is kept constant and the ordinate is increased, there will be a larger number for the slope. This equates to a steeper slope. Walking up a hill with a steeper slope means that the change in vertical distance is increasing more than the change in horizontal distance. Walking on flat ground means that the vertical distance is not changing with horizontal distance—the slope is zero. Walking downhill, the vertical distance is decreasing while the horizontal distance is increasing. This is a negative slope. Positive, negative, and zero slopes mean the same things regardless of what you put on the abscissa or ordinate. You will look at slopes a lot in this book, so always keep in mind what they mean by visualizing the hill.

Terrain with positive, negative, and zero slopes.
Average versus Instantaneous Velocity

All three representations (physical, mathematical, graphical) presented thus far tell you the same thing: Runner A covered the same distance (had a larger displacement) in a smaller amount of time (another way of saying had a larger displacement in the same amount of time), his velocity was greater than Runners B and C, and it had the steepest slope on the position–time curve.

But that does not provide very much information, and it certainly does not tell Runner B or C what they would have to do to beat Runner A in the future. Part of the problem may be that the values we calculated were over the duration of the entire race, or the average velocity. Average velocity assumes the velocity did not change throughout the race, but was this the case? If it took you 2 hours to get to grandma’s house 100 miles away, then your average speed was 50 miles per hour. But you were not driving 50 miles per hour the whole time: you sped up, slowed down, stopped at a traffic light or two, and so on. Did the same thing happen to the runners?

To obtain more detailed information, you may wish to chop the race into small bits. If you could examine it so that the time changes were infinitesimally small (that is \( t + \Delta t \) as close to zero as you can get), you could look at the instantaneous velocity—the velocity at a particular moment in time. (Incidentally, your car’s speedometer measures instantaneous speed.) That would give you a clearer picture of not only the outcome of the race, but also what happened during the race—which could explain why the outcome was the way it was.

If timers were placed every 10 meters, then you would know how long it took to run each of the 10 10-meter segments. The data are recorded in Table 2.1. The table contains a lot of numbers, and it might be hard to figure out what is going on. A visual representation of this data might be helpful. Plotting the position of each runner as a function of time would look like Figure 2.8.

Physically, velocity is how fast an object is moving in a particular direction. Mathematically, it is the ratio of displacement (change in position) and change in time. Graphically, the velocity is the slope of position plotted with respect to time: the steeper the slope, the greater the velocity and the faster the speed (see Box 2.3 for more details). From Table 2.1 and Figure 2.9, it appears as though the runners were very similar during the first two seconds (the slopes are practically on top of one another), but then they start to diverge after that. Calculating the velocity at every interval and plotting it as a function of time may give a better picture, as was done in Figure 2.9.
2.1 Linear Kinematics in One Direction

Box 2.3 Essential Math: Tangents and Chords

The slope of a curve compares the rates of change of two variables. In biomechanics, we are often interested in comparing the rate of change of one variable to the rate of change of time. This is often shortened to “the time rate of change of [insert whatever variable here], or even shorter to “the rate of change of [whatever variable].” For example, velocity, which is the time rate of change of position, is the slope of the position–time curve. If you are interested in the average velocity, you would examine the slope from the position at the first time period of interest to the position at the last time period of interest. If the velocity is constant, the position–time curve would actually be a straight line, and the slope would be identical everywhere, at every instant, on the “curve” (because it is constant). That rarely happens in human movement; usually the velocity is changing throughout the period of interest. In that case, the position–time curve truly is a curve. The average is still computed the same way: the ratio of the change in position to the change in time. Graphically, its slope is the chord, or straight line drawn from the start to the finish of the period of interest. If we want to know the instantaneous velocity, we would need to look at the slope of the tangent to the curve at that instant. A tangent is a straight line just touching the curve at a single point—the point being the instant you are interested in. If the velocity is constant, the tangent and chord will have identical slopes. If the velocity is changing, at some points, the slope of the tangent will be larger than the slope of the chord (the instantaneous velocity is higher than average), and at other times the slope of the tangent will be smaller than the tangent of the chord (the instantaneous velocity is smaller than average). But at least at one point, the slopes of the tangent and chord will be the same (you cannot jump from 4 m/sec to 6 m/sec without going 5 m/sec for at least a brief instant).

Figure 2.9

Figure 2.9 Runners’ velocity versus time. Note the Runner B actually had a slightly higher peak velocity than did Runner A, even though he lost the race.

2.1.3.2 Acceleration

Examining Figure 2.9, notice that Runner C did not attain the top velocity that the other runners did and could not hold his top velocity for very long. But there is a peculiar thing about the performance of Runner B: his top velocity actually exceeded that of Runner A! So why did he lose the race? This is an interesting question, and not readily apparent, unless the graph is examined very closely. It will be easier to see if Runner C is eliminated from the picture and just the first part of the race is examined (Figure 2.10).
Looking closely, you will notice two things. First, although the two runners have reached the identical velocity during this time period, it took Runner B a little more time to get up to that velocity. Second, the slope of Runner A’s curve is steeper than that of Runner B’s. In other words, the ratio of the change in velocity to the change in time is different between the two runners.

This quality, the ratio of the change in velocity to the change in time, is acceleration. Physically, it is how quickly velocity changes (either increases or decreases), or the rate of the change in velocity. A measure of a car’s performance is how quickly it can go from “0 to 60,” zero miles per hour to 60 miles per hour (a change of 60 mph), when you put your foot on the “accelerator.” Mathematically, it is the ratio of the change in velocity per the change in time:

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{change in time}} = \frac{\Delta v}{\Delta t}$$

(2.6)

And so it has units of miles per hour per second, or meters per second per second (m/sec², pronounced “meters per second squared”). So far, the discussion has been limited to the objects of interest (the runners) moving in one, single direction—which was identified as positive. In this circumstance, and this circumstance only, the sign (positive or negative) tells another useful piece of information: if the person is speeding up, the acceleration is positive. Conversely, if the person is slowing down, the acceleration is negative.

**Important Point!** A positive acceleration means a body is speeding up only if there is a single direction of travel.

Just as there is a difference between the average and instantaneous velocity, there is a difference between the average and instantaneous acceleration. Compare the first four points on Figure 2.10 (the actual data are presented in Table 2.2). Calculating the average acceleration over this period, you will notice that there is a slight (2.6%) difference in acceleration between Runners A and B. Yet if you shrink the time intervals, distinct differences in the acceleration patterns emerge. Coming out of the blocks, Runner A had an 11.17% greater acceleration than Runner B, and this was crucial to

### Table 2.2 Data for the First Four Points of Runner A and Runner B

<table>
<thead>
<tr>
<th></th>
<th>Runner A</th>
<th></th>
<th>Runner B</th>
<th></th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>t</td>
<td>v</td>
<td>Δt</td>
<td>a</td>
<td>Δv</td>
<td>% Difference</td>
</tr>
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<td>1</td>
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<td>4.23</td>
<td>0.85</td>
<td>2.72</td>
</tr>
</tbody>
</table>
his success. This important piece of information would have been lost had the intervals been too large. In fact, had you calculated the average acceleration of the two runners over the entire race, you would have found no difference between them! This finding again highlights the importance of a high number of data points: crucial information can be lost if the intervals are too large. Large numbers of data can be confusing in tabular form—just look how confusing Table 2.2 can be with only four points of data. Graphs are a great aid for this type of analysis.

Graphically, the acceleration is the slope of the velocity–time curve. Inspecting Figure 2.9 again, in several places along the curve Runner C appears to be slowing down. This can be verified by graphing the acceleration as a function of time (Figure 2.11).

Notice that in three places along the race Runner C “lost” speed, or decelerated. Comparing Runners A and B, we verify that Runner A “out accelerated” Runner B, which is why he won the race, even though Runner B had a greater instantaneous velocity. Runner A got too far ahead, and Runner B simply did not have time to catch up.

Average velocity will tell you who won the race (and average speed will tell you how long it will take you to drive to grandma’s house). But it will not tell you why someone won a race. And you cannot use it as an excuse to get out of a speeding ticket (“But officer, my average speed was only 40 miles per hour!”). To figure out why someone won a race, you need to know the following: the top speed (instantaneous speed), the time it takes them to get to the top speed (acceleration), the duration they hold their top speed, and the difference between top speed and final speed.2

You are now armed with information that can assist Runners B and C. Runner B needs to work on his acceleration. Runner C needs to work on top speed and speed endurance.

### 2.1.3.3 Absolute versus Relative Velocity

So far, we have been discussing absolute motion, that is, motion of each runner relative to the (fixed) Earth. This is a very useful way to describe motion and is used often, but there are times when it may be useful to examine motion of one body moving relative to another (moving) body. Knowing how fast you are driving in your car is important to ensure that you can safely navigate the road and any fixed obstacles that may be on it (and avoid speeding tickets). But it is not enough to prevent an accident; you also need to know how fast you are going in relation to other cars. When discussing the velocity of one body moving in relation to another, it is called relative velocity, and the formula is

\[ v_{B/A} = v_B - v_A \]  

### Important Point!

Equation 2.7 is valid if both the velocity of A and the velocity of B were calculated in the same frame of reference.

Which is read as, “The velocity of B relative to A is equal to the velocity of B (relative to your fixed reference frame) minus the velocity of A (relative to your fixed reference frame).” This may sound a bit confusing, but think about it for a second. If the velocity of A is zero, then the velocity of B relative to A is simply the velocity of B in the fixed reference frame. If the velocity of B relative to A is zero, then the velocity of B and the velocity of A are equal.

Returning to the case of the two runners, A and B, Figure 2.12 is a graph of the velocity of B relative to A (using Equation 2.7). The negatives mean that A was running faster than B, whereas the positives mean that B was running faster than A. Figure 2.12 shows you what you already determined looking at the velocities and accelerations: A was running faster than B in the beginning part of the race, but B was running faster than A in the second part of the race. A got too far out in front of B, and B could not catch him. This again highlights the importance of acceleration when the
22 Lesson 2 Describing Motion: Linear Kinematics in One Dimension

Figure 2.12 The velocity of Runner B relative to Runner A. Note that at the beginning of the race, Runner A is faster than Runner B (negative relative velocity), but Runner B is faster than Runner A (positive relative velocity) during the second half of the race.

movement times are short. Although it may appear that you did not gain any new information by examining the relative motion between the two runners, you will see how it is important in later lessons.

Section Question Answer
Several critical elements are involved in the race: peak speed, acceleration, length of time at peak speed, and the difference between peak speed and final speed. Runner A won the race because he had the best combination of these elements. Runner B needed to improve his acceleration, and Runner C needed to improve all but his acceleration. You would only know these things by examining the instantaneous velocities and accelerations of the entire race.

COMPETENCY CHECK
Remember:
1. Define the following: acceleration, average, instantaneous, rate, relative velocity, speed, slope, and velocity.

Understand:
1. Based on Equation 2.3, the time to complete a movement will decrease if the distance is ________ or the ________ is increased.

2. Calculate the velocity for the following:

<table>
<thead>
<tr>
<th>$v'$</th>
<th>$v''$</th>
<th>$\Delta v$</th>
<th>$\Delta t$</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m/s</td>
<td>10 m/s</td>
<td>0</td>
<td>1 sec</td>
<td>10 m/s</td>
</tr>
<tr>
<td>10 m/s</td>
<td>15 m/s</td>
<td>5 m/s</td>
<td>0.5 sec</td>
<td>10 m/s</td>
</tr>
<tr>
<td>0 m/s</td>
<td>15 m/s</td>
<td>15 m/s</td>
<td>0.01 sec</td>
<td>10 m/s</td>
</tr>
<tr>
<td>15 m/s</td>
<td>100 m/s</td>
<td>85 m/s</td>
<td>5 sec</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>

In each case, is the body speeding up or slowing down?

Apply:
1. Give an example of a movement or activity where speed or velocity is unimportant.
2. Give an example of a movement or activity where speed or velocity is important.
3. Describe a situation where velocity may be important but acceleration would be unimportant.

2.2 LINEAR KINEMATICS IN TWO DIRECTIONS

Section Question
The Shuttle Run (Figure 2.13) is one of the tests used to assess physical fitness by the President’s Council on Physical Fitness and Sports, as well as other organizations. Two blocks are placed on a line 30 feet away from a starting line. On the command “go,” the student runs to the first block, retrieves it, and returns to the starting line. After placing the block down, the student retrieves the second block in a similar manner. The score is the time it takes to complete the course. What does the Shuttle Run measure? Can we analyze it the same way we analyzed the 100-meter sprint?

At first glance, the 100-meter sprint and the Shuttle Run appear similar in that they both involve running as fast as you can, even though the Shuttle Run is much shorter (about 36.6 meters). The biggest difference, though, is that the sprint requires the runner to reach top speed as fast as he or she can and then maintain that speed through the finish line, while the Shuttle Run involves speeding up, slowing down, stopping, and changing direction. In the previous section, you
2.2 Linear Kinematics in Two Directions

Figure 2.13 The Shuttle Run as described by the President’s Council on Physical Fitness and Sports.

only dealt with changing magnitudes. You need to increase the sophistication of your analysis to deal with changing magnitudes and directions.

2.2.1 Displacement (\(\Delta p\)) and Distance (\(d\))

Define your frame of reference with the starting line as the origin, and the direction from the starting line to the blocks as “positive.” (Note that the lines should be superimposed on top of each other in Figure 2.13, but for purposes of the figure they are spread a little bit apart). If you wish to describe the length from the origin to where you pick up the first block (point “B”), you would say that is 30 feet. If you wish to describe the length from the origin to where you drop off the first block (point “C”), you see that you are back at the starting point (the origin), so the length, the displacement, is zero feet. But the actual distance you ran is 60 feet. The Shuttle Run illustrates that if you change directions, displacement and distance will not be the same.

Important Point! If a body starts and ends at the same spot, the displacement is always “zero,” even though the round-trip distance could be great!

As a vector, displacement has both a magnitude and a direction. In one dimension (but two directions), you can extract three key pieces of information:

1. The axis
2. The magnitude of the change in position
3. The direction of the change in position

As long as you are working in one dimension, the axis will be self-evident because there is only one axis. As you start working in 2-D and 3-D, this will become more important. The magnitude is simply how large the change is: A large number means a bigger change. Finally, there will either be a plus or minus sign in front of the number. (Note: If the direction is positive, the “+” sign is usually dropped and implied. Only the “−” sign is specified).

For example, let us say that the person is 15 feet away from the origin at time “1” (crossing line F), and arrives at point B at time “2.” The displacement would be:

\[
\Delta p = p_2 - p_1
\]
\[
\Delta p = 30 \text{ ft} - 15 \text{ ft} = 15 \text{ ft}
\]

This means that the body displaced 15 feet in the positive direction. Now what happens if the positions are reversed (the person leaves Point B at time “2” and crosses Line F at time “3”)?

\[
\Delta p = p_1 - p_2
\]
\[
\Delta p = 15 \text{ ft} - 30 \text{ ft} = -15 \text{ ft}
\]

This means the body displaced 15 feet in the negative direction. It is important to realize that, unlike in algebra, “−15” is not less than “+15.” The magnitudes of the displacements are identical, 15. Case 2 just happens to be in the opposite direction of Case 1, which is what the negative sign implies. Now what happens if we have two displacements, with the runner going from A to F and then from F to B?

From A to F:
\[
\Delta p = p_F - p_A
\]
\[
\Delta p = 15 \text{ ft} - 0 \text{ ft} = 15 \text{ ft}
\]

From F to B:
\[
\Delta p = p_B - p_F
\]
\[
\Delta p = 30 \text{ ft} - 15 \text{ ft} = 15 \text{ ft}
\]

From A to B:
\[
\Delta p = p_B - p_A
\]
\[
\Delta p = 30 \text{ ft} - 0 \text{ ft} = 30 \text{ ft}
\]

Important Point! The plus or minus sign on a vector only indicates direction. It does not mean that positive values are larger than negative values.

Note that the displacement from \(t'\) to \(t''\) is equal to the displacement from \(t'\) to \(t''\) plus the displacement from \(t''\) to \(t''\), even though it is unnecessary to perform the first two calculations to get to the third. This is certainly not a problem as long as the direction does not change. But what if it does?

In this example, at \(t'\) the runner is 15 ft from the origin, at \(t''\) the distance is 30 ft from the origin, and at \(t''\) her position returns to where it was at \(t', 15\) ft from the origin.
2.2.2 Velocity ($v$)

Now you can explore how changing direction changes the velocity vector. The velocity between several different points during the shuttle run was calculated from Table 2.3. The results are provided in Table 2.4. Note that when you go from Point A to Point B, the speed and velocity are identical: 12 ft/sec. What happens when you go from Point B to Point C? The magnitudes are the same (12 ft/sec), but the velocity has a negative sign in front of it. That negative sign indicates the direction, which in this case is negative (going from right to left across the page). Just like with displacement, “−12 ft/sec” is not less than “12 ft/sec,” it is just in the opposite direction. More precisely, you should write this as “$v = −12$ ft/sec.”

**Important Point!** The sign of the velocity is always in the direction of the displacement.

As before, you can extract three pieces of information:

1. The axis (x)
2. The magnitude of the velocity (12 ft/sec)
3. The direction of the travel (negative, or right to left)

But what about the velocity between points A and C? What is the zero velocity all about? If the total change in position, or displacement, is zero (in other words, you started and ended in the same place), then the total change in velocity is also zero. That is why you need to be careful about the time period over which you average the movement. You get a better appreciation of the velocity throughout the movement by examining the velocity at each point in time: the instantaneous velocity. Examining lots of numbers can be tedious, and you really will not get a feel for what is going on. Graphing the data is a better alternative. The displacement and velocity, as functions of time, are plotted at the top and middle of Figure 2.14.

**Important Point!** Important information is lost if you look at the difference between the initial and final over a large period of time. Graphs give a visual representation of what is happening throughout the entire movement.

### Table 2.3 Position, Distance, and Time During the Shuttle Run

<table>
<thead>
<tr>
<th>Data point Location</th>
<th>t (s)</th>
<th>d (ft)</th>
<th>$\Delta p$ (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>30</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>60</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>E</td>
<td>120</td>
<td>120</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 2.4 Distance, Displacement, Speed, and Velocity During the Shuttle Run

<table>
<thead>
<tr>
<th>$\Delta t$ (s)</th>
<th>$\Delta p$ (ft)</th>
<th>$\Delta v$ (ft/s)</th>
<th>$v$ (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From A to B:</td>
<td>0.5</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>From B to C:</td>
<td>0.5</td>
<td>−15</td>
<td>−12</td>
</tr>
<tr>
<td>From A to C:</td>
<td>1</td>
<td>30</td>
<td>10</td>
</tr>
</tbody>
</table>
Graphically, the velocity is the slope of the position–time curve: the steeper the slope, the greater the velocity. Check this by inspecting the top and middle of Figure 2.14. You should also notice that when the slope is negative, the velocity is also negative.

**Important Point!** A negative velocity does not mean a body is slowing down, only that it is moving with a certain speed in a negative direction.

Looking at the data in Table 2.4, you would be tempted to conclude that the velocity had not changed during the entire run. After all, at every point you examined the velocity was the same: 12 ft/s. In fact, if you would calculate the velocity between the other data points (C to D and D to E), then you would come up with the same velocity at each interval, 12 ft/s. But this does not quite match the picture in Figure 2.14. At some points the velocity is zero, and at others the magnitude is much greater than 12 ft/s. If you were to average the velocity across all those data points it would be 12 ft/s, but that number represents only a few of the actual data points. In reality, the velocity is constantly changing throughout the run.

**Important Point!** Zero velocity on a curve indicates that either a body is not moving, or it changed direction.

A change from a positive direction to a negative one (and vice versa) will always require the velocity to be zero during the transition—however brief. Returning to the Shuttle Run example, it should become apparent that the “points” where the velocity is zero are A, B, C, and D. (Point “E” would probably not be zero if we are encouraging the person to “run through” the finish line, but it is set at zero for the purposes of this example.) Consistent with the reference frame, going from point A to point B and point C to D would be the positive directions, whereas going from point B to point C and point D to E would be in the negative directions. In between the points, you are speeding up and slowing down as your speed leaves and approaches zero.

### 2.2.3 Acceleration (a)

The speeding up and slowing down indicates that the velocity is changing. The rate at which velocity changes, or how quickly you are speeding up or slowing down in a particular direction, is acceleration. Acceleration can represent a change in the magnitude of velocity (speed), the direction of the velocity vector, or both.

**Important Point!** Acceleration represents a change in the magnitude of velocity, the direction of the velocity vector, or both.

Returning to the Shuttle Run example, calculate the acceleration between several different time points. The data are presented in Table 2.5, with the results in Table 2.6. You will notice a couple of peculiar things. First, going from A to F you have a positive acceleration, but going from F to B you have a negative acceleration—even though you are going in a positive direction. The same can be said for going from B to F to C (it is a negative direction, but you have a positive acceleration during the second half). Why is that? Second, going from A to B, B to C, and A to C, the accelerations are all zero. What does that mean?
Let us tackle the first question. From A to F you are speeding up (increasing your velocity) in a positive direction: Positive change in velocity times positive direction equals positive acceleration. From F to B you are slowing down (decreasing your velocity) in a positive direction: Negative change in velocity times positive direction equals negative acceleration. A similar case can be made for going from B to F and F to C. Unlike velocity, which gives us both the magnitude and direction of your velocity, in a positive direction: Negative change in velocity times positive direction equals positive acceleration. From F to B you are slowing down (decreas- ing your velocity) in a positive direction: Negative change in velocity times positive direction equals positive acceleration. From B to C you are accelerating in the negative direction: Positive change in velocity times negative direction equals positive acceleration. (Remember that a negative acceleration means not determine the direction just by looking at the sign of the acceleration. (Remember that a negative acceleration means you were slowing down only in one direction.) Slowing down in the positive direction and speeding up in the negative direction both give \(-15.1\) ft/sec\(^2\). This principle is summarized in Table 2.7. To see how acceleration data is applied in the area of motor control, see Box 2.4.

**Important Point!** A negative acceleration could indicate a body is speed up or slowing down. To indicate a body is slowing down, some people will say it is "decelerating." Likewise, they will reserve use for "acceleration" to indicate a body is speeding up, even though it is not technically correct.

Table 2.5  Position, Velocity, and Time During the Shuttle Run

<table>
<thead>
<tr>
<th>Data point</th>
<th>Location</th>
<th>(p(\text{ft}))</th>
<th>(v(\text{ft/s}))</th>
<th>(t(\text{s}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>15</td>
<td>30</td>
<td>1.25</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>30</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>15</td>
<td>90</td>
<td>3.75</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0</td>
<td>120</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2.6  Change in Time, Change in Velocity, and Acceleration During the Shuttle Run

<table>
<thead>
<tr>
<th>(\Delta t(\text{s}))</th>
<th>(\Delta v(\text{ft/s}))</th>
<th>(\Delta a(\text{ft/s}^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>From A to F</td>
<td>1.25</td>
<td>18.9</td>
</tr>
<tr>
<td>From F to B</td>
<td>1.25</td>
<td>(-18.9)</td>
</tr>
<tr>
<td>From A to F</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>From B to F</td>
<td>1.25</td>
<td>(-18.9)</td>
</tr>
<tr>
<td>From F to C</td>
<td>1.25</td>
<td>18.9</td>
</tr>
<tr>
<td>From B to C</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>From A to C</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Notice that at each leg of the run, the acceleration is zero. That brings up a second principle regarding acceleration: Whenever the velocity starts at zero and ends at zero, the *average* acceleration must be zero. Remember that these values are averaged across the time periods and may represent few (if any) of the actual data points in the sample. The larger the time sample, the less information you will have about the acceleration. If you make the time periods very small, you can get a good approximation of the instantaneous acceleration at each point. Just like with velocity, looking at tabular data is only helpful if you have a small number of data points. With large amounts of data, it is more useful to look at a graph.

Table 2.7  The Sign of the Acceleration Vector as a Function of the Sign of Direction and the Sign of the Velocity

<table>
<thead>
<tr>
<th>Increasing Velocity (+)</th>
<th>Decreasing Velocity (−)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Direction (+)</td>
<td>Negative Direction (−)</td>
</tr>
<tr>
<td>Positive Acceleration (+)</td>
<td>Acceleration (−)</td>
</tr>
<tr>
<td>Negative Acceleration (−)</td>
<td>Positive Acceleration (+)</td>
</tr>
</tbody>
</table>

Box 2.4  Applied Research: Biomechanics in Motor Control

When many people think of acceleration, they think of sporting activities. But in reality, accelerations are required any time you start and stop a movement. The simple act of reaching for a cup requires that you accelerate to start the movement (positive acceleration) and decelerate to stop the movement (negative acceleration). Going from positive to negative acceleration requires that the acceleration cross the zero line. In this investigation, researchers had subjects perform various reaching tasks of increasing complexity at both slow and fast speeds. They were able to show that if a movement was completely “preplanned,” then the acceleration curves were smooth with one, single crossing of the zero line. Movements that used “online” feedback to make corrections to the movements had either: (a) multiple crossings of the zero line and/or (b) significant deviations from the smooth curve. Clearly, acceleration is an important variable for the central nervous system to consider when planning movement. Investigators study acceleration patterns to learn how movements are planned and executed in both healthy populations and persons with neurological impairments (stroke, Parkinson’s disease, etc.).

## 2.2 Linear Kinematics in Two Directions

### Important Point!
Acceleration will be zero whenever:
1. The velocity is zero
2. The velocity is changing from positive to negative
3. The velocity is not changing

Acceleration is the ratio of the change in velocity to the change in time. Graphically, ratios are represented by the slope of one value graphed as a function of the other. The velocity–time and acceleration–time curves of the Shuttle Run are represented in the middle and bottom of Figure 2.14, respectively. Notice that the acceleration is positive when the slope of the velocity–time curve is positive and negative when the slope is negative, as it should be (one leg of the run is displayed in Figure 2.15). You will also notice that the acceleration is zero every time the velocity reaches a peak, either positive or negative. The acceleration will be momentarily zero whenever you change from speeding up to slowing down (or vice versa).

### Figure 2.15
Comparing velocity and acceleration profiles. When the velocity slope is positive, the acceleration is positive. When the velocity slope is negative, the acceleration is negative. At the peak velocity, the acceleration is zero. When the velocity starts and ends at the same point, there is no change in velocity, and the areas under the positive and negative acceleration curves must cancel.

### Figure 2.16
Squat.

Whenever the change in acceleration is zero, the average acceleration must be zero. That does not mean that the acceleration is constant, or that the average positive acceleration is the same as the average negative acceleration. What it means is that the areas under the positive and negative acceleration curves need to cancel each other out. By visually inspecting the symmetry of the curve, it is apparent that this is the case. What happens when movements are not so symmetric?

### Important Point!
The area under the acceleration–time curve represents a change in velocity. If the change in velocity is zero, the areas under the positive and negative acceleration curves must be the same.

### Section Question Answer
The obvious differences between the 100 m sprint and the Shuttle Run are that the Shuttle Run has several changes in direction, and you do not run for more than ~9 m before you have to change direction. Because of the changes in directions, displacement and distance are not equivalent like they are in the 100 m sprint. This means that you must appreciate both scalars and vectors. Practically speaking, it takes about 50 to 60 m to reach peak speed in a sprint. Therefore, peak velocity is not a critical element in the Shuttle Run. Rather, it is a test of your capacity to accelerate and decelerate.

### 2.2.3.1 Asymmetric Acceleration Profiles

### Section Question
In keeping with his new motto, "If you want to be fast, you have to train fast," Coach I. M. Strong began having his athletes perform all their squat exercises as rapidly as possible. Noting that they could not squat fast with a heavy load, Coach Strong decreased the weight so he could have them "moving really fast." Is this a good idea?

Take a closer look at the squat exercise by examining the path of the barbell (Figure 2.16). During a real squat, the
The first thing you have to do is establish your frame of reference. In the previous running examples, the direction of movement was horizontal along the surface of Earth, and it was called the x-axis. The path of the barbell is in the vertical direction, so it is called the y-axis, and you should make it your reference axis. Locate the origin at the center of the barbell in the top position (1.37 m above the ground), and indicate “up” is the positive direction. Although you could have put the origin on the ground, it would make the math messier. Now you are ready to conduct your analysis.

First, see what happens when the exercise is performed at a relatively even cadence: 1 second on the way down, a 1-second pause at the bottom, and 1 second on the way up. The data for position, distance, and time are presented in Table 2.8, whereas the average velocity and acceleration data are presented in Table 2.9. Notice on the table that for velocity (v) and acceleration (a), a leading superscript “y” was added. It is a good habit to start including a leading superscript to denote the axis so that you know which direction you are talking about. (It will become even more important in the next section.) Compare Tables 2.6 and 2.9 and look for the following patterns: when you start and end in the same position, the displacement is zero and the velocity (and acceleration) is zero; and for any interval where the starting velocity is zero and the ending velocity is zero, the change in acceleration is also zero. Graphing the data (Figure 2.17), it is easy to see because the curves on the way down and on the way up are symmetric (maybe unnaturally so) that the areas

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Location</th>
<th>(\Delta p ) (m)</th>
<th>( d ) (m)</th>
<th>( t ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Top</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Intermediate</td>
<td>-0.225</td>
<td>0.225</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>Bottom</td>
<td>-0.45</td>
<td>0.45</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>Bottom</td>
<td>-0.45</td>
<td>0.45</td>
<td>2.0</td>
</tr>
<tr>
<td>4</td>
<td>Intermediate</td>
<td>-0.225</td>
<td>0.675</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>Top</td>
<td>0</td>
<td>0.90</td>
<td>3.0</td>
</tr>
</tbody>
</table>
under the curves cancel. What happens when you examine Coach Strong’s practice?

Let us limit the discussion to the “up” phase of the lift. If she were to move “as quickly as possible,” the velocities would be very high for the first part of the movement. Because she is required to stop (have a zero velocity at the end of movement, otherwise she would leave the ground), the velocities toward the end of the movement would have to be comparatively low. Examining Figure 2.18, you will notice that this is the case: The velocities are skewed to the left.

How does such a movement affect the acceleration profile? Recall that if the movement begins with a zero velocity and ends with a zero velocity, then the average acceleration has to be zero. The positive and negative portions of the graph must cancel each other. The rapid increase in velocity in the beginning of the movement means correspondingly high accelerations. To have the area under the negative curve cancel the area under the positive curve, she must either: (a) have a very rapid deceleration at the end, or (b) spend a longer time with negative acceleration. Because it is somewhat difficult to rapidly stop at the end, it is more likely that she will spend less time accelerating and more time decelerating (Figure 2.19). This has been demonstrated experimentally (Box 2.5).

Alternate training methods should probably be employed. If the person were to jump up in the air, she would not be required to stop at the top of the lift (i.e., the velocity at the end
In each case, is the body speeding up or slowing down?

Apply:

1. List activities where acceleration would be more important than maximum velocity.

2.3 **GAIT**

**Section Question**

Walking speed is an important ability that determines the functional independence of older adults (Figure 2.20). How can you improve walking speed? Is it the same for running?

Walking and running are forms of locomotion, referred to as **gait**. Average gait speed over a distance (over a time interval) is the average of speed of each step a person takes. A step is defined as the period from the initial contact of one foot to the initial contact of the other foot (Figure 2.21). Recall that speed is the ratio of distance per unit of time. If you know the length of each step (how “big” a step a person takes) and the **cadence** (or step

**COMPETENCY CHECK**

**Remember:**

1. Define the following: absolute value, acceleration, displacement, position, net value, vector, and velocity.

**Understand:**

1. Explain why you cannot tell the direction of travel from the acceleration vector.
2. Explain why the area under the acceleration and deceleration curves must be equal if the initial and final velocities are the same.
3. Calculate the velocity for the following:

<table>
<thead>
<tr>
<th>( \Delta v )</th>
<th>( \Delta t )</th>
<th>( v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m/s</td>
<td>1 s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>15 m/s</td>
<td>0.05 s</td>
<td>125 m/s</td>
</tr>
<tr>
<td>150 m/s</td>
<td>10 s</td>
<td>5 m/s</td>
</tr>
</tbody>
</table>

For each case, what is the direction of travel?

4. Calculate the acceleration for the following:

<table>
<thead>
<tr>
<th>( \Delta v )</th>
<th>( \Delta t )</th>
<th>( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 m/s</td>
<td>1 s</td>
<td>10 m/s</td>
</tr>
<tr>
<td>15 m/s</td>
<td>0.5 s</td>
<td>5 m/s</td>
</tr>
<tr>
<td>0 m/s</td>
<td>0.01 s</td>
<td>70 m/s</td>
</tr>
<tr>
<td>150 m/s</td>
<td>5 s</td>
<td>100 m/s</td>
</tr>
</tbody>
</table>

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Gait speed is calculated using step length and step rate (frequency). Two steps equal one stride (initial contact of one foot to the initial contact of the same foot; Figure 2.21). Either way will give you essentially the same answer (as long as the gait is symmetrical on both sides).

Examining Equation 2.8, you will note that gait speed is the product of step length and step rate (Figure 2.22). Theoretically, if you double either one, you will double your gait speed. There are limits to how big a step you can take. So you cannot increase either one indefinitely. If you are working with an older adult who has impaired gait speed, you must first determine if the problem is one of step length or step rate (or both) because they are the only two variables in the equation. If the problem is one of step length,
Section Question Answer

Walking speed is determined by step length and step rate. Theoretically, improving either one will lead to an increase in walking speed. However, there is a limit to how big a step you can take. After that, further improvements in walking speed would come from increasing step rate. The same applies to running speed.

COMPETENCY CHECK

Remember:
1. Define the following: cadence, gait, step, and stride.

SUMMARY

In this lesson, the simplest motion (1-D) was described using the key concepts in Table 2.10. Knowing how position changes with time, you should be able to determine both velocity and acceleration. These are sometimes called the spatiotemporal characteristics of movement because they relate to both space and time. You should be able to describe each of these concepts physically, mathematically, and graphically. Displacement is the change in position, or location in a reference frame. Velocity is the amount of displacement in a given amount of time, or how quickly a body is moving in a particular direction and is represented by the slope of the position–time curve. Acceleration is the change in velocity in a given amount of time: how quickly a body is speeding up, slowing down, or changing direction. It is the slope of the velocity–time curve. You should also be able to apply these concepts to human movement using your own examples. These same concepts will be used when the movement gets more complex, but the basic ideas are still the same.

REVIEW QUESTIONS

1. Define the following terms: abscissa, absolute value, acceleration, average value, axis, body, cadence, direction, displacement, distance, frame of reference, gait, instantaneous value, kinematics, net value, ordinate, orientation, origin, point, position, relative speed, sense, scalar, slope, speed, step, stride, system, vector, and velocity.
2. Write the equations for displacement, velocity, acceleration, and gait velocity.
3. Which has the greatest speed, 10 m/sec or −20 m/sec? Why?
4. During a marathon, which kinematic variable is most important in determining the outcome of the race: average velocity or acceleration?

5. During a sprint, which kinematic variable is most important in determining the outcome of the race: velocity or acceleration?

6. List two ways you could improve gait velocity.

7. Pick any linear movement, and sketch a graph of position versus time, velocity versus time, and acceleration versus time.

REFERENCES
