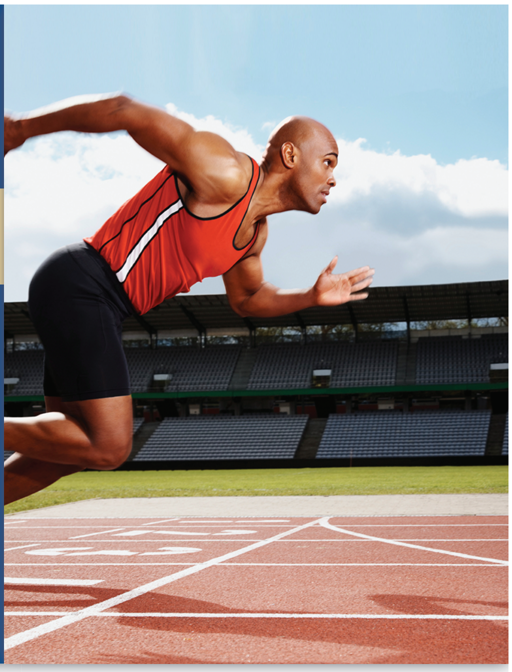

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CHAPTER 1

Basic Mechanics: Kinematic Variables

Chapter Objectives

At the end of this chapter, you will be able to:

- Describe the three-dimensional reference frame used to analyze human movements
- Explain the importance of the center of mass of a body
- Describe different types of motion
- Explain the relationships between the kinematic variables of position, velocity, and acceleration
- Use the equations of motion to determine the outcome of movement tasks
- Describe the different technologies that can be used to record linear and angular kinematic variables and the relative merits of each

Key Terms

Acceleration

Angular displacement

Central difference formulae

Equations of motion

First central difference method

General motion

Kinematic variables

Linear displacement

Position

Radial acceleration

Rotation

Second central difference method

Translation

Velocity

Chapter Overview

Mechanics is the study of the forces that act on a body and the changes in motion arising from these forces. This chapter will focus on the **kinematic variables** associated with a biomechanical analysis of human movements. Kinematic variables allow the description of the motion of a body without reference to variables that act to change the motion of the body. (The variables that act to change the motion of a body, kinetic variables, will be covered elsewhere.) An appreciation of the kinematic variables associated with an athlete's movements will allow the strength and conditioning practitioner to use specific technologies to assess an athlete's performance in a variety of movement tasks.

This chapter is not intended to be an exhaustive review of mechanical concepts. Rather, the mechanical variables that are pertinent to the fundamental movements covered in subsequent chapters will be addressed. This chapter should therefore be regarded as a reference for the later chapters as well as an introduction to mechanics. Readers should familiarize themselves with the SI units, vectors and scalars, vector analysis, and anatomic terminology before beginning this chapter. We begin our coverage of basic mechanics by defining the three-dimensional reference frame in which all movements take place.

The Mechanical Reference Frame

In any mechanical analysis of human movements, an appropriate reference frame is required that allows the description of the position of the body under analysis. A typical three-dimensional Cartesian coordinate system that is often used in biomechanical analyses is shown in Figure 1.1. In this reference frame, the *y*-axis corresponds to the principal horizontal direction of movement, while the *z*-axis corresponds to the vertical direction of movement. Note that this is not the coordinate system adopted by the International Society of Biomechanics, whose convention specifies the principal horizontal direction of movement along the *x*-axis, with the vertical axis being *y*. The designation of the orthogonal axes used to define the reference frame really has little effect on the subsequent analysis; what is important is that the reference frame is clearly defined. The convention shown in Figure 1.1, which will be used throughout this text, is that adopted by many technologies that the practitioner will encounter during mechanical analyses of human movements (e.g., motion-analysis systems, force plates).

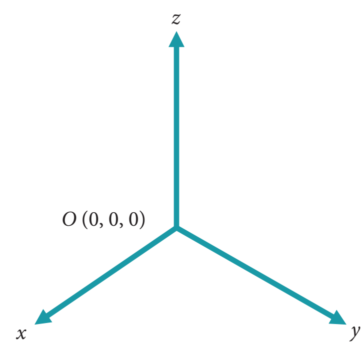

Figure 1.1 A three-dimensional reference frame typical of that used in biomechanical analyses of movements. The *y*-axis corresponds to the principal horizontal direction of movement. It is assumed that this reference frame does not move during any analysis.

Note: *O* is the origin of the reference frame.

The use of an appropriate reference frame allows the position of the system under analysis to be described at any point in time through reference to the position along a specific axis relative to the origin of the reference frame. For example, imagine an athlete during a 100-m sprint. If we set our reference frame such that the origin is at the start line and the athlete runs along the *y*-axis (the principal horizontal direction of motion), then at any point in time during the race we would be able to identify the position of the athlete in one-dimensional space. The selection of an appropriate reference frame during a biomechanical analysis provides meaning to the terms "at rest" and "in motion." Specifically, a body that is at rest will not change its position within the predefined reference frame, while one in motion will be changing its position along one, two, or three of the axes. Clearly, the body's state can be determined only if the body in question is being analyzed within an appropriate reference frame. Furthermore, the

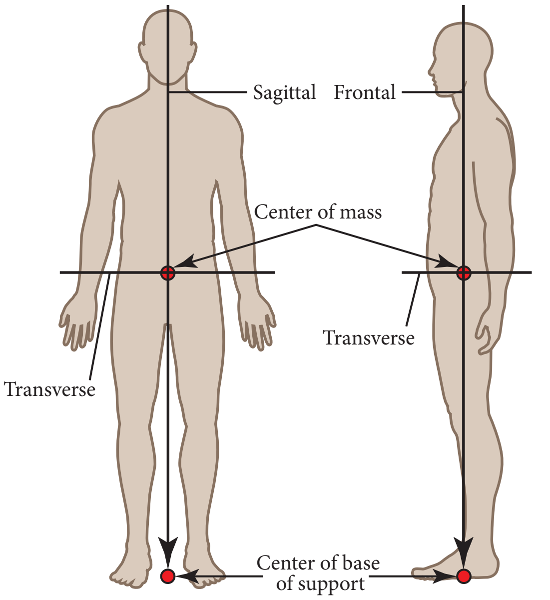

Figure 1.2 When the athlete is in the anatomic position, the center of mass is located close to the navel. The center of mass is located at the intersection of the frontal, sagittal, and transverse planes.

declaration of the reference frame in which the analysis is taking place provides meaning to the direction associated with the vector quantities that are used within a mechanical analysis of movement.

The Center of Mass

In a biomechanical analysis, the human body is often reduced to a point known as the center of mass (CM) when describing whole-body motion. Mass is the quantity of matter contained within a body (measured in kilograms), a quantity that will not be affected by the location in which the individual is being measured. The mass of a body is the same on the moon as it is on the Earth; it is the weight of the body that is dependent upon the magnitude of the gravitational force, and therefore measurement location (see Mechanical Concept 1.1). The CM is then defined as the virtual point about which the mass of the body is evenly distributed. The human body can be reduced to a point-mass system in many biomechanical analyses, with the CM becoming the reference for motion and the action of forces external to the body.

When stood in the anatomical position, the CM is located approximately around the navel (Figure 1.2), although by moving the body segments the location of the CM can move. For example, raising the arms above the head causes the CM to rise within the body. Similarly, when manipulating external masses, such as when performing resistance-training exercises, the location of the CM of the system (mass of athlete + external mass) can be modified considerably. For example, holding a loaded barbell above the head in an overhead squat increases the height of the CM above the ground considerably. As well as being the reference point for the motion of the body and the action of external forces, the CM represents the point through which an axis of rotation passes when the body is free to rotate in space. It should also be recognized that each individual segment that comprises the human body has a CM, while any implement that the athlete is manipulating will also have its own CM.

Mechanical Concept 1.1

Center of mass and center of gravity

The center of mass is the virtual point about which the mass of the body is evenly distributed. The center of gravity is the virtual point at which the gravitational force acts on a body and is the point where the weight force can be said to be acting. We can assume that the center of mass and the center of gravity coincide as humans operate within a constant gravitational field when on the Earth. However, in space, where the influence of gravity has been removed, the center of gravity no longer exists, while the center of mass remains. The term center of mass will be used throughout this text.

Describing Motion with Kinematic Variables

With the identification of a mechanical reference frame and the knowledge of the CM, we now have the beginnings of the mechanical description of motion. Kinematic variables can be used to describe the state of rest or motion of a body, and these variables include the position, velocity, and acceleration of the body under investigation.

Position

We have already introduced the idea that in order to be in motion, a body must be changing its **position** within an appropriate reference frame. Let's use the example of the 100 m sprinter again, where we are expressing the location of the athlete's CM along the principal horizontal direction of movement (y-axis). At time t_0 let's assume that the athlete's CM is located at the origin of the reference frame (0 m along the axis). At time t_1 we record the athlete's CM at 8 m from the origin along the axis. Given this information, we can now record the athlete's change in position as the final position minus the initial position along the y-axis to provide a variable known as the **linear displacement** (s) of the athlete during the time of analysis. In this particular example, the linear displacement of the athlete during the time of analysis is 8 m. It is this linear displacement undergone by the athlete within the reference frame that we use to establish a change in the athlete's linear position. Figure 1.3 provides an example of linear displacement associated with an athlete performing a standing long jump. It can be determined from this illustration that the position of the CM is at 0 m along the y-axis at t_0. At time $t_{1.87}$ the CM is recorded at 2.19 m along the y-axis. The linear displacement undergone by the CM during the time of analysis along the y-axis is therefore 2.19 m. The positive displacement value gives meaning to the direction of motion within the reference frame used. If the athlete had jumped in the opposite direction, the linear displacement undergone would have been – 2.19 m. Recognize

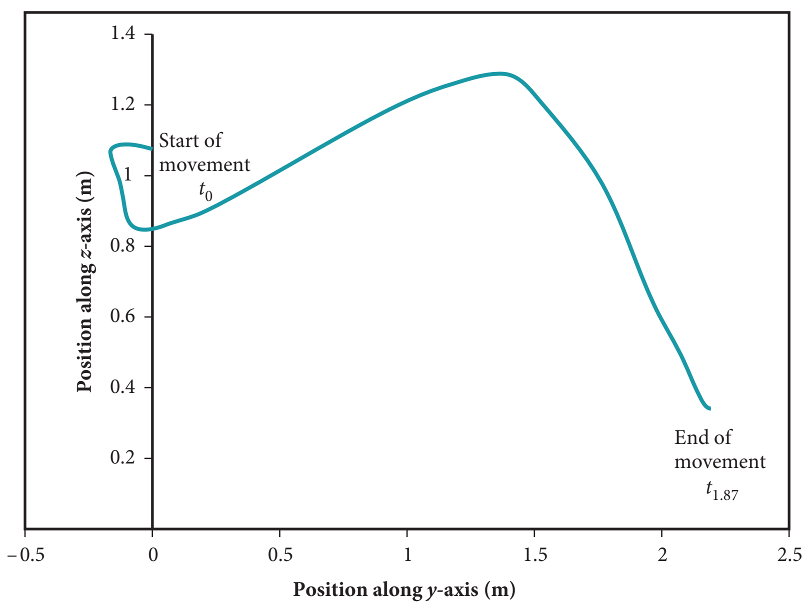

Figure 1.3 A graph showing the two-dimensional position of an athlete's center of mass viewed in the sagittal plane during a standing long jump.

that we have calculated the linear displacement of the CM during the time of the analysis. This is likely to be different from the distance between the feet from takeoff to landing that would typically be recorded during such a movement task. Finally, notice that the position of the CM has changed concomitantly along the *z*-axis during the time of analysis but that the axes are treated independently during the analysis.

The same methods can be applied to analyze the change in position of a body that is constrained to rotate about a fixed axis. Imagine an athlete performing a biceps curl with the object of the analysis being the motion of the dumbbell held in the hand. During the movement, the dumbbell rotates about an axis defined by the location of the elbow joint. Let the position of the dumbbell at time t_0 be 0° relative to the origin (the athlete is stood in the anatomical position with the elbow joint fully extended). At time t_1 the dumbbell is now 45° relative to the origin (the elbow joint has undergone flexion), so we can calculate the **angular displacement** (θ) by subtracting the initial angular position from the final angular position during the time of analysis. In this example, the angular displacement undergone by the dumbbell is 45° (or 0.79 rad). The positive value assigned to the angular displacement value indicates that the rotation occurred in a counterclockwise direction, which is defined as positive in the analysis of rotational movements.

So here we have two forms of motion both defined by the body under analysis changing position within a reference frame. In the first example, the linear displacement undergone by the athlete during the 100-m sprint resulted in **translation** of the sprinter's CM, while in the example of the biceps curl, the angular displacement moved through resulted in the **rotation** of the dumbbell. These two types of motion are used in all movements performed by athletes (see Mechanical Concept 1.2).

Mechanical Concept 1.2

Translational and rotational motion

Translational motion occurs when a body changes its position within a reference frame, without changing its orientation. Rotational motion occurs around an axis of rotation and requires the body to change its orientation with respect to the reference frame, which is assumed to be stationary. During a 100-m sprint, the CM of the athlete is translated without being rotated (the CM, being a point, cannot change its orientation within the reference frame). However, viewing the body of the sprinter during the race, we notice that the sprinter does change his or her orientation; the sprinter has a distinct forward lean during the early phases of the race and a more upright posture during the later phases. Indeed, during the stance phase of a running stride, the athlete's body may change its orientation as it is rotated about the stance foot. The CM can be translated only during this time. What is important to note, however, is that any translational motion associated with human movement only results from rotational motion as the segments of the body are constrained to rotate about axes defined by the anatomical joints. Using a specific example, the translational motion of a barbell during a back squat occurs as a result of the rotation of the body segments (trunk, thighs, legs, and feet). This combination of translational and rotational motion to achieve the goal of the task is referred to as **general motion**.

Velocity

While the change of position of a system within the reference frame provides information about the state of rest or motion of the system, it is the **velocity** of the system, defined as the rate of change of position during a time interval (Δt), that provides a more formal description of linear motion:

$$\bar{v} = \frac{\Delta s}{\Delta t} \qquad \text{Eq. (1.1)}$$

where $\bar{v}$ is the average linear velocity of the body during the time of analysis, Δs is the change in linear displacement over the time of analysis, and Δt is the time taken to undergo the change in linear displacement. (In the strict mechanical sense, the motion of a body is defined by its momentum, the product of mass and velocity. However, given that the mass of the bodies under investigation in a mechanical analysis of sporting movements remains constant, we can use velocity to describe motion.) The angular equivalent is as follows:

$$\bar{\omega} = \frac{\Delta \theta}{\Delta t} \qquad \text{Eq. (1.2)}$$

where $\bar{\omega}$ is the average angular velocity of the body during the time of analysis, $\Delta\theta$ is the change in angular displacement over the time of analysis, and Δt is the time taken to undergo the change in angular displacement. Although the average velocity of a body is informative, rarely will an athlete, or an object that is impelled by an athlete, experience a constant velocity. More likely, velocity will be changing either in magnitude or direction (see Worked Example 1.1). Therefore, instantaneous values of velocity are often calculated. In differential calculus, the instantaneous velocity can be calculated as the change as time approaches zero:

$$v = \frac{\mathrm{d}s}{\mathrm{d}t} \qquad \text{Eq. (1.3)}$$

where v is the instantaneous linear velocity, ds is an infinitesimal change in linear displacement, and dt is an infinitesimal change in time. In practical terms, the instantaneous velocity can be estimated using the **first central difference method** (see Worked Example 1.2).

Worked Example 1.1
Calculating average linear velocity during sprint running

Athlete A completes a 100-m sprint in 9.71 s, while Athlete B completes the race in a time of 9.84 s. Calculate their average linear velocities.

i. Use Equation (1.1)	$v = \Delta s/\Delta t$
ii. Athlete A	$v = 100/9.71$
iii. Athlete B	$v = 100/9.84$
iv. Answers	A = 10.30 m/s, B = 10.16 m/s

The values represent the average rate of change of linear position of the athlete over the duration of the race. By themselves, these velocity values provide little information to a strength and conditioning coach (other than informing them that both athletes

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under analysis are very fast, with Athlete A being faster than Athlete B). Observing the athletes during the race, we could assume their velocities were not constant throughout, so how much meaning can we attach to the average values that we have just calculated? Furthermore, the average values tell the strength and conditioning coach little about the phases of the race where the athlete could improve and where the coach can potentially direct the focus of training.

Tables 1.1 and 1.2 contain the time taken for the athletes to complete each of the 20-m phases of the race. We have used Equation (1.1) to calculate the athlete's average velocity during each of these phases.

Table 1.1
The Time Taken for Athlete A to Cover Each 20-m Phase of the 100-m Sprint and the Associated Linear Velocity

Displacement (m)	0–20	20–40	40–60	60–80	80–100
Time (s)	2.92	1.78	1.69	1.63	1.69
Velocity (m/s)	6.85	11.24	11.83	12.27	11.83

Table 1.2
The Time Taken for Athlete B to Cover Each 20-m Phase of the 100-m Sprint and the Associated Linear Velocity

Displacement (m)	0–20	20–40	40–60	60–80	80–100
Time (s)	2.91	1.80	1.71	1.68	1.74
Velocity (m/s)	6.87	11.11	11.70	11.90	11.49

Notice how in both cases the average velocity changes as the athlete progresses through the race. Also notice that rarely do the velocity values come close to the average values of 10.30 m/s and 10.16 m/s that were calculated for athletes A and B, respectively, across the duration of the entire race. From the average values calculated over the 20-m phases, the strength and conditioning coach can identify that Athlete B achieves maximal velocity during the same phase as Athlete A, but that the value is 3% lower than that achieved by Athlete A. The mechanical demands of sprint running during the maximal velocity phase of a sprint are distinct from those associated with the acceleration phase. As such, there are specific methods that can be used to improve maximal velocity sprinting. Notice that this information could not be determined from our original analysis using average velocity calculated over the duration of the entire race.

Worked Example 1.2
Calculating instantaneous linear velocity and acceleration

Instantaneous velocities and accelerations can be estimated from displacement data using **central difference formulae**. Instantaneous velocity can be estimated using the **first central difference method** as follows:

$$v_i = \frac{s_{i+1} - s_{i-1}}{2\Delta t} \quad \text{Eq. (1.4)}$$

where v_i is the instantaneous linear velocity of the data point of interest (s_i), s_{i+1} is the displacement data point one time interval after s_i, s_{i-1} is the displacement data point one time interval before s_i, and Δt is the time interval between consecutive data points.

Instantaneous acceleration can be estimated using the **second central difference method** as follows:

$$a_i = \frac{s_{i+1} - 2s_i + s_{i-1}}{\Delta t^2} \quad \text{Eq. (1.5)}$$

where a_i is the instantaneous linear acceleration of the data point of interest (s_i), s_{i+1} is the displacement data point one time interval after s_i, s_i is the displacement data point of interest, s_{i-1} is the displacement data point one time interval before s_i, and Δt is the time interval between consecutive data points.

Table 1.3 shows a small number of data points associated with the vertical position of an athlete's CM during a vertical jump as the athlete ascends from takeoff, measured using a motion-analysis system. Note that the values presented in the table have been rounded. We have calculated the instantaneous values for linear velocity and acceleration of the data points at times 0.005 s through 0.025 s using the first and second central difference formulae.

Table 1.3

The Vertical Position of an Athlete's Center of Mass as It Rises Toward the Apex of Flight During a Vertical Jump and the Instantaneous Vertical Velocity and Acceleration Values

Time (s)	Position (m)	v (m/s)	a (m/s^2)
0.000	1.486428	–	–
0.005	1.489400	(1.492128 – 1.486429)/(2 × 0.005) = 0.57	(1.492127 – 2 × 1.489400 + 1.486429)/(0.005^2) = –9.80
0.010	1.492127	(1.494608 – 1.489400)/(2 × 0.005) = 0.52	(1.494608 – 2 × 1.492127 + 1.489400)/(0.005^2) = –9.84
0.015	1.494608	(1.496844 – 1.492127)/(2 × 0.005) = 0.47	(1.496844 – 2 × 1.494608 + 1.492127)/(0.005^2) = –9.80
0.020	1.496844	(1.498834 – 1.494608)/(2 × 0.005) = 0.42	(1.498834 – 2 × 1.496844 + 1.494608)/(0.005^2) = –9.84
0.025	1.498834	(1.500578 – 1.496844)/(2 × 0.005) = 0.37	(1.500578 – 2 × 1.498834 + 1.496844)/(0.005^2) = –9.84
0.030	1.500578	–	–

Note: The first and last data points for velocity and acceleration are not calculated, as the first and second central differences require the data point prior to and following the data point of interest. There are mathematical techniques that can be implemented to calculate these missing data points, but usually in a biomechanical analysis more data are collected to account for these missing values.

From Table 1.3, notice that instantaneous velocity produces a series of positive values. This can be interpreted as the CM moving up in the reference frame used to analyze the athlete, producing a positive velocity vector. Also notice that the magnitudes of the positive values of velocity are decreasing as time progresses. Indeed, the rate at which the positive velocities are decreasing is reflected in the instantaneous accelerations of the CM. Notice that the acceleration values remain almost constant with the change in time (error associated with the

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data collection process and rounding the values precludes the attainment of constant values). We can interpret this as the system experiencing a constant negative acceleration—exactly what would be expected, as gravity is the only force that is acting on the CM following takeoff.

Table 1.4 shows a small number of data points associated with the vertical position of an athlete's CM during a vertical jump as the athlete descends from the apex of flight (the highest vertical position achieved). Notice again that the values presented in the table have been rounded. We have calculated the instantaneous values for linear velocity and acceleration of the data points at times 0.005 s through 0.025 s using the first and second central difference formulae.

Table 1.4

The Vertical Position of an Athlete's Center of Mass as It Descends from the Apex of Flight During a Vertical Jump and the Instantaneous Vertical Velocity and Acceleration Values

Time (s)	Position (m)	v (m/s)	a (m/s^2)
0.000	1.500578	–	–
0.005	1.498834	$(1.496844 - 1.500578)/(2 \times 0.005) = -0.37$	$(1.496844 - 2 \times 1.498834 + 1.500578)/(0.005^2) = -9.84$
0.010	1.496844	$(1.494608 - 1.498834)/(2 \times 0.005) = -0.42$	$(1.494608 - 2 \times 1.496844 + 1.498834)/(0.005^2) = -9.84$
0.015	1.494608	$(1.492127 - 1.496844)/(2 \times 0.005) = -0.47$	$(1.492127 - 2 \times 1.494608 + 1.496844)/(0.005^2) = -9.80$
0.020	1.492127	$(1.489400 - 1.494608)/(2 \times 0.005) = -0.52$	$(1.489400 - 2 \times 1.492127 + 1.494608)/(0.005^2) = -9.84$
0.025	1.489400	$(1.486428 - 1.492127)/(2 \times 0.005) = -0.57$	$(1.486428 - 2 \times 1.489400 + 1.492127)/(0.005^2) = -9.80$
0.030	1.486428	–	–

Note: The first and last data points for velocity and acceleration are not calculated, as the first and second central differences require the data point prior to and following the data point of interest. There are mathematical techniques that can be implemented to calculate these missing data points, but usually in a biomechanical analysis more data are collected to account for these missing values.

Notice that instantaneous velocity values are now negative; the CM is now moving down in the reference frame, resulting in a negative velocity vector. Also notice that the magnitudes of the negative values of velocity are increasing as time progresses. The rate at which the negative velocities are increasing remains almost constant with the change in time. This change in velocity, which is the same as that calculated for the data points as the CM was rising after takeoff, is due to the action of gravity on the CM. The acceleration associated with the gravitational force is -9.81 m/s^2. While the example here used linear values, the central difference formulae can be used with angular displacement data as the input.

Acceleration

The rate of change of linear velocity is known as **acceleration**, with average acceleration being calculated as follows:

$$\bar{a} = \frac{\Delta v}{\Delta t} \qquad \text{Eq. (1.6)}$$

where $\bar{a}$ is the average linear acceleration of the body during the time of analysis, Δv is the change in linear velocity over the time of analysis, and Δt is the time taken to undergo the change in linear velocity. The angular equivalent is as follows:

$$\bar{\alpha} = \frac{\Delta\omega}{\Delta t} \quad \text{Eq. (1.7)}$$

where $\bar{\alpha}$ is the average angular acceleration of the body during the time of analysis, $\Delta\omega$ is the change in angular velocity over the time of analysis, and Δt is the time taken to undergo the change in angular velocity. In differential calculus, the instantaneous acceleration can be calculated as the change in time approaches zero:

$$a = \frac{d^2 s}{dt^2} \quad \text{Eq. (1.8)}$$

where a is the instantaneous velocity, ds is an infinitesimal change in linear displacement, and dt is an infinitesimal change in time. In practical terms, the instantaneous acceleration can be estimated using the second central difference method (see Worked Example 1.2). Table 1.5 shows the values of linear velocity and acceleration achieved during different movement tasks.

Table 1.5
Values of Linear Velocity and Acceleration Achieved During Different Movement Tasks

Movement	Velocity (m/s)	Acceleration (m/s^2)
Baseball struck by bat	41.7[h]	30,000[b]
Typical release of a javelin	30[b]	
Kicking a soccer ball	30[b]	3,000[b]
Cheetah sprinting	29[a]	
Ostrich sprinting	17[a]	
Shot put release	14.1[f]	
Human sprinting	12.4[c]	3.5[d]
Vertical projection of CM during high jump	4.64[e]	26.4[e]
Snatch lift with maximal load	1.65[g]	

Note: CM is center of mass.
[a]Data from Alexander, R. M. (2003). *Principles of Animal Locomotion*. Princeton, NJ: Princeton University Press.
[b]White, C. (2011). *Projectile Dynamics in Sport*. Oxon, UK: Routledge.
[c]Data from http://www.sportscientists.com.
[d]Blazevich, A. (2007). *Sports Biomechanics. The Basics: Optimising Human Performance*. London, UK: A & C Black Publishers.
[e]Ae, M., Nagahara, R., Ohshima, Y., Koyama, H., Takamoto, M., & Shibayama, K. (2008). Biomechanical analysis of the top three male high jumpers at the 2007 World Championships in Athletics. *New Studies in Athletics, 23,* 45–52.
[f]Gutiérrez-Davila, M. (2009). Biomechanical analysis of shot put at the 12th IAAF World Indoor Championships. *New Studies in Athletics, 24,* 45–61.
[g]Hoover, D. L., Carlson, K. M., Christensen, B. K., & Zebas, C. J. (2006). Biomechanical analysis of woman weightlifters during the snatch. *Journal of Strength and Conditioning Research, 20,* 627–633.
[h]Crisco, J. J., Greenwald, R. M., Blume, J. D., & Penna, L. H. (2002). Batting performances of wood and metal baseball bats. *Medicine and Science in Sports and Exercise, 34,* 1675–1684.

Relationships between kinematic variables

The definitions of displacement, velocity, and acceleration allow the relationships between these kinematic variables to be expressed in a series of equations, known as the **equations of motion**:

$$v_f = v_i + at \quad \text{Eq. (1.9)}$$

$$s = v_i t + \frac{1}{2}at^2 \quad \text{Eq. (1.10)}$$

$$v_f^2 = v_i^2 + 2as \quad \text{Eq. (1.11)}$$

where v_f is the linear velocity of the body at the end of the period of analysis, v_i is the linear velocity of the body at the beginning of the period of analysis, a is the linear acceleration experienced by the body, t is the period of time over which the analysis occurs, and s is the linear displacement that the body undergoes during the period of analysis. These equations become very useful in determining the outcome of human movements given the knowledge of certain kinematic variables associated with the movement (see Worked Example 1.3).

Worked Example 1.3
Using the equations of motion

1. An athlete performs a vertical jump where the vertical velocity of her CM is 3.25 m/s at takeoff. Calculate the time of flight.
   i. Use Equation (1.9) $v_f = v_i + at$
   ii. Solve for t $t = (v_f - v_i)/a$
   iii. Input the known variables $t = (0 - 3.25)/-9.81$

   In this instance, v_f represents the vertical velocity at the apex of flight, a known value of 0 m/s. Therefore, the time calculated is the time taken for the CM to reach the apex. a is the acceleration associated with gravity, which needs to be included because the CM is moving along the vertical axis of our reference frame.

   iv. Double the time calculated $t = 0.33129 \times 2$
   v. Answer $t = 0.66258$

   The CM is assumed to follow a parabola during the time of flight such that the time taken to reach the apex of flight will be the same as that taken to descend from the apex. Therefore, the time of flight in this example is 0.66 s.
2. Given the time of flight calculated in Question 1, determine the athlete's jump height.
   i. Use Equation (1.10) $s = v_i t + ½at^2$

   Given that we are going to calculate jump height (s) from flight time alone, we will have $v_i = 0$ m/s, a value that is achieved when the CM is at the apex of flight. Therefore, what we will actually calculate is the displacement undergone by the CM as it falls from the apex. Assuming the CM follows a parabola during flight, the displacement up to the apex will equal the displacement down from the apex. As we will be analyzing only half of the flight phase, we will require only half of the total flight time ($t = 0.33129$ s).

   ii. Input the known variables $s = (0 \times 0.33129) + (-4.905 \times 0.33129^2)$
   iii. Answer $s = -0.54$

   The displacement is calculated as −0.54 m. Remember, this is the displacement undergone by the CM as it descends from the apex of flight. Assuming a parabola during flight, the displacement undergone as the CM rises to the apex, and therefore the jump height, is the same as during its descent. Because the direction of motion is different, however, we remove the negative sign from our answer to get a jump height of 0.54 m.

Note that the CM will only follow a parabola during flight if the posture at takeoff is the same as that upon landing. This is unlikely to be the case, with the athlete more extended at takeoff compared to landing. This will be reflected in the CM undergoing a greater displacement as it descends from the apex compared to its rise to the apex. Therefore, calculating jump height from the time of flight such as when using a contact mat may result in an overestimation of jump height (Moir, 2008).

3. Given the takeoff velocity for the athlete in Question 1, calculate her jump height.

i. Use Equation (1.11)	$v_f^2 = v_i^2 + 2as$
ii. Solve for s	$s = (v_f^2 - v_i^2)/2a$
iii. Input the known variables	$s = (0^2 - 3.25^2)/(2 \times -9.81)$
iv. Answer	$s = 0.54$ m

Notice that the value calculated is positive. In our reference frame, this means that the CM has undergone an upward displacement from takeoff to the apex of flight (compare this to the negative value calculated in Question 2, which calculated the displacement during the descent of the CM from the apex of flight).

In the examples used here, the body was treated as a point-mass system where the behavior of the CM becomes the focus of the analyses. Furthermore, drag forces associated with the movement of the body through the air (air resistance) are ignored. This assumption is valid for a slow-moving body such as a human performing a jump, but is invalid when the body begins to move faster (indeed, the retarding effects of drag increase with v^2 for humans moving through air). A value of $v \geq 5$ m/s is generally used for the inclusion of drag forces in a mechanical analysis (Grimshaw, Lees, Fowler, & Burden, 2006).

We can combine the equations of motion to determine the horizontal range traveled by a body during flight:

$$s = \frac{v^2 \sin\theta \cos\theta + v \cos\theta \sqrt{v^2 \sin^2\theta + 2gh}}{g} \qquad \text{Eq. (1.12)}$$

where s is the horizontal range traveled by the body, v is the velocity at release, θ is the angle of release defined by the angle of the velocity vector (determined by the magnitude of the horizontal and vertical components of the release velocity), g is gravitational acceleration, and h is the difference in height between release and landing. The body can be an implement thrown by an athlete (e.g., javelin, discus), a ball that is kicked or thrown, or even the athlete himself or herself, such as during a long-jump event where the body is defined as the CM of the athlete. Although this Equation (1.12) fails to account for the fluid-dynamic forces of drag and lift, which could have substantial effects on the range of the body, it is very informative for the practitioner because it tells us that the linear velocity of the body at release exerts the greatest influence on the range traveled by the body during flight.

Acceleration experienced by a rotating body

Consider a point on a body that is rotating, such as the head of a golf club during a golf swing. If the instantaneous linear velocity of the point of interest is shown at various times during the movement, the direction of the velocity vector will be

Worked Example 1.4
Radial acceleration when running around a bend

Athletes A and B perform a 200-m sprint. Both athletes attempt to achieve the same linear velocity of 10 m/s, but Athlete A runs the bend in lane 1 (radius of 37.4 m) while Athlete B runs the bend in lane 8 (radius of 43.7 m). Calculate the radial acceleration required for both athletes.

i. Use Equation (1.13)	$a_R = v^2/r$
ii. Input the known variables for Athlete A	$a_R = 10^2/37.4$
iii. Input the known variables for Athlete B	$a_R = 10^2/43.7$
iv. Answers	A = 2.67 m/s^2, B = 2.29 m/s^2

Notice that the athlete in lane 1 has to produce a greater radial acceleration in order to continue along the curved path compared to the athlete in lane 8, despite the same linear velocity. Of greater concern is the origin of this acceleration. The required acceleration can be generated only when the athlete is in contact with the ground (stance phase), and it comes from a frictional force. Assuming the athletes are of the same mass, our analysis shows that Athlete A has to supply a frictional force that is 17% greater than that supplied by Athlete B. This potentially means less vertical force production for Athlete A, which would have substantial effects on Athlete A's sprinting velocity. An alternative to mitigate the problem, as per Equation (1.13), is, of course, to reduce the linear velocity around the bend—not a satisfactory solution. This is the reason that no athletes are placed in lane 1 in the 200-m race at athletic championships and that the bends are banked on indoor running tracks that have reduced radii.

continually changing in the specified reference frame, even if the magnitude of the vector remains constant. Given that velocity is a vector variable, a change in its direction constitutes a change in velocity, and therefore the rotating body experiences an acceleration. This **radial acceleration** acts toward the axis of rotation and can be calculated as follows:

$$a_R = \frac{v^2}{r} \qquad \text{Eq. (1.13)}$$

where a_R is the radial acceleration experienced at the rotating body, v is the instantaneous linear velocity of the rotating point, and r is the radius of the rotating point. It is the radial acceleration that keeps a body moving along a curved path during the movement. Equation (1.13) tells us that the requisite radial acceleration to ensure the continuation of the curved path of the body increases with the square of linear velocity, but is reduced with increases in the associated radius. This has implications for running around a bend (see Worked Example 1.4).

Technology to Record Kinematic Variables

There are various technologies available to the strength and conditioning practitioner to assess the kinematic variables associated with the performance of his or her athletes during running, jumping, and resistance training exercises. These technologies include timing gates, contact mats, Global Position System devices, position transducers, accelerometers, and motion-analysis systems. Kinematic data associated with the motion of an athlete's CM can also be gathered from force data collected from a force plate, a technology that is discussed elsewhere.

Timing gates

Timing gates use photocells to record the timing of events (see Mechanical Concept 1.3). For example, timing gates that are positioned at known distances along the path of motion of a body can be used to calculate the speed of the body under investigation (Figure 1.4). (Because the specific axes of motion cannot be identified using this method, the scalar of speed is calculated rather than the vector of velocity.) Timing gates are typically used in the assessment of running performance where the path of motion taken by the body must be known in advance and consideration to the type of timing gate (number of photocells), the height of the timing gates, and the distance between consecutive pairs of timing gates is required (Yeadon, Kato, & Kerwin, 1999; see Applied Research 1.1). It should be recognized that the data recorded from timing gates will only provide the average speed over a known distance. Running speeds recorded from timing gates have been shown to be reliable (Moir, Shastri, & Connaboy, 2004).

Mechanical Concept 1.3

Photocell technology in timing gates

A photocell is a sensor that exhibits photoconductivity, changing its electrical resistance in response to alterations in a light source. In the case of timing gates, the light source is an infrared beam that is reflected back from a reflector placed a short distance from an emitter. An interruption in the beam caused by the motion of a body through the beam causes a change in the resistance of the photocell, resulting in an increase in the voltage output. The time-history of voltage changes can be recorded to provide information about the temporal characteristics of the interruptions of the beam. If emitter–reflector pairs of timing gates are positioned at known distances along the path of the body under investigation, then the average speed can be calculated based upon the time histories of successive beam interruptions.

Some timing gates used for the analysis of running speed have single photocells, while others have multiple photocells (either two or three) located vertically. Timing gates containing multiple photocells produce an increase in the output voltage only when the beams to each of the photocells are interrupted simultaneously. Such an arrangement guards against the occurrence of false signals associated with single photocell timing gates caused by the beam being broken by the outstretched arm or leg of an athlete running through the timing gates. Timing gates comprising multiple photocells are likely to record the times associated with the torso of the athlete breaking the beams, allowing an approximation of the speed of the athlete's CM to be obtained, and are therefore likely to be more accurate than single photocell timing gates for measuring sprint times (Earp & Newton, 2012; Yeadon et al., 1999).

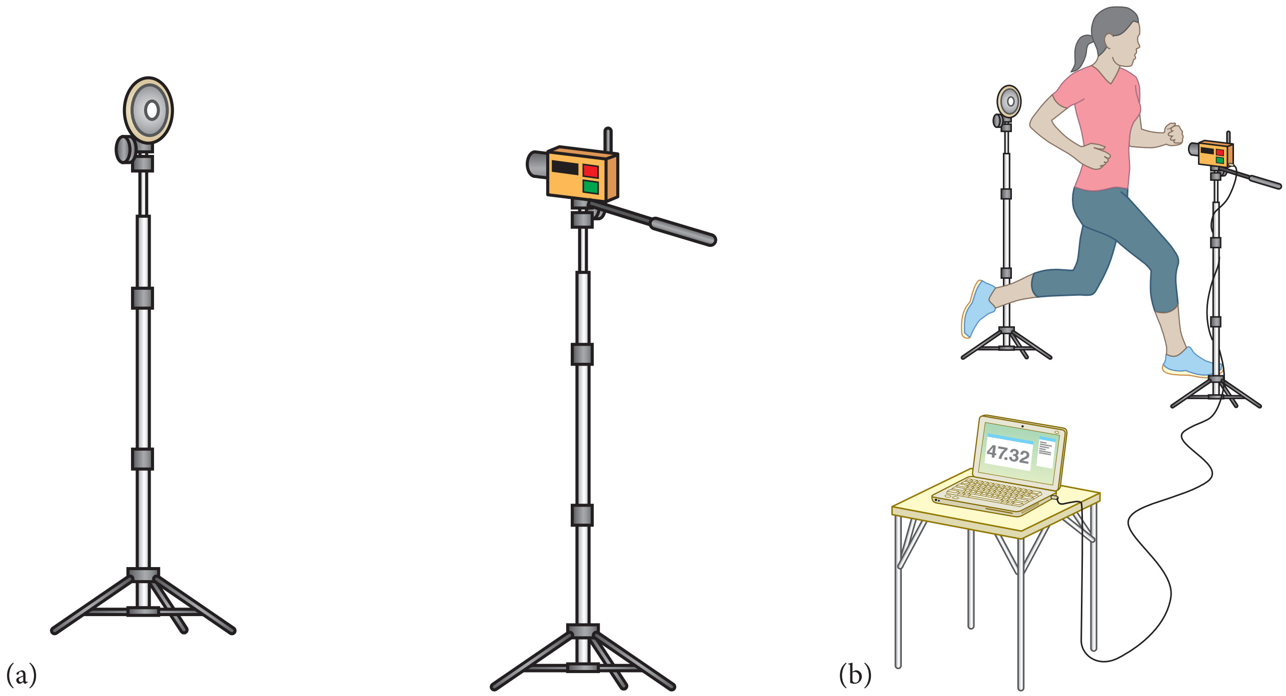

Figure 1.4 Timing gates used to record running speed. (a) An emitter–reflector pair. An infrared beam from the emitter (foreground) is reflected back from the reflector placed directly opposite. The interruption of the beams associated with timing gates set at known distances along the path of motion allows the determination of speed. (b) The use of photocells to record the sprinting speed of an athlete.

Applied Research 1.1

Recording sprinting speed using timing gates

The authors assessed the errors in running speeds when using different types of timing gates (single and double photocell) and when setting the gates at different distances along the path of motion. One participant ran at five nominal speeds (5–9 m/s) along a straight running track. Pairs of timing gates were placed along the runway with distances ranging from 1.6 to 2.4 m between consecutive emitter–reflector pairs in the direction of motion. The times obtained from gates using single photocell were compared to those obtained from gates with double photocells. The gates were set at a height such that the lowest photocell was 1.05 m from the ground, corresponding to approximately the height of the participant's hips. A video-based motion-analysis system was used to obtain the actual speed of the participant's CM during each trial, and the speeds from the timing gates were compared to those obtained from the motion-analysis system. The authors reported that the errors in running speed obtained from the timing gates were smaller when the distance between consecutive gates along the path of motion was increased, while the smaller errors in running speed were associated with double photocell gates compared to the single photocell gates. The error in running speeds obtained from single photocell timing gates placed at approximately hip height was 0.1 m/s when the distance between the gates in the direction of motion approximated the stride length of the runner. The authors concluded that timing gates with double photocells should be used when possible and that the distance between the gates in the direction of motion should be set to multiples of the running stride.

Yeadon, M. R., Kato, T., & Kerwin, D. G. (1999). Measuring running speed using photocells. *Journal of Sports Sciences, 17*, 249–257.

Figure 1.5 A contact mat used to record the time in the air for an athlete during a vertical jump. The pressure exerted by the athlete when stepping on the mat activates microswitches contained within the mat. The pressure is removed when the athlete leaves the mat at takeoff, deactivating the switches and beginning the timing unit. The microswitches are activated upon landing, stopping the timing unit to provide the time in the air.

Contact mats

Contact mats contain microswitches that are activated in response to pressure exerted on the mat, being deactivated once the pressure is removed (Figure 1.5). By connecting the microswitches to a timing unit, a contact mat can be used to provide the time elapsed between consecutive activations caused by the pressure exerted by an athlete's foot contact, allowing contact mats to be used to calculate vertical jump height with the data provided upon completion of the movement. However, the validity of the jump height recorded from a contact mat has been questioned (Buckthorpe, Morris, & Folland, 2012; see Applied Research 1.2), although jump height recorded from a contact mat has been shown to have acceptable reliability (Moir, Shastri, & Connaboy, 2008).

Global Positioning System-based technology

The Global Positioning System (GPS) allows the coordinates of an appropriate receiver to be determined, providing positional information of the receiver in real time (see Mechanical Concept 1.4). GPS receivers can be worn by athletes during practices or competitions (if permitted) to record the distances covered and the speeds achieved (Figure 1.6). Unlike timing gates, the path of motion of the athlete does not have to be determined in advance, allowing the athlete to move freely within the environment, so GPS-based technology can be used to determine kinematic variables associated with player motion in field and court sports. Moreover, the information is gathered online, with no requirements for further calculations, and the high sampling frequency associated with the GPS units allows instantaneous speeds to be approximated. The running speeds obtained from GPS-based technologies are reliable, although the values tend to be lower compared to the speeds obtained from timing gates (Waldron, Worsfold, Twist, & Lamb, 2011; see Applied Research 1.3).

Applied Research 1.2

Recording vertical jump height using a contact mat

The authors compared the height achieved during countermovement vertical jumps performed with an arm swing in a group of 40 participants. Jump height was recorded from a contact mat, a jump-and-reach device (Vertec), and a force plate. The jump height recorded from the force plate served as the criterion measure to which the values from the contact mat and the jump-and-reach device were compared. The vertical force trace derived from the force plate was converted to acceleration by subtracting body mass, and the acceleration was double-integrated to return the vertical displacement of the center of mass (CM) throughout the jump. Jump height was determined as the difference between the height of the CM when the participant was standing before the jump and the maximal vertical displacement achieved during the flight phase of the jump. The time in the air for each jump derived from the contact mat was entered in to an equation of motion to determine the vertical displacement of the CM. The jump-and-reach device comprised a series of plastic swivel vanes arranged in half-inch increments along a telescopic metal pole. The metal pole was adjusted such that the lowest vane was at a height equivalent to the maximal displacement achieved by the participant's dominant hand reaching overhead. Jump height was calculated from the highest vane displaced by an overhead swinging arm motion at the apex of each participant's jump. The authors reported that both the contact mat and the jump-and-reach device returned jump heights that were significantly below that associated with the criterion measure. These differences arose due to the inability of the contact mat and the jump-and-reach devices to account for the rise of the CM prior to takeoff (takeoff height). When this displacement was taken into account, the jump height returned by the contact mat was then greater than that derived from the criterion measure. The authors propose that neither the contact mat nor the jump-and-reach device provide valid measurements of vertical jump height.

Buckthorpe, M., Morris, J., & Folland, J. P. (2012). Validity of vertical jump measurement devices. *Journal of Sports Sciences, 30*, 63–69.

Figure 1.6 (a) A GPS receiver used to track player motion. (b) The receiver is housed in a vest worn by the player.

Photos courtesy of Catapult Sports.

Mechanical Concept 1.4

GPS-based player tracking technology

The Global Positioning System (GPS) is a U.S.-owned utility that uses 24 satellites orbiting the Earth at a height of approximately 20,200 km to provide accurate positioning and timing information. Each satellite orbits the Earth twice daily, and the constellation of satellites ensures that at least four satellites are within view from almost any area on the planet. GPS devices use radio waves from the orbiting satellites to determine the receiver's geocentric coordinates—that is, the coordinates of the receiver relative to the Earth's center—allowing the positional information of the receiver to be obtained in real time. The calculation of these coordinates is dependent upon accurate measurements of time, which are derived from atomic clock readings. Although largely unaffected by weather, the accuracy of GPS readings can be affected by other atmospheric conditions (e.g., space weather events [Rama Rao et al., 2009]). GPS readings can be affected by obstructions within the environment that interfere with the acquisition of the satellites (e.g., buildings, trees, landscape), which precludes the use of traditional GPS devices in an indoor environment. Even when the GPS units are used in an open-air court setting (e.g., tennis) where multiple satellites are acquired, the reliability of the data have been shown to be compromised (Duffield, Reid, Baker, & Spratford, 2010). However, recent advances in technology have permitted the use of portable "satellites" to be placed within sporting stadia, mitigating the problems associated with satellite reception when using GPS-based systems and allowing the collection of kinematic data during indoor sports.

Applied Research 1.3

Comparing the linear kinematics of athletes recorded from timing gates and GPS devices

Running velocity is an important variable in many sports, so methods to measure it are important in the mechanical analyses of athletes. Typically, an athlete's linear velocity will be recorded using timing gates. However, this method requires that the athlete must follow a specific path during the time of analysis. Global Positioning System (GPS) allows the determination of running velocities as the athlete moves freely within the environment. The authors compared the velocity values recorded from both timing gates and GPS devices for a group of young rugby players over distances ranging from 10 to 30 m. The authors reported that both systems produced reliable velocity values, although the reliability of the values obtained from the timing gates was slightly better. Furthermore, the GPS devices systematically underestimated the magnitude of the athletes' velocities compared to the timing gates. Despite these issues, the authors concluded that GPS devices are able to quantify small, yet practically meaningful, changes in sprint performance.

Waldron, M., Worsfold, P., Twist, C., & Lamb, K. (2011). Concurrent validity and test-retest reliability of a global positioning system (GPS) and timing gates to assess sprint performance variables. *Journal of Sports Sciences, 29*, 1613–1620.

Figure 1.7 A linear position transducer attached to a barbell via a cable is used to record the velocity of the barbell during a snatch movement.

Photo courtesy of Tendo Sport Machines.

Position transducers

A position transducer allows the determination of the displacement of a body in motion (see Mechanical Concept 1.5). Linear position transducers (LPTs) can be used to determine the velocity of the athlete during jumping and running movements, as well as to determine the velocity of the barbell during resistance exercises (Harris, Cronin, Taylor, Boris, & Sheppard, 2010; Figure 1.7). The data obtained from an LPT

Mechanical Concept 1.5

Position transducer technology

A position transducer is a device that converts the change in position of a cable attached to the body under investigation into a voltage. The position transducers typically used in strength and conditioning contain photocells that change their electrical resistance in response to alterations in a light source. The cable of the device rotates a slotted disk when the body under investigation is moved, causing the light source for the photocell to be repeatedly blocked and revealed, which causes a pulse in the voltage signal that is proportional to the rotation of the slotted disk. The time history of the voltage change can then be calibrated to allow the determination of the change in position of the body under investigation. This signal can be differentiated to calculate the velocity and acceleration of the body.

An issue with the use of position transducers for analyzing movements is that the output does not allow for the calculation of the kinematic variables along the specific axes of motion. For example, it is not apparent how much the horizontal motion of the barbell contributes to the output obtained during weightlifting movements. Some commercially available position transducers do record the angle of the cable during the movement, allowing for the determination of the motion along the different axes (Harris et al., 2010), while the use of multiple position transducers will also allow for the calculation of extraneous motion during the movement (Cormie, Deane, & McBride, 2007).

Applied Research 1.4

The use of multiple LPTs increases the accuracy of kinematic data obtained during resistance movements

The authors recorded kinematic and kinetic data during jump squats performed with loads equivalent to 30% and 90% of each participant's one-repetition maximum back squat. The jump squats were performed with different combinations of linear position transducers (LPTs) attached to the barbell, with a single LPT attached to the barbell, or with two LPTs arranged in a triangular formation with the barbell. The use of two LPTs allowed the vertical motion of the barbell to be separated from the horizontal motion during the movement. The authors reported that the peak vertical velocity obtained from the double-LPT arrangement tended to be lower than that obtained from the single LPT during both jumping conditions. This finding was due to the horizontal motion during the movement being unaccounted for with the single-LPT arrangement. The authors concluded that the use of a single LPT is more convenient, although the practitioner should be aware of the overestimation in the kinematic variables obtained during movements that may involve significant horizontal motion.

Cormie, P., Deane, R., & McBride, J. M. (2007). Methodological concerns for determining power output in the jump squat. *Journal of Strength and Conditioning Research, 21*, 424–430.

are provided upon completion of the movement with no need for further calculations. The high sampling frequencies associated with the devices makes them useful for the analysis of kinematic variables during fast movements (e.g., vertical jumps, resistance exercises), and the kinematic data obtained have been shown to be reliable (Hori et al., 2007). However, extraneous movements during the execution of the exercise being performed can compromise the validity of the data obtained, necessitating the use of multiple LPTs for accurate measurements (Cormie et al., 2007; see Applied Research 1.4).

Accelerometers

Accelerometers are devices that are able to detect the acceleration of a body under investigation (see Mechanical Concept 1.6). Accelerometers are small devices that can be attached to an athlete or to an object being manipulated by an athlete (e.g., a barbell)

Mechanical Concept 1.6

Accelerometer technology

An accelerometer is a device that converts a mechanical signal (an acceleration) into an electrical signal (a voltage). This electromechanical effect is achieved by either piezoelectric or capacitance sensors within the device. Piezoelectric accelerometers contain crystal structures (quartz or ceramics) that are deformed as the result of an acceleration, creating a voltage that is recorded. The magnitude of the voltage provides information about the magnitude of the acceleration, while the orientation of the crystal structures allows the direction of the acceleration to be determined. Capacitance accelerometers rely on the change in capacitance of a sensing element (typically silicon) that is converted to a voltage to determine the applied acceleration. Integration of the acceleration data allow the determination of the velocity and displacement of the body under investigation.

(continues)

(continued)

Commercially available accelerometers are calibrated to different axes, with uni-, bi-, or triaxial devices available. However, these axes are orientated to the casing of the device to provide a frame of reference, necessitating the correct orientation of the accelerometer when attaching it to the body under investigation. The inclusion of gyroscopes and magnetometers allow accelerometers to be fixed within a global reference frame, easing the interpretation of the data obtained. Furthermore, the high acceleration amplitudes and sampling frequencies associated with the latest commercially available accelerometers enhance the event detection capabilities of these devices.

without interfering with the movement (Figure 1.8). The high sampling frequencies associated with commercially available devices allow instantaneous acceleration to be estimated, and the signal can be integrated to provide velocity and position data for the movement. Furthermore, accelerometers are portable and the data obtained from accelerometers have been shown to be both valid and reliable (Requena et al., 2012; see Applied Research 1.5).

Motion-analysis systems

Motion-analysis systems use images collected from either video or opto-reflective cameras to provide kinematic data of movements (see Mechanical Concept 1.7). The images are then digitized either manually or automatically to provide the position of the body under analysis within the field of view. Two-dimensional (planar) kinematics are obtained when a single camera is used, while three-dimensional data require the use of a minimum of two cameras. The video-based motion-analysis systems are typically limited to two-dimensional analyses, requiring consideration of the plane in

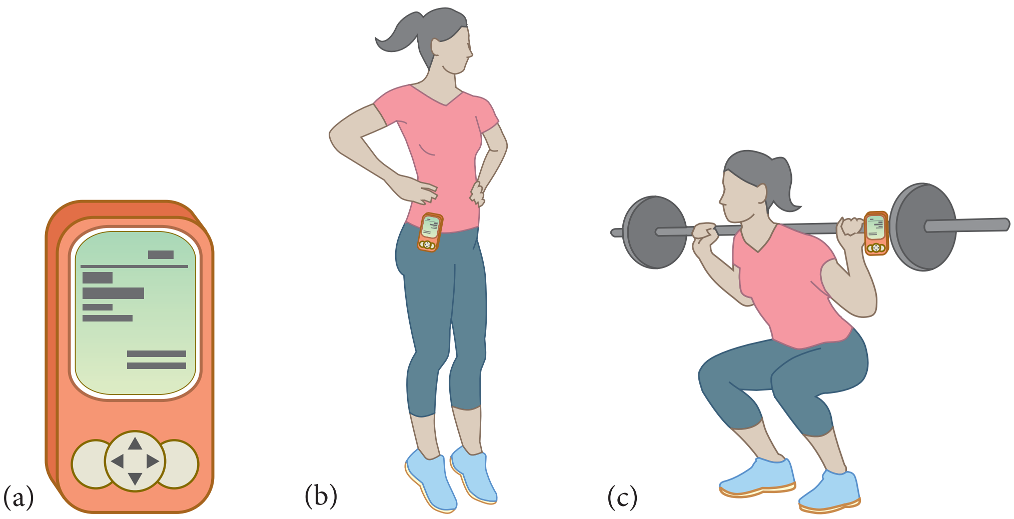

Figure 1.8 (a) An accelerometer used to assess movements. (b) An accelerometer attached to an athlete during a vertical jump test. (c) An accelerometer attached to the barbell during a resistance exercise.

Applied Research 1.5

Recording the kinematics of a vertical jump with an accelerometer

The authors assessed the validity of the data obtained from an accelerometer during a vertical jump by comparing it with that obtained from a high-speed video camera and a linear position transducer. A triaxial accelerometer containing gyroscopes and a magnetometer was placed on the lumbar region of each participant's back during a series of vertical jumps to approximate the location of the center of mass. The acceleration data were sampled at 1,000 Hz and was integrated to provide the vertical velocity of the participant during each jump. The flight time was determined from the acceleration trace at the time when the vertical acceleration was equal to or less than the gravitational acceleration. Each jump was simultaneously videoed with a high-speed digital camera (1,000 frames/s) to provide flight time data, and the cable of a position transducer was attached to a belt worn by the participants to provide velocity data. The authors reported no difference in the flight time obtained from the accelerometer compared to that obtained from the high-speed camera, while the takeoff velocity obtained from the accelerometer was comparable to that obtained from the position transducer. The kinematic data derived from the accelerometer were also found to have acceptable reliability. The authors concluded that an accelerometer attached to the lumbar region of an athlete can be used to obtain valid and reliable kinematic data during a vertical jump.

Requena, B., Requena, F., Garcia, I., Saez-Saez de Villareal, E., & Pääsuke, M. (2012). Reliability and validity of a wireless microelectromechanical-based system (Keimove™) for measuring vertical jumping performance. *Journal of Sports Science and Medicine, 11*, 115–122.

which to view the movement, while the accuracy of the data obtained from the analysis can be limited by the sampling frequency of the video cameras used (Figure 1.9). Both the linear and angular position of the body under analysis can be obtained from motion analysis data, while differentiating the signal allows other kinematic variables

Figure 1.9 The effects of different sampling frequencies in the motion analysis of a soccer kick using a two-dimensional video-based motion analysis system. (a) At a sampling frequency of 50 Hz, foot–ball contact can be observed in only one frame. (b) At a sampling frequency of 250 Hz, foot–ball contact is observed in four frames. (c) At a sampling frequency of 1000 Hz, foot–ball contact is observed in many frames.

Reproduced from Payton, C. J. (2008). Motion analysis using video. In C. J. Payton & R. M. Bartlett (Eds.), *Biomechanical Evaluation of Movement in Sport and Exercise. The British Association of Sport and Exercise Sciences Guidelines* (pp. 8–32). New York, NY: Routledge.

Mechanical Concept 1.7

Opto-reflective motion-analysis systems

Opto-reflective motion-analysis systems provide optical representation of the body under investigation, which is identified via the placement of reflective markers on the body (Figure 1.10). The markers reflect infrared radiation emitted by LED arrays mounted on each camera. The cameras are then able to

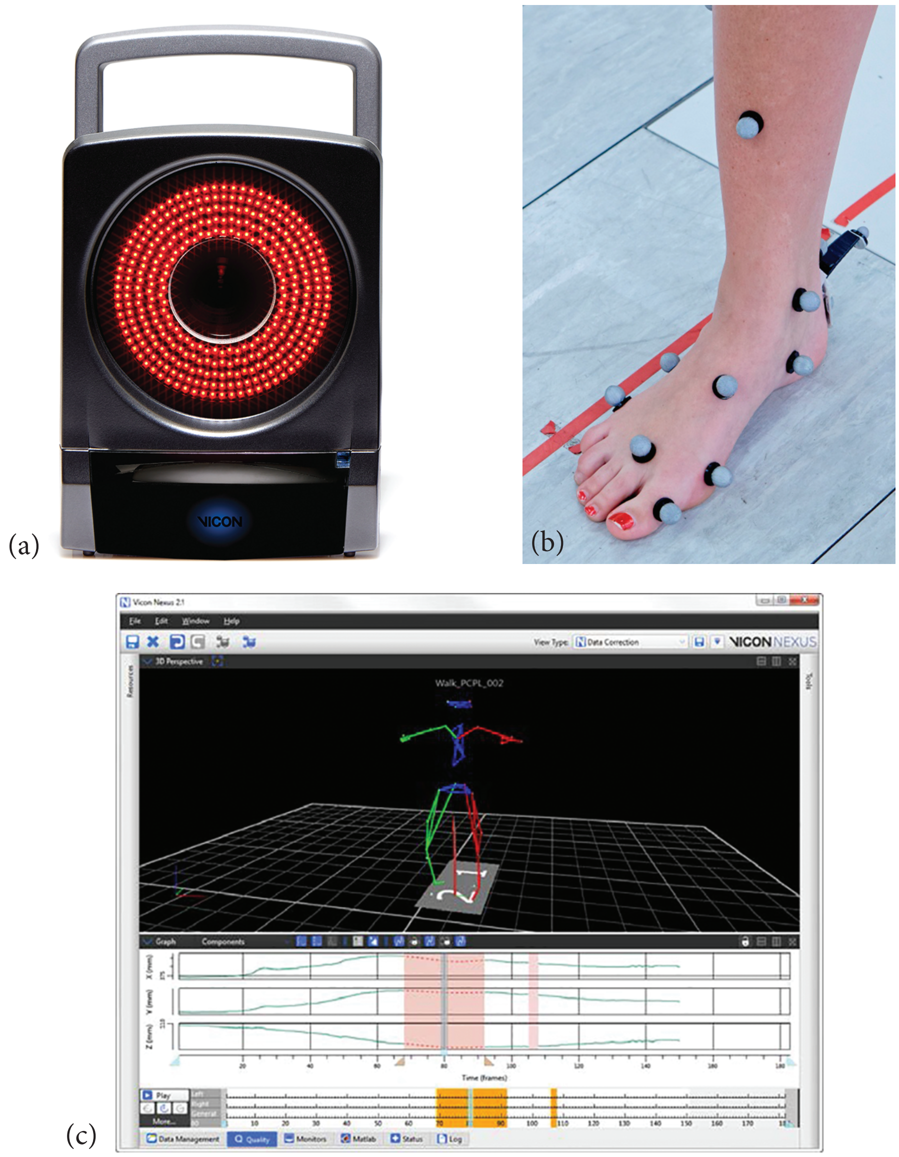

Figure 1.10 (a) An opto-reflective camera with an LED array. (b) Reflective markers placed on anatomical landmarks to allow the body segments to be located within three-dimensional space. (c) The digital output obtained from a three-dimensional opto-reflective motion analysis system.

Photos courtesy of Vicon Motion Systems Ltd.

locate the reflective markers within their field of view, allowing the position of the body under investigation to be determined in two- or three-dimensional space.

The number of reflective markers used depends upon the analysis being performed, but a full-body analysis can require more than 40 markers, increasing the preparation time when these systems are used. Each reflective marker should be viewed by a minimum of two cameras to allow the position within three-dimensional space to be obtained, requiring the use of multiple cameras to reconstruct the marker sets associated with the motion of body segments during most movements. Typically, opto-reflective motion-analysis systems use six to eight cameras placed around the calibrated volume in which the movements will be performed (Milner, 2008). High sampling frequencies can be achieved with opto-reflective motion-analysis systems, with frequencies as high as 10,000 Hz for commercially available systems. However, the spatial resolution of the cameras is severely reduced at these high frequencies.

to be calculated. However, the higher derivatives (e.g., velocity) obtained from commercially available, video-based motion-analysis systems are less reliable than those obtained from opto-reflective systems due to the limited signal processing capabilities of the software (Melton, Mullineaux, Mattacola, Mair, & Uhl, 2011). Furthermore, the errors associated with kinematic data obtained from video-based motion-analysis systems tend to be greater than those obtained from opto-reflective systems (Elliott, Alderson, & Denver, 2007; see Applied Research 1.6).

Applied Research 1.6

Recording angular kinematics of athletes

Motion-analysis systems are used in mechanical analyses to determine the kinematics of a specific movement. There are two broad categories of motion-analysis systems. Video-based systems use video footage of the movement recorded from a digital video camera. The video data are then digitized to determine the relative position of the body segments. Opto-reflective systems use infrared light reflected back by reflective markers that are placed on specific anatomical landmarks to automatically determine the relative position of the body segments. These authors compared the accuracy of a video-based system with an opto-reflective system in determining joint angles during specific movements made by a mechanical arm. The use of a mechanical arm allowed the determination of the actual joint angles to which those derived from the motion-analysis systems were compared. It was found that the opto-reflective system produced the lowest error in the measured joint angle (0.6°), although the error associated with the video-based system was relatively small (2.3°). The authors concluded that motion-analysis systems can be used to accurately record the angular kinematics associated with movements.

Elliott, B. C., Alderson, J. A., & Denver, E. R. (2007). System and modeling errors in motion analysis: implications for the measurement of elbow angle in cricket bowling. *Journal of Biomechanics, 40*, 2679–2686.

Chapter Summary

Any mechanical analysis of human movement requires the selection of an appropriate reference frame to allow the description of the position of the body under investigation; the specific reference frame should be identified prior to any biomechanical analysis. The body being analyzed is often reduced to its CM, defined as the virtual point about which all of the mass of the body is evenly distributed. There are two forms of motion, with linear motion referring to that along a straight or curved path and angular motion referring to the rotation of the body about a fixed axis. All human movements involve both types of motion. The kinematic variables of position, velocity, and acceleration allow the motion of the body to be described. The position of the body defines its location within the specified reference frame; the velocity of the body describes the rate at which the body is changing position; acceleration describes the rate at which the body is changing velocity. The equations of motion define the relationships between these kinematic variables, allowing the practitioner to determine the outcome of movements given knowledge of the initial kinematic conditions of the body. There are different technologies available to the strength and conditioning practitioner that allow them to record both linear and angular kinematic variables, including photocells, GPS, LPTs, accelerometers, and motion-analysis systems. Each of these technologies has benefits and costs associated with its use.

Review Questions and Projects

1. Describe the three-dimensional reference frame used to describe linear motion of a system under analysis, and explain the importance of the different axes when analyzing movements.
2. An athlete runs a 40-yard sprint in 5.05 s. Calculate the average velocity (speed) during the event.
3. Explain why the average speed calculated in Question 2 has limited value for the strength and conditioning practitioner when attempting to develop an effective training program.
4. Explain how you would modify the measurement of the time during the 40-yard sprint to provide more useful information for the strength and conditioning practitioner.
5. What mathematical method allows the estimation of instantaneous velocity from position–time data?
6. A strength and conditioning coach uses video footage to assess an athlete during a vertical jump and determines that the athlete's flight time was 0.58 s. Calculate the jump height for the athlete.
7. Explain why calculating jump height based upon the time in the air tends to overestimate jump height.
8. An athlete performs a vertical jump and produces a vertical velocity of 3.56 m/s at takeoff. Calculate the time taken for the athlete's center of mass to reach the apex of flight.

9. Calculate the vertical jump height for the athlete in Question 8.
10. Discuss the technology that the strength and conditioning practitioner can use to record takeoff velocity during a vertical jump.
11. An athlete performs a running long jump and has a velocity of 9 m/s at takeoff and a takeoff angle of 20°. Calculate the horizontal range traveled by the CM of the athlete during flight assuming that the height of landing is equal to the height of takeoff.
12. Discuss the technology that the strength and conditioning practitioner can use to record the takeoff velocity and the takeoff angle of the long jump athlete.
13. An athlete steps from a 0.30-m box during the performance of a drop jump. Calculate the athlete's vertical velocity upon landing.
14. The contact time associated with the performance of a drop jump provides information about the muscular strength of the athlete beyond the height attained during the jump. Discuss the technology that the strength and conditioning practitioner can use to record this kinematic variable.
15. An athlete performs a bench-throw resistance exercise and projects the barbell 0.45 m vertically from the point of release. Calculate the vertical velocity of the barbell at release.
16. Given the definition of CM and the kinematic factors affecting the horizontal range traveled by the CM during flight, explain how the posture adopted by an athlete at takeoff during a long-jump event influences his or her performance.
17. Explain why the fastest athletes are placed in lanes 4–6 during 200-m sprint events at track and field championships.
18. A strength and conditioning coach wishes to assess the kinematics associated with the athletes' performances during a soccer workout (e.g., distances covered, running velocities). Discuss the relative merits of the different technologies, including timing gates, GPS, and motion-analysis systems.
19. A strength and conditioning coach wishes to measure the vertical jump heights of a group of athletes. The coach has a contact mat, a linear position transducer, an accelerometer, and a motion-analysis system available. Discuss the relative merits of each of these technologies.
20. A strength and conditioning coach is interested in analyzing the angular displacement at the shoulder and elbow joints for an athlete during a bench press. Discuss the limitations associated with a two-dimensional video analysis for the movement.

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