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

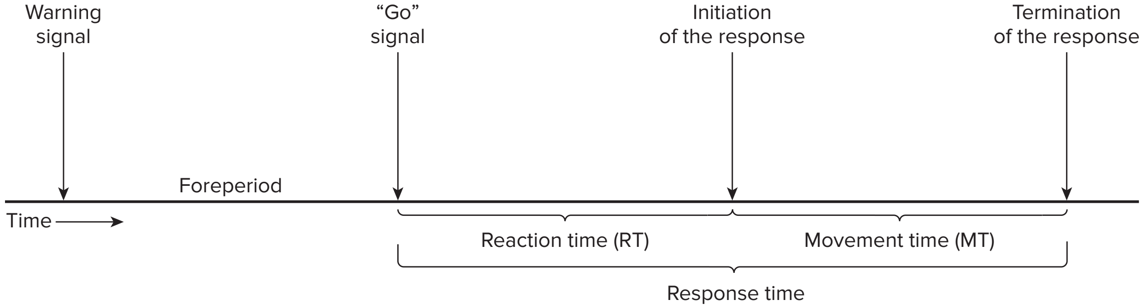


FIGURE 2.1 The events and time intervals related to the typical measurement of reaction time (RT) and movement time (MT).

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

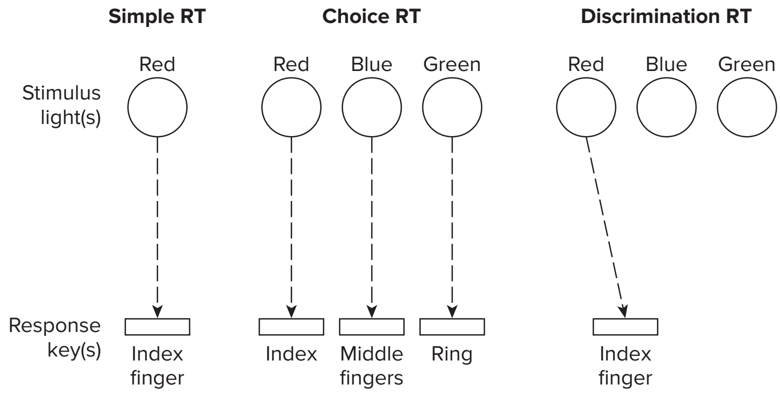


FIGURE 2.2 Three different types of reaction time (RT) test situations: simple RT, choice RT, and discrimination RT.

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.

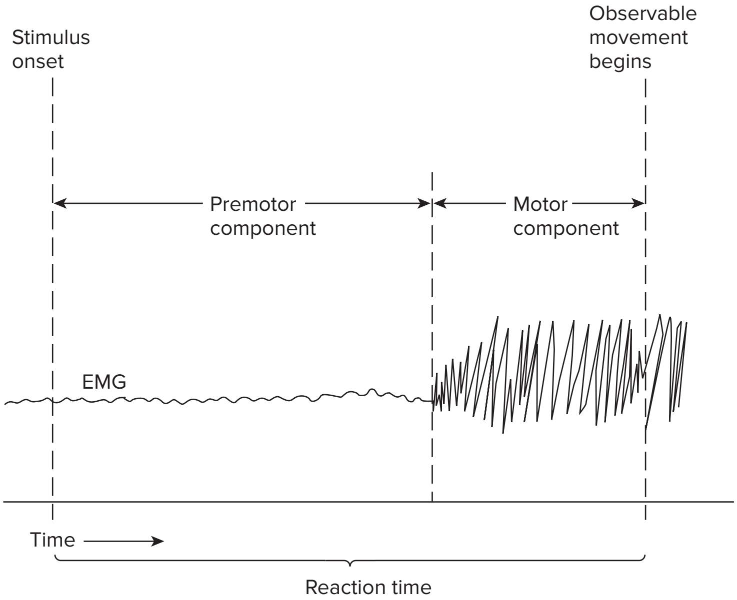


FIGURE 2.3 Schematization of fractionated reaction time indicating the relationship between the EMG signal activity and the premotor and motor components of the RT interval.

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.

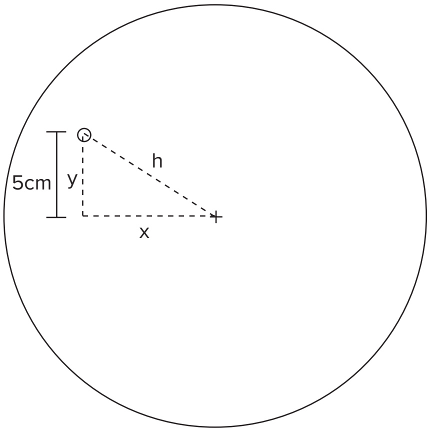


FIGURE 2.4 An example of measuring radial error (RE) to assess performance accuracy. The performance situation involves a person throwing a dart at a circular target. The goal of the throw is to hit the center of the target (represented by the +). The throw hit the location indicated by the O. RE is 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.

$$\begin{aligned} &\text{X-axis distance} = 10\text{ cm} \rightarrow 10^2 = 100 \\ &\text{Y-axis distance} = 5\text{ cm} \rightarrow 5^2 = \underline{\ \ 25} \\ &\text{Sum} = 125 \\ &\text{RE} = \sqrt{125} = 11.2\text{ cm} \end{aligned}$$

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

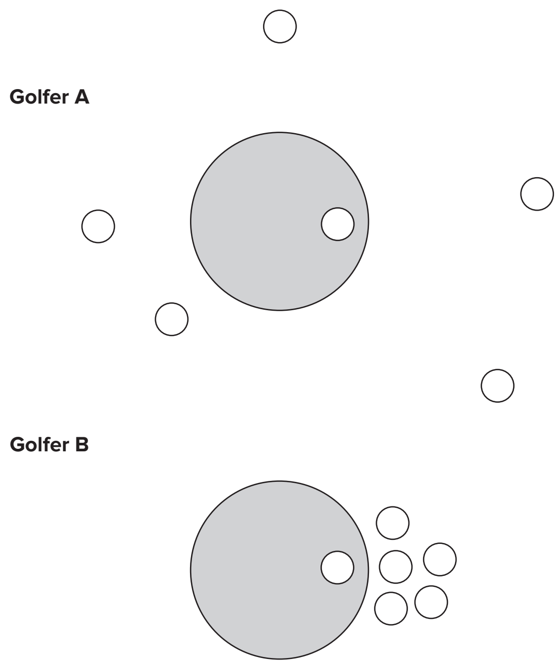


FIGURE 2.5 A golf putting example of a qualitative assessment of two-dimension performance outcome error. Golfers A and B putt six balls at a hole on the putting green. The grouping of the six putts by Golfer A shows a high degree of performance variability, while Golfer B shows a strong performance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

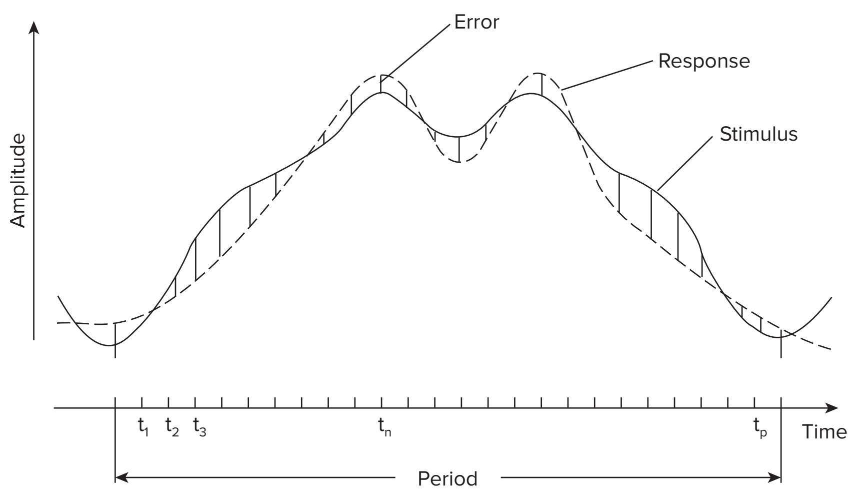


FIGURE 2.6 The difference between the subject's response and the stimulus at each specified time interval is used to calculate one root-mean-squared error (RMSE) score. *Source:* From Franks, I. M. et al. (1982). The generation of movement patterns during the acquisition of a pursuit tracking task. *Human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

A CLOSER LOOK

Calculating and Using Error Scores to Assess Accuracy, Bias, and Consistency for Gait

Suppose that you are a physical therapist working with Joe and Sam. You are working with them to maintain a consistent 50 cm stride length while walking. To determine the intervention approach each of them will need, you have both of them walk six strides on a runway. The following illustration shows their performance for each stride. The 50 cm distance targets for each stride are marked as vertical lines across the runway; the numbers represent the location of the foot placement on each stride by showing the direction (+ = too far; − = too short) and distance (cm) Joe and Sam missed the target stride length.

Note that both Joe and Sam have the *same AE,* but that

- Joe has a high negative CE but a low VE, which means that his 6 strides tend to be consistently short of the target stride length for his stride lengths.
- Sam has a low positive CE but a high VE, which means that his 6 strides are inconsistently long and short of the target stride length.

Discussion question: Based on the CE and VE differences, would the physical therapist have a more difficult rehabilitation problem ahead with Joe or Sam? Why?

Sam		+15 −12		+10 −12		+12	+5
Joe	−15	−12	−10	−12	−12	−5	

$$\text{Avg. AE} = \Sigma \left| x_i - T \right| / k$$

Where

x = score for repetition i
T = target score
k = number of repetitions

$$\text{Avg. CE} = \Sigma\,(x_i - T) / k$$

$$\text{VE} = \sqrt{\Sigma\,(x_i - Avg.\ CE)^2 / k}$$

Calculating the average AE, average CE, and VE:

	AE	AE	CE	CE
Stride No.	Joe	Sam	Joe	Sam
1	15	15	−15	15
2	12	12	−12	−12
3	10	10	−10	10
4	12	12	−12	−12
5	12	12	−12	12
6	5	5	−5	5
Total	66	66	−66	18
Avg	11	11	−11	3
VE			3.1	11.0

the subject tracked the specified pathway, we would calculate an RMSE score.

Calculate RMSE by determining the amount of error between the displacement curve produced by the subject's tracking performance and the displacement curve of the specified pathway (see figure 2.6). The actual calculation of RMSE is complex and requires a computer program that can sample and record the subject's movement in relation to the specified pathway at predefined points of time, such as 100 times each second (100 Hz; note that 1 Hz = 1 time/sec). At each of the 100 sampling points, the difference between the specified pathway location and the subject's movement location is calculated. This means that for the 100 Hz example, there are 100 error scores each second. If the specified pattern were 5 sec, there would be 500 error scores for the repetition. The computer then derives one score, RMSE, from these by calculating an average error score for the total pathway.

KINEMATIC MEASURES

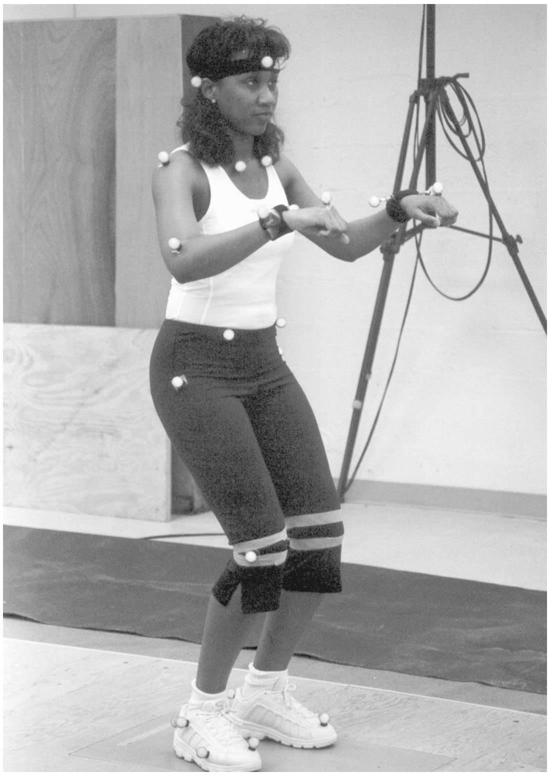
Kinematic measures, traditionally associated with biomechanics, have become important descriptors of performance in research on motor learning and control. The term **kinematics** refers to the description of motion without regard to force or mass. Three of the most common of such descriptors refer to an object's changes in spatial position, its speed, and its changes in speed. The terms used to refer to these kinematic characteristics are *displacement, velocity,* and *acceleration.*

Kinematic measures are performance production measures that are based on recording the movement of specific body segments while a person is performing a skill using a procedure commonly known as *motion capture*. This procedure involves first marking the joints associated with the body segments of interest in a distinctive way with tape, a marking pen, special light-reflecting balls, or light-emitting diodes (LEDs). The researcher then records the person's performance of the skill on videotape or by using special cameras. Computer software developed to calculate kinematic measures then analyzes the recordings. This approach is used in commercially available movement analysis systems. Other tools, like goniometers that directly measure joint angles and accelerometers that directly measure the acceleration of the whole body or a body part, are also available for recording kinematic measures.

Another way to obtain kinematic measures is to record the person's movement of an object, which was the case for the pursuit tracking task described earlier and depicted in figure 2.6. Here, a computer samples (i.e., detects at a specified rate per second) and records the movements of the tracking device. In this example, a horizontal lever on a tabletop was the movement device. A potentiometer attached to the axle of the lever provided movement-related information that the computer sampled. Similar samplings of movement can be taken from the movement of a joystick, a mouse, or a rollerball.

Displacement

The first kinematic measure of interest is **displacement**, which is *the change in the spatial position of a limb or joint during a movement.* Displacement describes changes in spatial locations as a person carries out a movement. We calculate displacement by using a movement analysis system to identify where the movement device or marked joint is in space (in terms of its X-Y coordinate in two-dimensional analysis or its X-Y-Z coordinate in three-dimensional analysis) at a given time. The system then determines the location of that joint for the next sampled time. The analysis system samples these spatial positions at specific rates,



This participant in a research study has reflective markers attached to various joints and body and head locations for kinematic movements analysis purposes.

Richard A. Magill, Ph.D

kinematics the description of motion without regard to force or mass; it includes displacement, velocity, and acceleration.

displacement a kinematic measure describing changes in the spatial positions of a limb or joint during a movement.

which vary according to the analysis system used. For example, a common videotape sampling rate is 60 Hz, which means the spatial position is detected and recorded 60 times each second. Faster sampling rates are possible, depending on the analysis system used. Thus, the spatial location of a movement device or limb can be plotted for each sampled time as a displacement curve. You can see an example in figure 2.7 in which the displacement of the wrist joint is portrayed at various times throughout the throwing of a dart.

Velocity

The second kinematic measure of interest is **velocity**, which is a time-based derivative of displacement. *Velocity,* which we typically call speed in everyday terms, refers to *the rate of change in an object's position with respect to time.* That is, how rapidly did this change in position occur and in what direction was this change (positive and negative signs are often used to specify direction)? Movement analysis systems derive velocity from displacement by dividing it by time. That is, divide a change in spatial position (between time 1 and time 2) by the change in time (from time 1 to time 2). Velocity is always presented on a graph as a position-by-time curve (see figure 2.7, in which the velocity curve is based on the same movement as the displacement curve). We refer to velocity in terms of an amount of displacement per an amount of time. The dart-throwing example in figure 2.7 shows the wrist's velocity as the number of degrees it moves per second. Zero velocity indicates the position of the wrist is not changing during the time period sampled. Positive values mean the wrist is moving in one direction and negative values mean it is moving in the opposite direction.

Acceleration

The third kinematic measure is **acceleration**, which describes *change in velocity during movement.* We derive acceleration from velocity by dividing change in velocity by change in time. We also depict acceleration curves as a function of time, as you can see in the acceleration graph in figure 2.7, which is based on the displacement and velocity graphs also in that figure. The acceleration curve depicts the speeding up and slowing down of the wrist's movements as the arm moves. The positive and negative signs mean that the accelerations are happening in opposite directions, that is, accelerating versus decelerating. Rapid acceleration means that a velocity change occurred quickly.

Linear and Angular Motion

In kinematic descriptions of movement, the measures of displacement, velocity, and acceleration can refer to either linear or angular motion. The distinction between these types of motion is important to understand and is a critical distinction in the analysis of movement. *Linear motion* refers to motion in a straight line and involves all the body or object moving the same distance over the same amount of time. *Angular motion,* which is sometimes called *rotary motion,* refers to motion that occurs about an axis of rotation and involves specific body segments as they rotate about joints, which are the axes of rotation for body segment movement. For example, if you want to describe the kinematics of walking, linear motion descriptions are appropriate for movement from one location to another because the whole body is moving linearly. However, if you want to describe the foot movement characteristics during walking, angular motion descriptions are more appropriate because the foot rotates about the ankle joint during walking.

A common way researchers describe angular motion is by measuring the motion of a limb segment as it rotates about a joint while a movement is occurring. Two examples are shown in figure 2.8. The top part of this figure shows an angle-angle diagram for a skilled runner. According to Enoka (2008), because we move by rotating body segments about each other, *angle-angle diagrams* provide an insightful means of examining movement by looking at the relationship between two joints during a movement. The angle-angle diagram usually plots the angle between two adjacent body segments against the angle of one body segment.

In figure 2.8, the angular displacement of the knee joint is compared to that of the thigh during the four discrete events of a running stride: takeoff, opposite footstrike, opposite foot takeoff, and opposite footstrike. Note that this angle-angle diagram produces a heart-shaped pattern, which is the classic knee-thigh

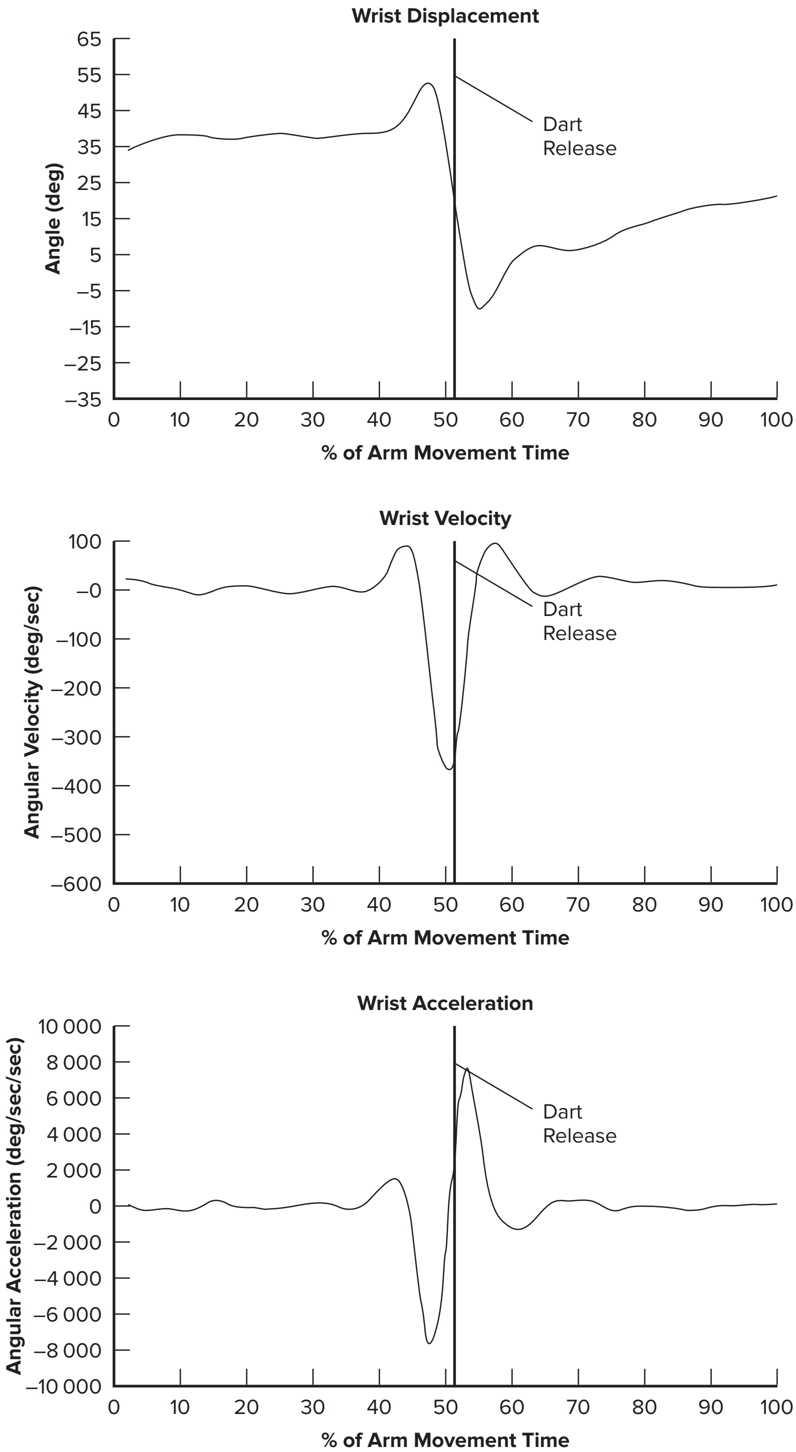


FIGURE 2.7 Recordings of displacement, velocity, and acceleration of the wrist joint during the performance of a dart throw. The X-axis in each graph is the percentage of the total movement time of the arm movement for the dart throw. The vertical line in each graph indicates the release of the dart, which occurred at approximately 51% of the total movement time of the arm movement. *Source:* Data from one participant in an experiment that was part of Jeansonne, J. J. (2003). *The effect of environmental context on performance outcomes and movement coordination changes during learning of complex motor skill*. Ph.D. dissertation, Louisiana State University.

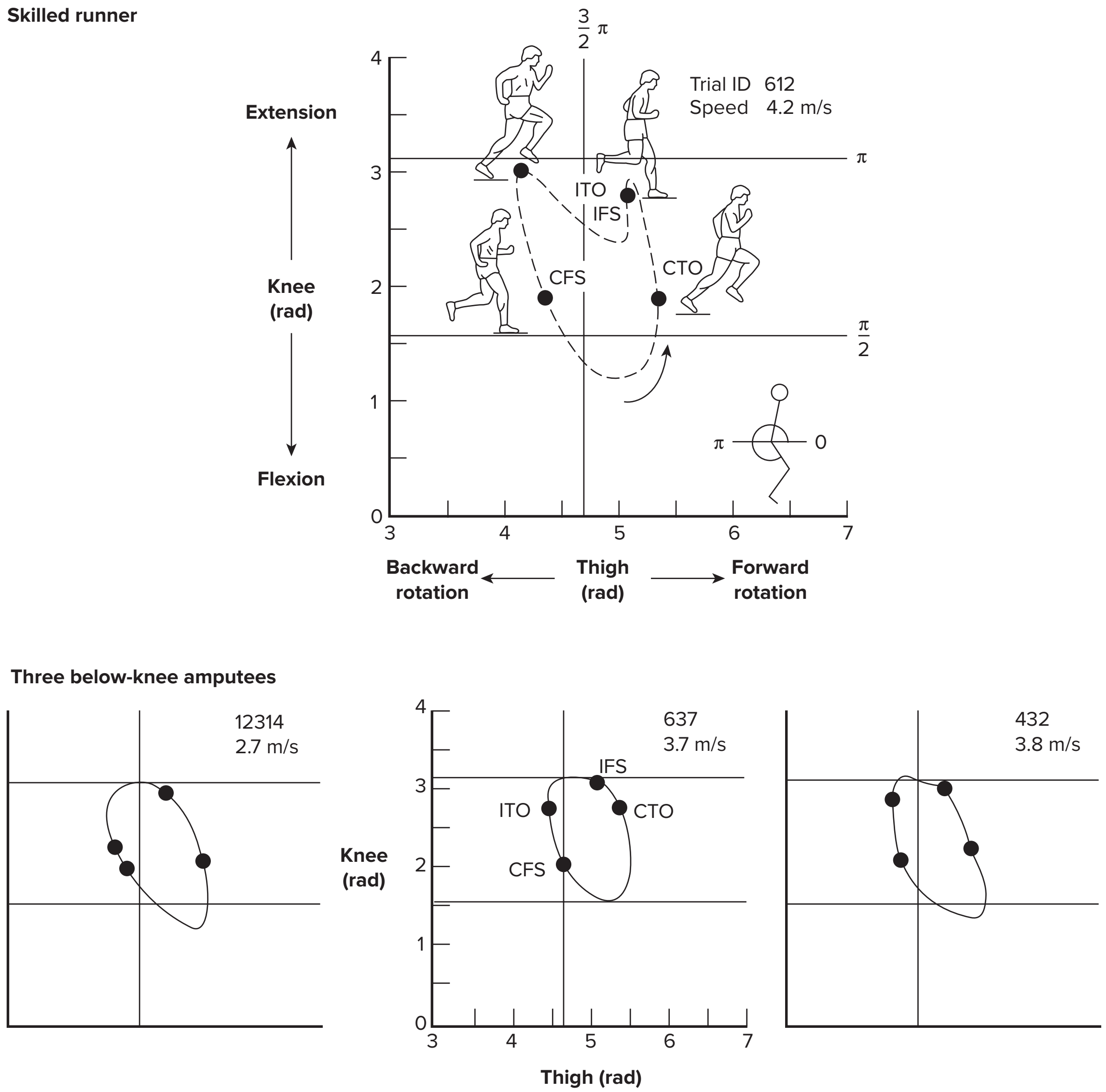


FIGURE 2.8 Angle-angle diagrams showing knee-thigh relationships during running by a skilled runner (top) and three below-knee amputees (bottom). The abbreviations indicate ipsilateral (left) footstrike (IFS), ipsilateral takeoff (ITO), contralateral (right) footstrike (CFS), and contralateral takeoff (CTO), which are the four components of a running stride. *Source:* From Enoka, R. M., et al. (1978). Below knee amputee running gait. *American Journal of Physical Medicine and Rehabilitation, 61,* 70–78.

relationship pattern during gait. The bottom part of the figure shows similar diagrams for three persons who had amputation below the knee and were wearing an artificial limb. What is noticeable here is that the amputees do not flex the knee joint at the beginning of the stance as the skilled runner does. These examples demonstrate that an important benefit of kinematic measures is that they allow us to describe the characteristics of critical components of a skill during movement.

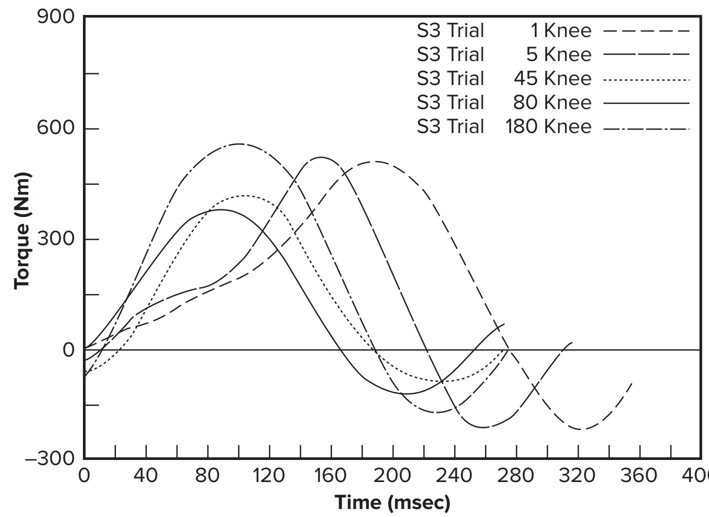


FIGURE 2.9 Results of an experiment by Sanders and Allen showing knee torques for one subject during contact with a surface after the subject drop-jumped from a platform and immediately initiated a vertical jump for maximum height. Each line on the graph represents performance for the trial noted in the key on the graph. *Source:* From Sanders, R. H., & Allen, J. B. (1993). *Human Movement Science, 12,* 299–326.

KINETICS

The term **kinetics** refers to the consideration of force in the study of motion. Whereas *kinematics* refers to descriptors of motion without concern for the cause of that motion, *kinetics refers to force as a cause of motion.* In other words, as Susan Hall (2019) stated in her textbook on biomechanics, "a force can be thought of as a push or pull acting on a body" (p. 61). Human movements can involve both external and internal sources of force. For example, gravity and air resistance are external forces that influence running and walking; water resistance is an external force that influences swimming movements. Muscles provide the basis for internal forces by pushing and pulling on joints of the body.

One way to see the importance of the role of force in our understanding of human movement is to note that all three of *Newton's laws of motion* refer to the role of force. In his first law, force is presented as necessary to start, change, or stop motion. His second law indicates that force influences the rate of change in the momentum of an object. And his third law presents force as being involved in the action and reaction that occurs in the interaction between two objects.

An important force-related characteristic of human movement is that human motion involves rotation of body segments around their joint axes. The effect of a force on this rotation is called *joint torque,* or rotary force (see figure 2.9 for an example of how to graphically present joint torque). Because

velocity a kinematic measure describing the rate of change of an object's position with respect to time. It is derived by dividing displacement by time (e.g., m/sec, km/hr).

acceleration a kinematic measure that describes change in velocity during movement; we derive it from velocity by dividing change in velocity by change in time.

kinetics the study of the role of force as a cause of motion.

of the many different types of force and their influence on human movement, researchers studying motor skill learning and control often include the measurement of forces as part of their research.

Researchers can measure certain forces directly using devices such as force plates, force transducers, and strain gauges. They use force plates to measure ground reaction forces, which are involved in the interaction between an object, such as a person, and the ground. Force plates are popular force measurement devices in laboratories and clinics in which locomotion research and rehabilitation take place. Researchers use force transducers and strain gauges to measure force that is muscle produced; these are popular in laboratory and clinical settings to determine the magnitude of force generated while a subject is performing limb movement tasks.

Newton's second law of motion allows us to measure force indirectly by taking into account the relationship of force to velocity or acceleration and to the mass of the object: *force* = *mass* × *acceleration.* Because of this, we can calculate force without needing to use mechanical and electronic force measurement instruments, if acceleration can be assessed from a kinematic analysis of the movement.

Sports scientists are very interested in the forces that act on the body or on objects propelled by the body as they move through the air and water. These forces are calculated using methods from fluid dynamics, a branch of fluid mechanics that examines how fluids flow. Knowing the lift and drag forces acting on a golf ball as it flies through the air or on the hand or a paddle as they move through the water can provide insights into the design of new equipment and new movement techniques to enhance human performance. For example, following the pioneering work of Robert Schleihauf (1979) on the hydrodynamics of swimming propulsion, Marinho and colleagues (2010) reported that spreading the fingers slightly during the pull phase of each swimming stroke can significantly enhance propulsive forces, and van Houwelingen and colleagues (2018) recently confirmed this finding. Thus, a very subtle modification of technique can have a dramatic effect on performance.

EMG

Movement involves electrical activity in the muscles, which can be measured by **EMG (electromyography)**. Researchers commonly accomplish this by either attaching surface electrodes to the skin over muscles or inserting fine wire electrodes into a specific muscle. These electrodes detect muscle electrical activity, which then can be recorded by a computer or polygraph recorder. Figure 2.10 shows some EMG recordings of electrical activity in the ipsilateral biceps femoris (BFi) and contralateral biceps femoris (BFc) of the legs and the anterior deltoid (AD) of the shoulder girdle for a task that required the person to move his or her arm, on a signal, from the reaction-time key to a position directly in front of the shoulder. The EMG signals presented for these muscles show when electrical activity began in the muscles; we can identify this activity by the increase in the frequency and height of the traces for each muscle. The actual beginning of movement off the RT key is designated in the diagram by the vertical line at the end of the RT recording (line 5 of figure 2.10).

Researchers use EMG information in a variety of ways. One that is most relevant to motor learning and control issues is the use of EMG recordings to indicate when a muscle begins and ends activation. Muscle activation begins when the EMG recording increases in frequency and height compared to when the muscle is not active. When EMG recordings include several muscles involved in the same movement, researchers can gain insight into the process of movement coordination by observing the sequence of muscle activation patterns. For example, in figure 2.10, the first muscle to show activation after the signal to move the arm was the ipsilateral biceps femoris (Bfi), which is a leg muscle on the same side of the body as the arm that moved; next in sequence was the anterior deltoid (AD), which moves the arm for the type of movement in the experiment. This activation sequence tells the researcher that more than arm muscle activity is involved for the simple arm movement performed in the experiment. The researcher would interpret the sequence of muscle activity as indicating that the body prepares itself for an arm

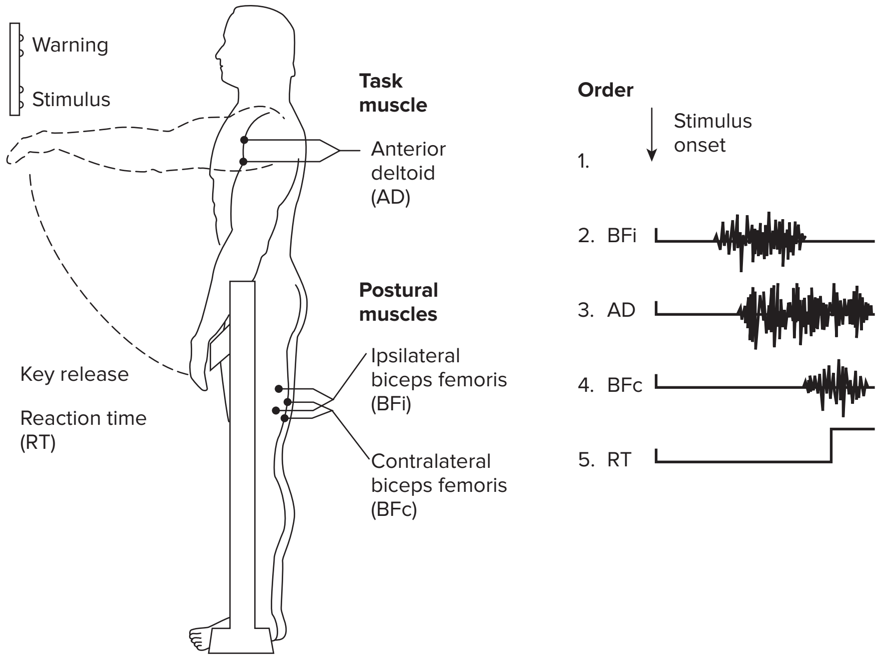


FIGURE 2.10 Using EMG recordings to measure a movement response. The figure on the left shows the reaction-time apparatus and where each electrode was placed to record the EMG for each muscle group of interest. The figures on the right show the EMG recordings for each of the three muscle groups and the reaction-time interval for the response. *Source:* From Lee, Wynne. (1980). *Journal of Motor Behavior, 12,* 187.

movement like this one by first activating leg muscles responsible for stabilizing body posture.

wMMG

Whole muscle mechanomyography is a relatively new, noninvasive technique for determining muscle activity. It detects and measures the lateral displacement of a muscle's belly following maximal percutaneous neuromuscular stimulation (PNS) via a needle that conducts an electric current. A laser sensor is typically used to measure the displacement of the muscle belly. The rise and fall of the stimulated muscle's belly correlates with the development of tension longitudinally within the muscle's tendons, although the rise and fall lags the tension in time. One advantage of wMMG over EMG is that growing evidence suggests that it has the potential to estimate muscle fiber composition within a single muscle (Djordjevic, Valencic, Knez, & Erzen, 2001; Gorelick & Brown, 2007, Than, Seidl, & Brown, 2019).

NIRS

Near infrared spectroscopy (NIRS) is another noninvasive way to measure activity within a muscle. It essentially determines the level of oxygenation in the muscle. Light of wavelengths between 600–1000 nm can penetrate skin, bone, fat, and connective tissue where it is either absorbed or scattered, permitting the determination of changes in blood volume as well as changes in the concentration of oxygenated

EMG (electromyography) a measurement technique that records the electrical activity of a muscle or group of muscles.

hemoglobin, deoxygenated hemoglobin, and oxygenated cytochrome-oxidase. The method typically uses a minimum of two light probes that have different wavelengths, most commonly 760 nm and 800 nm. The longer wavelength is equally absorbed by oxygenated and deoxygenated hemoglobin whereas the shorter wavelength is primarily absorbed by deoxygenated hemoglobin. The absorption difference between the two probes is then used as an index of skeletal muscle oxygen consumption.

Because the light wavelengths used by NIRS can penetrate the skull, the technique has also been used to assess brain activity. Scientists who study the brain are particularly interested in the technique because it is inexpensive and portable, potentially providing big advantages over the more established measures of brain activity, which are covered in the next section of the chapter. NIRS has some disadvantages, however, that have left many questioning its ultimate value as a technique for measuring brain activity. For example, the light probes cannot penetrate very deeply into the brain before the light is scattered and the path-length of a given wavelength of light is not well known for different types of tissue. Consequently, NIRS is limited to providing information about the outermost layer of the brain, the cortex. In addition, it has a limited spatial resolution. NIRS still has the advantage of being portable; an advantage that is particularly important for movement scientists because it enables brain activity to be measured while a participant is moving. Even that advantage may be fading, however, as researchers develop new ways to remove movement-related artifacts from the signals collected by more traditional measures of brain activity, like EEG (Kline, Huang, Snyder, & Ferris, 2015; Nordon, Hairston, & Ferris, 2018).

BRAIN ACTIVITY MEASURES

With the increase in the availability of technology to study brain activity, an increasing number of motor learning and control researchers are investigating the relationship between brain activity and the performance of motor skills. Rather than rely on behavioral measures from which they must infer brain activity, these researchers use various techniques to measure brain activity itself. Most of these techniques have been adapted from hospital and clinical settings where they are used for diagnostic purposes. For researchers who study motor learning and control from the level of neuromotor processes, these techniques provide a window into brain activity as a person performs a motor skill. In the following sections, we will briefly discuss some of the more prominent brain activity measurement techniques that are used by motor learning and control researchers and that you will see referred to in other chapters of this book.

EEG

Like skeletal and cardiac muscle, the brain produces electrical activity, which can be measured by **EEG (electroencephalography)**. Neurologists commonly use EEG to assess brain disorders. Researchers use this same noninvasive and painless procedure, which is similar to recording surface EMG for skeletal muscle. EEG recording involves the placement of several electrodes on a person's scalp. Typically, electrodes are placed on standard locations on the scalp to measure the voltage fluctuations from the activity of thousands or millions of neurons immediately beneath the electrodes. The number of electrodes can vary according to the needs of the researcher or equipment limitations. The electrodes can be individually placed on the scalp or, as is more common in research settings, contained in an elastic cap, or bonnet, in their appropriate locations.

The electrical activity detected by EEG electrode pairs is transmitted by wires to amplifiers and recording devices. Because brain activity is rhythmic, the EEG recordings relate to specific rhythms, which are commonly called *waves.* Four waves can be identified according to the speed of the rhythmic activity (see Figure 2.11). The fastest rhythms are the *beta waves,* which occur when an area of the cortex is active; next are *alpha waves,* which occur during quiet, awake states; *theta waves* are the next to slowest and occur during some sleep states; the slowest are *delta waves,* which are characteristic of deep sleep. In general, mental activity a.

b.

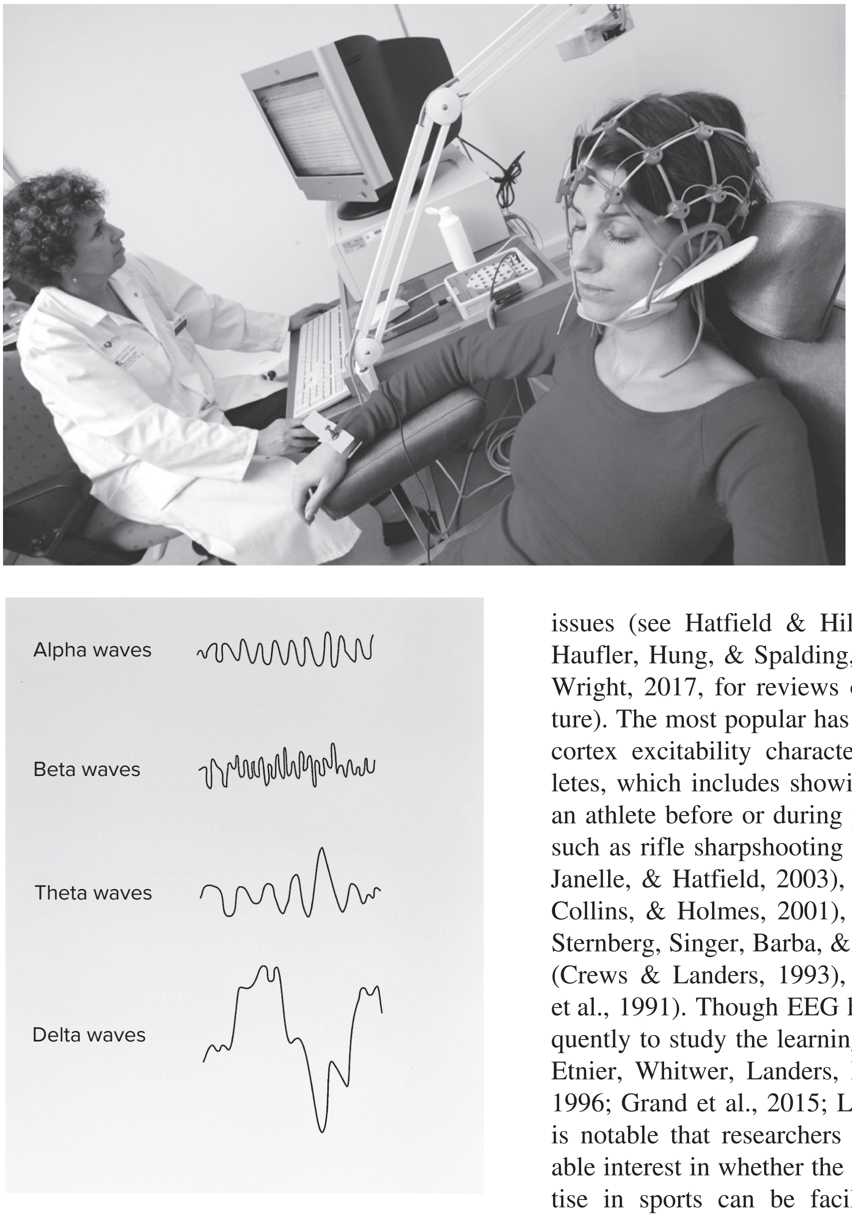


FIGURE 2.11 (a) Patient with electrodes attached to her head. (b) Four electroencephalographic tracings.
(a) Phanie/Science Source

generates the fast beta waves, while nondreaming sleep and coma produce slow theta waves.

In the study of motor skill performance, researchers have used EEG to investigate several issues (see Hatfield & Hillman, 2001, Hatfield, Haufler, Hung, & Spalding, 2004, and Holmes & Wright, 2017, for reviews of this research literature). The most popular has been to describe brain cortex excitability characteristics of skilled athletes, which includes showing the mental state of an athlete before or during performance, in sports such as rifle sharpshooting (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003), pistol shooting (Loze, Collins, & Holmes, 2001), dart throwing (Radlo, Sternberg, Singer, Barba, & Melnikov, 2002), golf (Crews & Landers, 1993), and archery (Landers et al., 1991). Though EEG has been used less frequently to study the learning of motor skills (e.g., Etnier, Whitwer, Landers, Petruzello, & Salazar, 1996; Grand et al., 2015; Landers et al., 1994), it is notable that researchers have shown considerable interest in whether the development of expertise in sports can be facilitated by EEG-based

EEG (electroencephalography) the recording of brain activity by the detection of electrical activity in specific areas on the surface of the cortex by several surface electrodes placed on a person's scalp. Brain activity is recorded as *waves,* which are identified on the basis of the speed of the rhythmic activity.

neurofeedback training (e.g., Ring, Cooke, Kavussanu, McIntyre, & Masters, 2015; Xiang, Hou, Liao, Liao, & Hu, 2018).

PET

One of the limitations of EEG as a technique for assessing brain activity is that it is limited to activity in the brain cortex surface and does not show the anatomical structures that are active in specific brain regions. The development of *neuroimaging techniques,* which provide clear and precise images of activity in specific brain regions, overcame this limitation and presented exciting opportunities for researchers to gain a better understanding of the relationship between observable motor skill performance and brain activity. *Positron emission topography (PET)* was the first of these techniques. Developed in the 1970s, PET scans show blood flow or metabolic activity in the brain and provide a window into all areas of the brain. The technique involves the injection into the bloodstream, or the inhalation, of a radioactive solution in which atoms emit positively charged electrons (i.e., positrons). Interaction of the positrons with electrons in the blood produces photons of electromagnetic radiation. The locations of these positron-emitting atoms can then be found by a scanner in which detectors pick up the photons' locations in the brain (see Bear, Connors, & Paradiso, 2001, for further details). Computer programs then analyze levels of activity of the photons in brain neurons. Increased activity "lights up" the brain area; the computer programs capture and produce images of these active brain areas. When the "lighted up" brain areas are color enhanced according to a color spectrum, the researcher can determine the amount of activity in each area.

Motor learning and control researchers who use PET imaging engage a person in the performance of a motor skill that can be performed in the PET scanner, which surrounds only the head but requires the person to be lying on his or her back throughout the scanning procedure. As the person performs specific aspects of the skill, the PET scan detects the activated brain regions. Although PET remains popular as a neuroimaging technique for researchers interested in the neural substrates of cognitive and motor activities, its use for this type of research has diminished in recent years. The primary reason has been the development of improved technology, which can provide greater image resolution, is more cost-effective, and does not require injection of a radioactive isotope into the bloodstream. However, continued technological innovations in PET instrumentation suggest that it will continue to have relevance for researchers and clinicians (Berg & Cherry, 2018).

fMRI

A common diagnostic technique used in many hospitals and clinics is *magnetic resonance imaging (MRI).* The MRI machine, or scanner, contains a magnetic field that realigns the body's hydrogen atoms, which become the basis for creating extraordinarily clear two- and three-dimensional images of body tissue. The MRI can produce an image of any part of the body from any direction (i.e., plane) in "slices" that are a few millimeters thick. In addition to imaging body tissue, the MRI can also assess changes in blood flow by detecting blood oxygenation characteristics. To study brain function, researchers take advantage of the blood flow detection capability of the MRI by using **fMRI (functional magnetic resonance imaging)**. The term *functional* is important because researchers use this technique to observe brain function (i.e., activity) while a person performs a task. When a part of the brain is active, more blood is directed to that area. The fMRI detects blood flow changes and can provide colored images that show active brain areas at a specified time, and it can provide quantitative results by computing BOLD (blood oxygenation level dependent) amplitudes, which researchers use to determine active areas of the brain. When researchers report their use of fMRI, they typically describe the specific brain areas from which the slices were taken and the size and direction of the slices. An important aspect of the use of fMRI for motor control and learning experiments is that, as with the constraints imposed by the PET scanner, researchers need to engage participants in tasks that can be performed within the physical confines and restrictions of the MRI machine. Although the use of fMRI is relatively new for research in motor control and learning, we find an increasing number of studies reporting its use. You will see some examples in various chapters throughout this book.

MEG

One of the most recent technological advances in brain activity assessment is *MEG (magnetoencephalography).* The assessment is a variation of the EEG (notice the "encephalography" similarity). While the EEG assesses electrical activity in the brain, the MEG assesses magnetic fields created by neuronal activity in the brain. One of MEG's advantages for researchers is that it provides a direct measure of brain function; this differs from other brain measures such as fMRI and PET that are secondary measures because brain activity is assessed on the basis of brain metabolism. MEG provides very high temporal resolution, which makes it especially useful for the identification of damaged brain tissue; this is critical for both diagnosis and surgical purposes, as well as for observing brain activity during the performance of cognitive and motor activities. The recording system for MEG involves the use of sensors that detect magnetic fields in the brain that result from neuronal activity. The spatial distributions of these fields are analyzed and used to determine the location of the activity. Researchers commonly combine results from MEG with those from EEG and MRI. The addition of the MEG results provides more accurate localization of the active brain structures associated with the activity in which the subject is engaged.

TMS

A method of assessing brain activity that is targeted directly at determining motor activity is **TMS (transcranial magnetic stimulation)**. Different from the types of brain activity measures that involve a scan of the brain and the recording of electrical, magnetic, or bloodflow activity of the brain, TMS excites or inhibits activity in a specific area of the cortex of the brain. As a result, the function of specific brain areas is inferred on the basis of how a person behaves when a brain area is stimulated in this way. TMS involves the external placement of a coil on a person's skull at a brain cortex location of interest. From this coil a short burst (referred to as a pulse) of a field of magnetic waves is directed at that area of the cortex. The pulse induces an electrical current in the brain. Because this electrical current changes brain activity in a specific area, researchers often use TMS to verify the function of a brain region based on the predicted function derived from brain activity measures such as fMRI or PET.

Researchers interested in determining the neurological basis for motor control and learning have found TMS to be a useful technique for their research. When TMS is applied to a specific area of the brain's motor cortex, it elicits a *motor evoked potential* (MEP) in corresponding muscles on the opposite side of the body. The amplitude of the MEP, which can be measured by EMG, provides an index of the excitability of the neural tracts that connect the cortex and the muscles. When TMS is applied repetitively (rTMS), it can induce longer lasting changes in the activity of the brain that make the brain areas stimulated more susceptible

fMRI (functional magnetic resonance imaging) a brain-scanning technique that assesses changes in blood flow by detecting blood oxygenation characteristics while a person is performing a skill or activity in the MRI scanner. It provides clear images of active brain areas at a specified time and can provide quantitative information about the levels of brain region activity.

TMS (transcranial magnetic stimulation) a noninvasive method of assessing brain activity that involves a short burst (referred to as a pulse) of a field of magnetic waves directed at a specific area of the cortex. This pulse of magnetic activity temporarily disrupts the normal activity in that area of the brain, which allows researchers to observe a subject's behavior when that area of the brain is not functioning.

to change. You will see examples of the use of these techniques in various chapters of this book.

MEASURING COORDINATION

One of the more exciting phenomena of recent motor learning and control research is the investigation of movement-related coordination. One reason for this is methodologically based. Prior to the advent of computer-based technology for movement analysis, kinematic measurement of movement was an expensive, labor-intensive, and time-consuming process involving frame-by-frame analysis of slow-motion film. With the development of the computer-based movement analysis systems, there has been a dramatic increase in research involving complex skills, which allows for the assessment of coordination.

A measurement issue concerns how best to assess coordination, which involves the movement relationship between joints or limb and body segments. Although researchers have developed several methods for quantifying coordination characteristics, we will consider only two as examples of the ways it is possible to measure coordination. Common to all these methods is analyzing the movement of limbs and limb segments in specific time (i.e., temporal) and space (i.e., spatial) patterns while a person performs a motor skill. One of the ways to observe these patterns is to create graphic angle-angle plots of the movements of joints associated with limb segments, such as the knee and thigh joints depicted in figure 2.8. However, a measurement issue has developed concerning angle-angle diagrams. We discuss this issue next.

Quantitative Assessment of Angle-Angle Diagrams

As researchers gained the capability to analyze complex movements, they tended to report only the qualitative kinematic descriptions of limb segment relationships. However, to make inferences about coordination from these descriptions, researchers needed to provide quantitative assessments of them. Although researchers have proposed various techniques, the cross-correlation technique has gained general acceptance.

Cross-correlation technique. The angle-angle diagrams that describe coordination patterns for two joints lend themselves to correlational analysis because researchers are interested in the relationship between the two joints at specific points in time. Because movement analysis of the joints provides many data points to compare (recall the discussion earlier in the chapter concerning kinematic measures), it is possible to correlate each data point (an X-Y spatial position at a specific point in time: i.e., the time when the movement analysis software sampled the joint's position in space) of one joint with each data point on the other joint. To do this type of correlation requires a statistical procedure known as cross-correlation, which is required when the relationship of interest occurs across a period of time. Rather than describe the details of computing a cross-correlation, it will suffice to say it results in a correlation coefficient that is interpreted as the extent to which the two joints follow similar movement patterns. (For more information about the cross-correlation technique, see Mullineaux, Bartlett, & Bennett, 2001, and Li & Caldwell, 1999.)

Relative Phase as a Coordination Measure

Many motor skills involve movements that are cyclic. This means that they repeat a movement pattern for a certain amount of time, such as walking or running (the step-cycle in gait in figure 2.8 is an example of a cyclic movement). These types of skills are especially interesting because they provide a quantifiable means of measuring coordination. This is accomplished by calculating the relative phase between two limb segments or limbs during one cycle, or part of a cycle, of the skill. A *phase* of a cyclic movement refers to a specific point on the cycle. Because any point on the cycle involves both a spatial position of a limb or limb segment and a point in time, the movements of the limb or limb segment can be

A CLOSER LOOK

An Index of Coordination for Swimming Strokes

Chollet and his colleagues in France developed a quantitative assessment of the coordination of swimming strokes, which they described as having practical value for assessing and improving swimming stroke performance by elite swimmers (Chollet, Chalies, & Chatard, 2000).

The Index of Coordination (IdC)
The researchers derived the IdC from video-based motion analysis of elite swimmers' performance. Four cameras (one underwater, one on a trolley above water at the side of the pool, one providing a frontal underwater view, and one above the pool tracking the swimmer's head) provided the data needed to calculate the IdC.

Backstroke Coordination and Swimming Speed
An excellent example of how a quantitative assessment of coordination can be used in a sport context was presented in an experiment involving elite swimmers performing the backstroke. Chollet, Seifert, and Carter (2008) calculated an IdC for arm movements for various swim speeds for each swimmer. The IdC was calculated from right and left arm position data during six phases of a stroke: 1. Entry and catch of the hand in the water; 2. Pull; 3. Push; 4. Hand lag time; 5. Clearing; 6. Recovery. The durations of the pull and push phases were summed to establish a propulsive phase; the sum of the durations of the other four phases was considered to be the non-propulsive phase.

Calculation of the IdC:

> ***IdC*** *= (time at the beginning of the propulsion in the first right arm stroke and the end of propulsion in the first left arm stroke)−(time at the beginning of the propulsion in the second right arm stroke and the end of propulsion in the first right arm stroke)*

The experiment involved 14 international-standard male swimmers performing the backstroke at four different speeds. The IdC analysis results showed that the swimmers maintained a standard arm stroke coordination mode regardless of speed.

Recommendations for swimmers and coaches: Based on the results of their quantitative coordination assessment the researchers presented three recommendations for enhancing swimming performance: Swimmers should

1. Minimize the clearing phase . . . and the hand's lag time at the thigh . . . by increasing the hand speed in this specific phase . . .
2. Modify their hand sweep from a "two-peak" to a "three-peak stroke pattern" with a partly propulsive clearing phase . . .
3. Compensate the loss of speed in the clearing phase . . . by increasing the distance per stroke.

In addition the authors claimed that the IdC can be "used by coaches to assess mistakes in backstroke coordination, particularly regarding the hand's lag time at the thigh" (p. 681).

described by a displacement-velocity graph that portrays the relationship between the spatial and temporal characteristics of the movements. This graph, which is called a *phase plot* (or *phase portrait*), presents the limb or limb segment's angular displacement on one axis and its angular velocity on the other axis. When a cyclic movement is graphed in this way, the result is a graph like the one in figure 2.12, which is based on the movement of a leg segment during the stance portion of a step cycle (from the heel strike of one foot to the toeoff of the same foot). The data points on the phase plot are the X-Y coordinates sampled at specific times in the movement analysis (e.g., if the sampling rate is 100 Hz, there will be 100 X-Y coordinate data points). The calculation of a movement's phase is complex and will not be described here. But you can see how a phase angle is derived from a phase plot by looking at the bottom panel of figure 2.12. Here a line is drawn from the origin of the X-Y coordinate to a specific point on the phase plot. The resulting angle is the *phase angle* for that point in

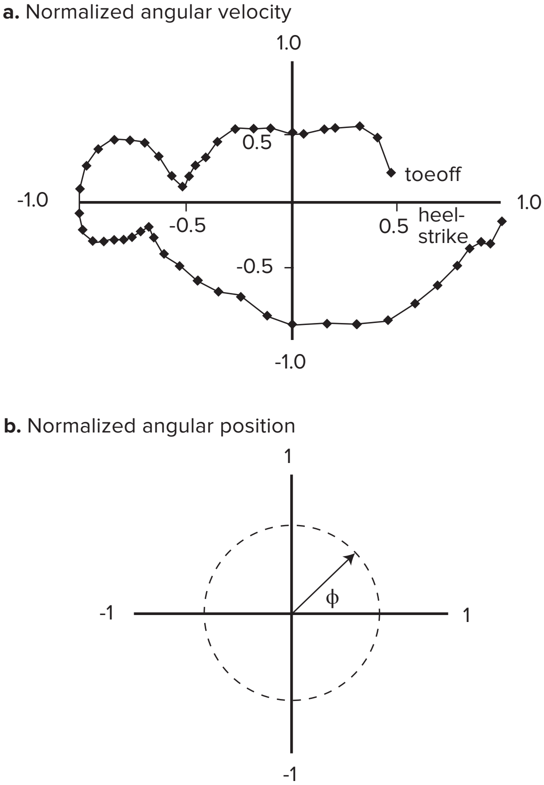


FIGURE 2.12 (a) A phase plot of the movement of a leg segment during the stance portion of one step cycle during running. (b) An example of the derivation of a phase angle from the phase plot shown above in panel (a). *Source:* Adapted from Hamill, J., van Emmerik, R. E. A., Heiderscheidt, B. C., & Li, L. (1999). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics, 14,* 297–308.

time of the movement. One way that researchers use phase angles to assess movement coordination is by comparing the phase angles of two limb segments, or limbs, at a specific point in time. This comparison establishes the **relative phase**, which is calculated by subtracting the phase angle for one limb segment or limb from the phase angle of the other limb segment or limb. Relative phase can range from 0 (or 360 degrees), which indicates an *in-phase relationship* between the limb segments or limbs, to 180 degrees, which indicates an *antiphase* (or *out-of-phase*) *relationship.*

The interpretation of relative phase as an index of coordination is that a high degree of coordination between the two joints or limbs is associated with a relative phase that remains consistent for several cycles of the movement.

In addition to using relative phase as an index of coordination between limb segments, researchers commonly use it to describe the relationship between two arms or two legs, or between one arm and one leg. For example, the two legs are 180 degrees out of phase during walking because one limb is always half a cycle behind the other limb. In contrast, the two legs are in phase (the phase relationship between them is 0 or 360 degrees) during jumping because they move in exactly the same way. When the relative phase relationship between two limbs is highly consistent across several movement cycles, the two limbs are considered to be strongly coordinated or “tightly coupled.” An example of how the relative phase between the two arms can be represented graphically is shown in figure 11.4 in chapter 11.

The relative phase measurement described in the preceding paragraphs is referred to as *continuous relative phase,* because it presents the relative phase of a cyclic movement throughout the movement’s cycle. Another type of relative phase measurement, known as *point estimate relative phase,* refers to only one point in the movement cycle. As indicators of coordination, the point-estimate relative phase is a more general indicator. The continuous relative phase provides a more detailed analysis of coordination.

relative phase an index of the coordination between two limb segments or limbs during the performance of a cyclic movement. It is based on calculating the phase angles for each limb segment or limb at a specific point in time and then subtracting one phase angle from the other. Relative phase ranges from 0 (or 360 degrees), which indicates an in-phase relationship between the limb segments or limbs, to 180 degrees, which indicates an antiphase (or out-of-phase) relationship.

SUMMARY

An essential element in understanding motor learning is the measurement of motor performance. All concepts presented in this text are based on research in which researchers observed and measured motor performance. Measuring motor performance is essential for the assessment of motor deficiencies, as well as for the evaluation of performance by students or patients as they progress through practice and therapy regimes. In this chapter, we focused on different ways to measure motor performance, along with the ways we can use these measurements in motor learning research and applied settings.

Following are the performance measurement issues and examples discussed in this chapter:

- Two categories of performance measures: performance outcome measures (which measure the result of the performance of a movement activity) and performance production measures (which measure movement-related characteristics that produce the performance outcome of a movement activity).
- Performance outcome measure examples: reaction time (RT), movement time (MT), and three measures of performance outcome error (AE, CE, and VE) for one- and two-dimension movement goals.
- Performance production measure examples: three kinematic measures (displacement, velocity, and acceleration), joint torque as a kinetic measure, and EMG. Also included were five measures of brain activity: EEG, PET scans, fMRI, MEG, and TMS.
- Concerns about the qualitative and quantitative measurement of movement coordination, including the cross-correlation technique and the use of relative phase.

POINTS FOR THE PRACTITIONER

- The measurement of motor skill performance is important for providing a quantitative basis for the assessment of performance capabilities and limitations, the locus of the source of performance limitations, and evidence of skill improvement resulting from your intervention strategies.
- You can measure the outcome of motor skill performance and/or the movement and neurological basis for the outcome. Select the types of measures based on the performance-related information you need to address your goals for the person or people with whom you are working.
- Reaction time can be a useful measure to provide information about a person's readiness to perform a skill in a specific situation.
- Error measures can provide information about the types of movement problems a person needs to correct to achieve the action goal of a skill.
- Kinematic, kinetic, EMG, brain activity, and coordination measures can help assess a person's movement-related problems when performing a skill. In addition to needing the appropriate technology to determine these measures, you need to ensure that the measures are interpreted correctly.

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STUDY QUESTIONS

1. (a) Describe the differences between performance outcome measures and performance production measures. (b) Give three examples for each of these measures of motor performance.

2. (a) Describe how simple RT, choice RT, and discrimination RT situations differ. (b) What does it mean to fractionate RT? (c) How does MT differ from RT?

3. What different information can be obtained about a person's performance by calculating AE, CE, and VE when performance accuracy is the movement goal?

4. How would you determine the type of problem a golfer needs to correct based on the results of a series of missed putts?

5. How can performance error be determined for a continuous skill such as steering a car on a road?

6. Describe three kinematic measures of movement and explain what each measure tells us about the movement.

7. What do the terms *linear motion* and *angular motion* mean when used in reference to descriptions of movement? When would you use each of these types of analysis if you were measuring a person's walking performance?

8. What is meant by the term *kinetics* as it is related to measuring human movement?

9. What information about a movement can be obtained by using EMG?

10. Describe three techniques commonly used to measure brain activity during the performance of a motor skill. What are the limitations of each technique in terms of the types of motor skills that could be used?

11. Briefly describe two techniques that can be used to tell us something about the coordination characteristics of two limbs or two limb segments.

Specific Application Problem:

Describe a situation in which you are working with people to help them improve their performance of a motor skill. Your supervisor has asked you to respond to several questions before you begin this work:

(a) What are some performance outcome measures that you could use to assess their performance?
(b) What would be the advantages and disadvantages of each?
(c) Which outcome measures would you use and why?
(d) Since you have the appropriate technology available, what kinematic measures would help you assess their performance?
(e) How would the information the kinematic measures provide help you in assessing their performance of the skill?