CHAPTER 2

The Measurement of Motor Performance

Concept: The measurement of motor performance is critical to understanding motor learning.

After completing this chapter, you will be able to

- Describe the differences between and give examples of performance outcome measures and performance production measures
- Describe the differences among simple, choice, and discrimination RT situations
- Describe three measures for measuring performance outcome accuracy for skills that require discrete spatial and/or temporal accuracy in one and two dimensions and for continuous skills that require spatial and temporal accuracy
- Define three kinematic measures of motion and describe one way to calculate each measure for a specific movement
- Describe ways that EMG can be used to provide information about human movement
- Describe several techniques for measuring brain activity during the performance of a motor skill
- Describe how angle-angle diagrams provide useful information about the coordination characteristics of limbs or limb segments
- Describe two methods of quantifying the measurement of coordination during the performance of a motor skill

APPLICATION

Suppose that you are a physical educator teaching your students a tennis serve. What characteristic of performance will you measure to assess students' progress? Consider a few possibilities. You could count the number of serves that land in and out of the proper service court. Or you could mark the service court in some way so that the "better" serves, in terms of where they land, are scored higher than others. Or you could develop a measure that is concerned with the students' serving form.

Now imagine that you are a physical therapist helping a stroke patient learning to walk again. How will you measure your patient's progress to determine if what you are doing is beneficial to his or her rehabilitation? You have several possible walking characteristics to choose from. For example, you could count the number of steps made or the distance walked on each walking attempt; these measures could give you some general indicators of progress. If you wanted to know more about some specific walking-related characteristics, you could measure the balance and postural stability of the person as he or she walked.

Or you could assess the biomechanical progress the person was making by analyzing the kinematic characteristics of the movements of the legs, trunk, and arms. Each of these measurements can be valuable and will tell you something different about the person's walking performance.

In both of these performance assessment situations, your important concern as an educator or therapist is using a performance measure, or measures, to make as assessment. As a first step in addressing this problem, you must determine which aspects of performance you should measure to make a valid performance assessment. Then, you must determine how to measure those aspects of performance. The following discussion will help you to know how to accomplish this two-step measurement process by describing several different motor skill performance measures. Throughout this text, we will refer to the various measures introduced in this section, especially as researchers use these measures to investigate various concepts.

Application Problem to Solve Select a motor skill that you might help someone learn or relearn in your future profession. Which aspects of the person's performance of this skill should you measure to validly assess his or her performance capabilities and limitations? Describe the types of measures you would use to assess these aspects of the person's performance, and describe how these measures would help you determine what you would do to help this person.

DISCUSSION

There are a variety of ways to measure motor skill performance. A useful way to organize the many types of motor performance measures is by creating two categories related to different levels of performance observation. These categories map onto the different levels of analysis—actions, movements, and neuromotor processes—that were introduced in chapter 1. We will call the first category **performance outcome measures**. Included in this category are measures that *indicate the outcome or result of performing a motor skill.* For example, measures indicating how far a person walked, how fast a person ran a certain distance, and how many points a basketball player scored all tell us something about the outcome of the person's performance. Performance outcome measures provide us with information about the results of actions, where the major concern is whether or not the goal of the task was accomplished.

Notice that performance outcome measures do not tell us anything about the movements of the limbs, head, or body that led to the observed outcome. Nor do these measures provide any information about the activity of the nervous system and the various muscles involved in each action. To know something about these types of characteristics, we must use **performance production measures**. The measures in this category *tell us how the brain and body produced the outcome*. They tell us such things as how the nervous system is functioning, how the muscular system is operating, and how the limbs or joints are moving before, during, or after a person performs a skill. Performance production measures provide information that is relevant to the movement and neuromotor processes levels of analysis.

Although additional categories of performance measures could exist, these two represent the motor skill performance measures found in this text. Table 2.1 presents examples of these two categories of measures. For the remainder of this discussion, we will discuss several examples of some of the more common performance measures found in the motor learning and control research literature.

performance outcome measures a category of motor skill performance measures that indicates the outcome or result of performing a motor skill (e.g., how far a person walked, how fast a person ran a certain distance, how many points a basketball player scored).

performance production measures a category of motor skill performance measures that indicates how the nervous, muscular, and skeletal systems function during the performance of a motor skill (limb kinematics, force, EEG, EMG, etc.).

TABLE 2.1 Two Categories of Motor Skill Performance Measures

Category	Examples of Measures or Measurement Device	Performance Examples
1. Performance outcome measures	Time to complete a task, e.g., sec, min, hr	Amount of time to run a mile or type a word
	Reaction time (RT), e.g., sec, msec	Time between starter's gun and beginning of movement
	Amount of error in performing criterion movement, e.g., AE, CE, VE	Number of cm away from the target in reproducing a criterion limb position
	Number or percentage of errors	Number of free throws missed
	Number of successful attempts	Number of times the beanbag hit the target
	Time on/off target	Number of seconds cursor in contact with target during a computer tracking task
	Time on/off balance	Number of seconds stood in stork stance
	Distance	Height of vertical jump
	Trials or repetitions to completion	Number of trials or repetitions it took until all responses are correct
2. Performance production measures	Displacement	Distance limb traveled while moving a cursor on a computer monitor to a target
	Velocity	Speed limb moved while moving a cursor on a computer monitor to a target
	Acceleration	Acceleration/deceleration pattern while moving a cursor on a computer monitor to a target
	Joint angle	Angle of each joint of arm at impact in hitting ball
	Joint torque	Net joint torque of the knee joint at takeoff on a vertical jump
	Electromyography (EMG)	Time at which the biceps initially fired during a rapid flexion movement
	Electroencephalogram (EEG)	Brain wave pattern while shooting an arrow in archery
	Positron-emitting topography (PET)	Brain areas active while typing on a computer keyboard
	Functional magnetic resonance imaging (fMRI)	Brain areas active while finger tapping to a metronome

REACTION TIME

The common measure indicating how long it takes a person to prepare and initiate a movement is **reaction time (RT)**. Figure 2.1 shows that RT is the interval of time between the onset of a signal (stimulus) that indicates the required movement and the *initiation* of the movement. Note that RT does not include any movement related to a specific action, but only the time *before* movement begins.

The stimulus (or "go") signal is the indication to act. In laboratory or clinical settings, the signal can take one of a variety of forms, such as a light, a buzzer, a shock, a word on a screen, or a spoken word or sound. As such, the signal can relate to any

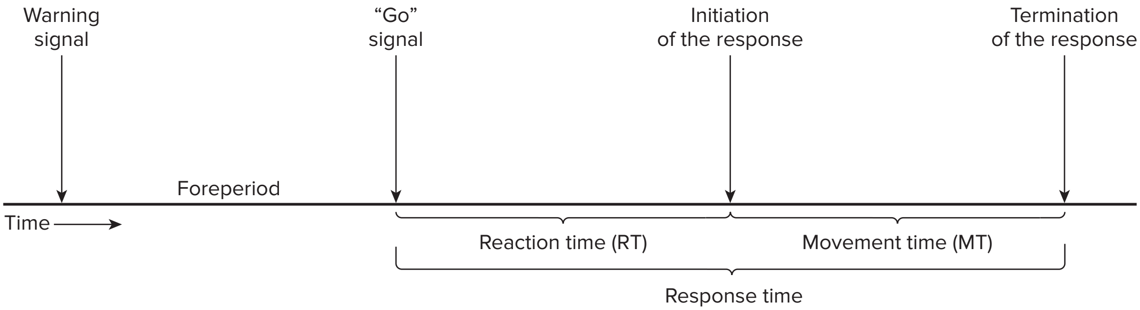

FIGURE 2.1 The events and time intervals related to the typical measurement of reaction time (RT) and movement time (MT).

sensory system—vision, hearing, or touch. The person can be required to perform any type of movement. For example, the person might be required to lift a finger off a telegraph key, depress a keyboard key, speak a word, kick a board, or walk a step. Finally, to assess optimal RT, some type of warning signal should be given prior to the stimulus signal.

The Use of RT as a Performance Measure

Reaction time has a long history as a popular measure of human motor skill performance. Although RT can be used as a performance measure to assess how quickly a person can initiate a required movement, researchers and practitioners also use it as a basis for inferring other characteristics related to performing a motor skill.[1] The most common is to identify the environmental context information a person may use while preparing to produce a required action, which will be the topic of discussion in chapter 8. For example, if one performance situation results in a longer RT than another situation, the researcher can determine what may have led to the different RT lengths, which then can tell us something about influences on the amount of time it takes us to prepare an action. In chapter 8 you will study several ways that researchers use RT as a performance measure to investigate how we prepare to perform a motor skill and the factors that influence this preparation.

[1]For an extensive review of the history and uses of RT, see an article by Meyer, Osman, Irwin, and Yantis (1988) that discusses the use of RT as a key measure of "mental chronometry," which investigates the time-based mental processes underlying human performance.

Another use of RT is to assess the capabilities of a person to anticipate a required action and determine when to initiate it. In a sport situation, a basketball coach may want to know how long it takes a point guard to recognize that the defender's actions indicate the guard should pass the ball rather than shoot it. When used in this way, RT provides information about decision making. Thus, in addition to indicating how fast a person responds to a signal, RT also provides a window for examining how a person interacts with the performance environment while preparing to produce a required action.

Relating RT to Movement Time and Response Time

In any situation in which a person must move in response to a signal, two additional performance measures can be assessed. You saw these measures in figure 2.1 as movement time (MT) and response time. **Movement time (MT)** begins when RT ends. It is the interval of time between the initiation and

reaction time (RT) the interval of time between the onset of a signal (stimulus) and the initiation of a response (e.g., the amount of time between the "go" signal for a swimming sprint race start and the swimmer's first observable movement).

movement time (MT) the interval of time between the initiation of a movement and the completion of the movement.

A CLOSER LOOK

Examples of the Use of RT and MT to Assess Skill Performance Problems in Decision-Making Situations

Sport Skill Example

An offensive lineman in football must perform his assignment as quickly as possible after the center snaps the ball. If the lineman is consistently slow in carrying out his assignment, the problem could be that he is not giving enough attention to the ball snap, he is not sure about his assignment, or he moves too slowly when carrying out his assignment. The first two problems relate to RT (the time between the ball snap and the beginning of the lineman's foot movement); the third relates to MT (the time between the beginning of foot movement and the completion of the assignment). By assessing both RT and MT in an actual situation, the coach could become more aware of the reason for the lineman's problem and begin working on helping the lineman improve that specific part of the problem.

Car Driving Example

Suppose you are helping a student in a driving simulator to reduce the amount of time he or she requires to stop the car when an object suddenly appears in the street. Separating RT and MT would let you know if the slow stopping time is related to a decision-making or a movement speed problem. If RT (the time between the appearance of the object and the person's foot release from the accelerator) increases across various situations, but MT (the time between the foot release from the accelerator and foot contact with the brake pedal) is constant, you know that the problem is primarily related to attention or decision making. But if RT remains relatively constant whereas MT changes across various situations, you know the problem is movement related. In either case, by measuring both RT and MT you can more specifically help the person to improve his or her performance in these situations.

the completion of a movement. **Response time** is the total time interval, involving both RT and MT.

An important characteristic of RT and MT is that they are relatively *independent* measures. This means that RT does not predict MT or vice versa. The independence of RT and MT as performance measures indicates that if one person in a group of people has the fastest RT in a performance situation, that person may not have the fastest MT in the group. Thus, RT and MT measure different aspects of human performance. You will learn more about the independence of these two performance measures in chapter 3.

Types of RT Situations

Figure 2.2 depicts three of the most common types of RT situations. For illustration purposes, this figure shows a light as the stimulus signal and lifting a finger from a computer keyboard key as the required movement. However, the three types of RT situations discussed here do not need to be limited to these characteristics.

When a situation involves only one signal and requires only one movement in response, the RT situation is known as **simple RT**. In the example presented in figure 2.2, the person must lift a finger from the keyboard key when a light comes on. Another type of RT situation is **choice RT**, where there is more than one signal to which the person must respond, and each signal has a specified response. The example in figure 2.2 indicates that the person must respond to the red light by lifting the index finger from a keyboard key, to the blue light by lifting the middle finger from a different key, and to the green light by lifting the ring finger from a third key. The third type of RT situation is **discrimination RT**, where there is also more than one signal, but only one response. In the figure 2.2 example, the person is required to lift his or her finger from the telegraph key only when the red light comes on. If the blue or green light is illuminated, the person should make no response.

Although these examples of simple, choice, and discrimination RT situations refer to laboratory conditions, these different types of RT situations also exist in everyday life and in sport environments. For example, a sprinter in track is involved in a *simple RT situation* when he or she starts a race. He or she hears a verbal warning signal from the starter, then

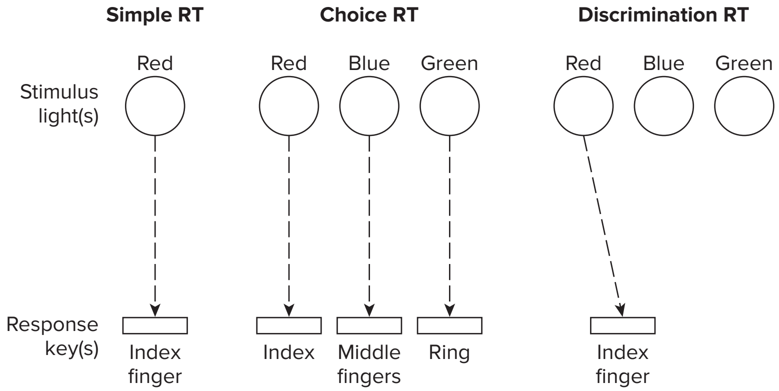

FIGURE 2.2 Three different types of reaction time (RT) test situations: simple RT, choice RT, and discrimination RT.

hears the gun sound, which is the signal to begin to run. *Choice RT situations* are more common in everyday activities, such as when driving a car you come to an intersection with a traffic signal that has three possible signals, each of which requires a different movement. If the light is red, you must depress the brake pedal and come to a complete stop. If the light is yellow, you need to prepare to stop. And if the signal is green, you can continue to keep the accelerator pedal depressed to move through the intersection. Softball hitters experience *discrimination RT situations* each time they face a pitch. They must discriminate which pitches will land within the strike zone and only swing at those pitches. They must inhibit any tendency to swing at pitches that will miss the strike zone. Each pitch represents a stimulus that needs to be discriminated in this example and each swing represents the response.

RT Interval Components

Through the use of electromyography (EMG), which will be discussed later in this chapter, to measure the beginning of muscle activity in an RT situation, a researcher can *fractionate* RT into two component parts. The EMG recording will indicate the time at which the muscle shows increased activity after the stimulus signal has occurred. However, there is a period of time between the onset of the stimulus signal and the beginning of the muscle activity. This "quiet" interval of time is the first component part of RT and is called the *premotor time*. The second component is the period of time from the increase in muscle activity until the actual beginning of observable limb movement. This RT component is called the *motor time*. You can see an illustration of how RT is fractionated in figure 2.3. In addition you can see some actual examples of fractionated RTs at the end of this chapter in figure 2.10, which presents examples of EMG recordings. The RT interval is shown along with EMG recordings for three muscle groups. Although not indicated in the figure, the premotor time for each EMG recording is the interval of time prior to the beginning of

response time the time interval involving both reaction time and movement time; that is, the time from the onset of a signal (stimulus) to the completion of a response.

simple RT the reaction time when the situation involves only one signal (stimulus) that requires only one response.

choice RT the reaction time when the situation involves more than one signal and each signal requires its own specified response.

discrimination RT the reaction time when the situation involves more than one signal but only one response, which is to only one of the signals; the other signals require no response.

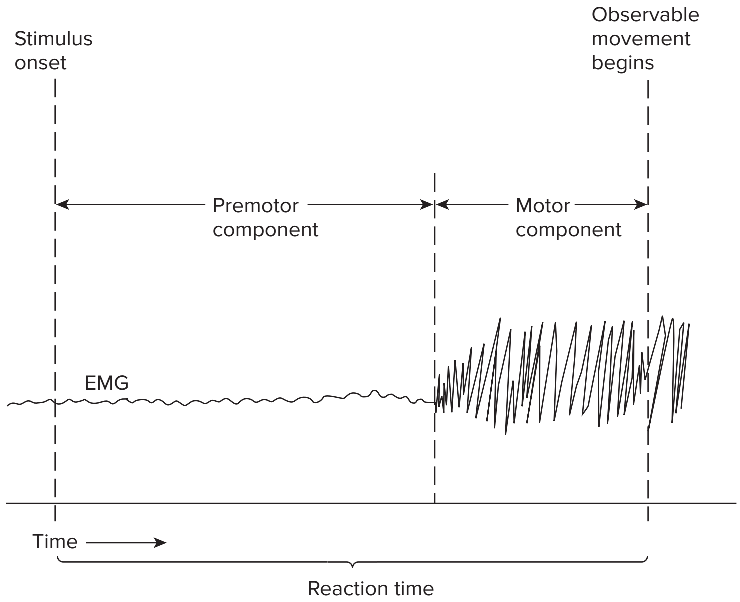

FIGURE 2.3 Schematization of fractionated reaction time indicating the relationship between the EMG signal activity and the premotor and motor components of the RT interval.

LAB LINKS

Lab 2 in the Online Learning Center Lab Manual for chapter 2 provides an opportunity for you to measure and compare RT and MT.

muscle activity; the motor time is the remainder of the RT interval in which muscle activity is recorded.

As you will see in chapter 8, by fractionating the RT interval into two parts, researchers interested in understanding the action preparation process are able to obtain more specific insights into what occurs as a person prepares to move. Most researchers agree that the premotor time is a measure of the receipt and transmission of information from the environment, through the nervous system, to the muscle itself. This time interval is commonly considered as an indicator of *perceptual and cognitive decision-making activity* in which the person engages while preparing an action. The motor time interval indicates that there is muscle activity before observable limb movement occurs. Researchers commonly agree that this activity indicates a time lag in the muscle that it needs in order to overcome the inertia of the limb after the muscle receives the command to contract.

ERROR MEASURES

The amount of error a person makes as a result of performing a skill has had a prominent place in human performance research and in everyday living activities and sport. *Accuracy* can involve either spatial accuracy, temporal accuracy, or both. *Spatial accuracy* refers to situations involving space dimensions, such as distance. *Temporal accuracy* refers to situations involving time dimensions. For both types of accuracy situations error measures allow us to evaluate performance for skills for which accuracy is the action goal. Skills as diverse as reaching to grasp a cup, throwing a dart at a target, walking along a prescribed path, and driving a car on a street require people to perform actions that demand spatial and/or temporal accuracy. To assess performance outcome for these types of skills, the amount of error a person makes in relation to the goal is an important and meaningful performance measure.

Error measures not only provide indicators of performance accuracy but certain types of error measures also tell us about possible causes of performance problems. This is especially true if performance is assessed for more than one repetition. For a series of repetitions (typical in a sport skill instruction or a rehabilitation setting), the instructor or therapist can determine whether the observed movement inaccuracy is due to problems associated with *consistency* or to those associated with *bias.* An inconsistent performance is one that varies from trial to trial. A biased performance is one that errs in a particular direction, for example it might tend to be too slow or short of the target on trial after trial. These important measures provide the practitioner with a basis for selecting the appropriate intervention to help the person overcome the inaccuracy. *Consistency problems* suggest the basic movement pattern needed to perform the skill has not been acquired, whereas *bias problems* indicate that the person has acquired the movement pattern but is having difficulties adapting to the specific demands of the performance situation. We will discuss the measurement of these characteristics, along with some motor skill performance examples, in the following section.

Assessing Error for One-Dimension Movement Goals

When a person must move a limb a specified amount in one dimension, as when a patient attempts to achieve a certain knee extension, the resulting spatial error will be a certain distance short of or past the goal. Similarly, if a pitcher in baseball is attempting to throw the ball at a certain rate of speed, the resulting temporal error will be either too slow or too fast in relation to the goal. Measuring the amount of error in these situations simply involves finding the difference between the performance value (e.g., 15 cm, 5°, 20 sec) and the target or goal amount. If a patient's goal were to extend the knee to 150 deg and she extended it to 130 deg her movement would be 20 deg too short ($130 - 150 = -20$), whereas if she extended it to 170 deg it would be 20 deg too long ($170 - 150 = +20$).

We can calculate at least *three error measures* to assess the general accuracy characteristics of performance over repeated performances, and to infer possible causes of the accuracy problems. To obtain a general indicator of how successfully the goal was achieved, we calculate **absolute error (AE)**. AE is *the absolute difference between the actual performance on each repetition and the goal.* For multiple-repetition situations, summing these differences and dividing by the number of repetitions will give you the average absolute error for the repetitions. AE provides useful information about the *magnitude of error* a person has made on a repetition or over a series of repetitions. This score gives you *a general index of accuracy* for the session for this person. But evaluating performance solely on the basis of AE hides important information about the source of the inaccurate performance. To obtain this information, we need two additional error measures.

One reason a person's performance may be inaccurate is that the person has a tendency to over-shoot or to undershoot the goal, which is referred to as *performance bias.* To obtain this information, we must calculate **constant error (CE)**, which is the signed (+/−) deviation from the goal. When calculated over a series of repetitions, CE provides a meaningful *index of the person's tendency to be directionally biased* when performing the skill. Calculating CE involves making the same calculations used to determine AE, except that the algebraic signs are used for each repetition's performance. Note that we can calculate AE and CE for a single repetition but we typically average AE and CE over several trials.

Another reason for performance inaccuracy for a series of repetitions is *performance consistency* (or, conversely, variability), which is measured by calculating **variable error (VE)**—a measure that is very similar to the *standard deviation of the person's CE scores for the series of repetitions.* The standard deviation tells you how far on average each score for each repetition is from the CE.

absolute error (AE) the unsigned deviation from the target or criterion, representing amount of error. A measure of the magnitude of an error without regard to the direction of the deviation.

constant error (CE) the signed (+/−) deviation from the target or criterion; it represents amount and direction of error and serves as a measure of performance bias.

variable error (VE) an error score representing the variability (or conversely, the consistency) of performance.

Assessing Error for Two-Dimension Movement Goals

When the outcome of performing a skill requires accuracy in the vertical and horizontal directions, the person assessing error must make modifications to the one-dimension assessment method. The general accuracy measure for the two-dimension situation is called *radial error (RE),* which is similar to AE in the one-dimension case. To calculate RE for one repetition, calculate the hypotenuse of the right-angle triangle formed by the intersection of the X-axis (extended horizontally from the center of the target) and the Y-axis (extended vertically from the center of the location of the performance result). This calculation involves the following steps:

- Measure the length of the error in the horizontal direction (i.e., X-axis); square this value.
- Measure the length of the error in the vertical direction (i.e., Y-axis); square this value.
- Add the squared X-axis and Y-axis error values; take the square root of the total.

An example of the calculation of RE is shown in figure 2.4. To determine the average RE for a series of repetitions, simply calculate the mean of the total RE for the series.

Performance bias and consistency are more difficult to assess for the two-dimension case than in one dimension, because the algebraic signs + and – have little meaning for the two-dimension case. Hancock, Butler, and Fischman (1995) presented a detailed description of calculating measures of bias and consistency in the two-dimension situation. Rather than go into the details of this calculation, which is commonly used only in motor learning and control research, we will consider a general approach to the problem here. For a series of repetitions, a researcher or practitioner can obtain a *qualitative assessment of bias and consistency* by looking at the actual grouping of the locations. For example, if two golfers each putt six balls at a hole on a practice green, from the same location, and the results are as shown in figure 2.5, a quick assessment of the grouping of each golfer's putts reveals that the golfers have specific but different problems to overcome to improve their putting performance. Although both golfers holed one putt, Golfer A scattered the other five balls around the hole, which indicates a movement *consistency problem,* while Golfer B grouped the other five balls to the right of the hole, which indicates a movement *bias problem.* As for the one-dimension situation, the practical benefit of assessing these characteristics is that the strategies used to improve performance would differ for the bias and the consistency cases.

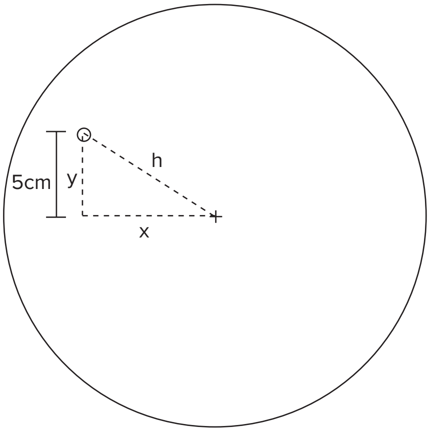

FIGURE 2.4 An example of measuring radial error (RE) to assess performance accuracy. The performance situation involves a person throwing a dart at a circular target. The goal of the throw is to hit the center of the target (represented by the +). The throw hit the location indicated by the O. RE is the hypotenuse (h) of the right-angle triangle formed by the intersection of the X-axis and Y-axis. The following example of X-axis and Y-axis distances associated with this location demonstrates the calculation of RE for this throw.

X-axis distance = 10 cm → $10^2 =$ 100
Y-axis distance = 5 cm → $5^2 =$ 25
Sum = 125
RE = $\sqrt{125} = 11.2$ cm

Assessing Error for Continuous Skills

The error measures described in the preceding two sections are based on accuracy goals for discrete skills. Some continuous motor skills also require accuracy. For example, when a person must walk along a specified pathway, performance assessment can include measuring how well the person stayed on the pathway. Or if a person is in a car simulator and must steer the car along the road as projected on

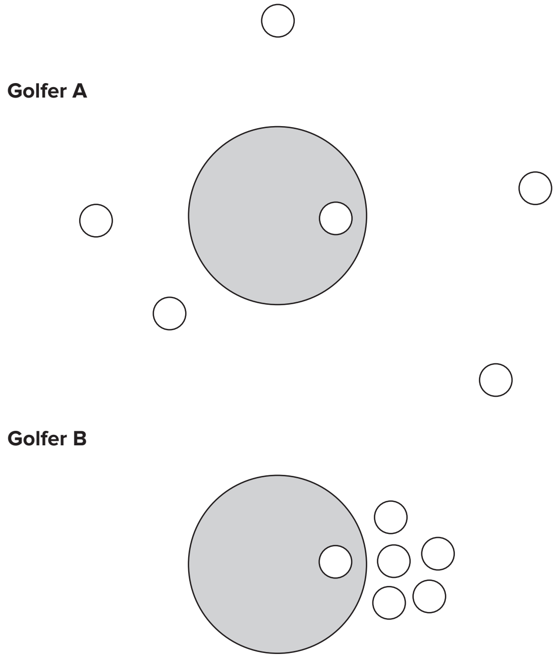

FIGURE 2.5 A golf putting example of a qualitative assessment of two-dimension performance outcome error. Golfers A and B putt six balls at a hole on the putting green. The grouping of the six putts by Golfer A shows a high degree of performance variability, while Golfer B shows a strong performance bias (i.e., tendency) for putting to the right of the hole.

a screen, a measure of performance can be based on how well the person kept the car on the road. Error measures for these types of skills must be different from those used to assess discrete skill performance.

A commonly used error score for continuous skills is the **root-mean-squared error (RMSE)**, which you can think of as AE for a continuous task. To understand how this error measure is determined and used, consider the following example taken from performing a continuous skill known as *pursuit tracking*. To perform this skill, subjects move a joystick, steering wheel, or lever to make an object, such as a cursor, follow a specified pathway. The specified pathway can be described kinematically as a displacement curve. Figure 2.6 provides an example. The displacement curve represents the subject's tracking performance. To determine how accurately

root-mean-squared error (RMSE) an error measure used for continuous skills to indicate the amount of error between the performance curve produced and the criterion performance curve for a specific amount of time during which performance is sampled.

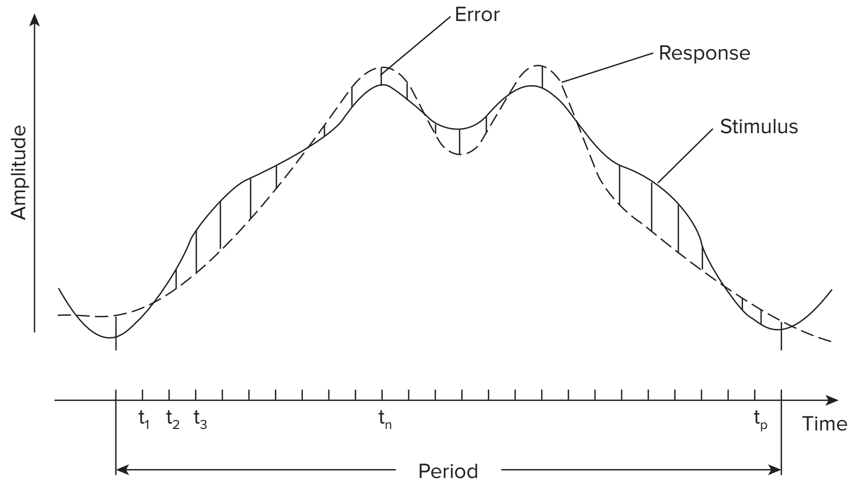

FIGURE 2.6 The difference between the subject's response and the stimulus at each specified time interval is used to calculate one root-mean-squared error (RMSE) score. *Source:* From Franks, I. M. et al. (1982). The generation of movement patterns during the acquisition of a pursuit tracking task. *Human Movement Science, 1,* 251–272.