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# Biomechanics and Physiology of Posture and Gait

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CHAPTER 12

# BIOMECHANICS AND PHYSIOLOGY OF POSTURE AND GAIT

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Maintenance of posture and locomotion are, to varying degrees, critical components of all land-based exercise and athletic activities. The biomechanics and physiology of posture and locomotion have been among the most extensively studied of human activities. This chapter (*a*) introduces the exercise professional to biomechanical and physiological issues associated with postural control and gait and (*b*) provides a basis for understanding the experimental methods used to make quantitative biomechanical and physiological measurements associated with postural control and gait, the outcome variables, the interpretation of the variables, and the limitations of the interpretations. The reference list provides sources through which detailed treatment of many of the concepts may be explored. The first part of this chapter presents a framework of biomechanical fundamentals as they relate to the biomechanics of postural control and postural stability. The second part of this chapter presents some of the basic relationships between the biomechanics and physiology of gait, specifically as they relate to the topic of economy.

## POSTURAL CONTROL AND STABILITY

The human tasks that include standing, walking, and running share many common neuromuscular and biomechanical mechanisms to which other motor tasks are subservient. Two of these mechanisms are postural control and stability.

### Postural Control

Postural control is the ability to predict, detect, and encode changes in posture; select and adapt a response; and execute the response within the biomechanical constraints of the body and the physical constraints of the environment (1). The extent to which these processes are effective manifests as postural stability. Three common conditions during which the postural control system must function include maintaining postural stability against the force of gravity; maintaining postural stability in the presence of self-initiated motions, such as lifting a weight; and maintaining postural stability in response to externally applied loads or forces, such as walking into a fixed object.

Postural control depends on the vestibular, visual, and somatosensory systems, which provide feedback to the central nervous system (CNS). This feedback, processed by the CNS, is used to generate muscle activation signals necessary for postural corrections. The vestibular (and otolith) system feedback, housed in the inner ear, provides information related to head position and motion with respect to gravity. The visual system provides information related to head position and motion relative to an external coordinate system. The somatosensory system provides information related to the position and motion of joints. Mechanoreceptors in the skin, for example those in the plantar surface of the foot, provide information regarding pressure that is used to accommodate postural sway that occurs while standing.

The systems that provide postural feedback are redundant. The CNS must decode the incoming signals to determine the status of the system. For example, for a person in a car, the movement of another vehicle detected with peripheral vision indicates only general motion. Often one cannot immediately determine whether the perceived motion is that of the vehicle in which one is seated or that of the second vehicle. However, without shifting the gaze, the person can use feedback from the vestibular and sensorimotor systems to determine whether the perceived motion can be attributed to motion of the vehicle in which the person is riding.

### Postural Stability

The term stability broadly refers to whether a system (body) returns to its original stable position or motion or another stable position or motion after it is subjected to a perturbation (disturbance). In humans, the term postural stability generally refers to standing upright. It has traditionally been characterized as a relationship between the center of gravity or center of pressure (measured, for ex-

ample, with a force plate) and the base of support. The base of support is defined by the size and shape of the contact area defined by the body segments that are in contact with the supporting surface. If the horizontal center of gravity or center of pressure is within the boundaries of the base of support, the basic requirement for static postural stability is satisfied.

The location of the center of gravity is a function of the mass of the body and the manner in which the mass is distributed or oriented. For example, the center of gravity shifts anteriorly and superiorly when the shoulder joint flexes 90°. From a practical standpoint, estimation of the location of the center of gravity can be time consuming and associated with error. Fortunately, the use of force plates makes the quantification of static postural stability fairly straightforward. Quantifying postural stability using force plate data relies to a great extent on determining the center of pressure rather than the center of gravity. The center of pressure is the location on the surface of a force plate through which the resultant force acts. Motion of the center of pressure reflects but does not mirror motion of the center of gravity. However, when the center of pressure lies within the boundaries of the base of support, the basic requirements for static postural stability are satisfied.

Numerous laboratory and clinical tests are available for measuring postural control and postural stability, although there are numerous challenges (2). Laboratory tests have been criticized as having little clinical application and in some cases little biomechanical application. On the other hand, clinical tests have been criticized as having less than satisfactory sensitivity. An example of such difficulties is the general acceptance that physiological changes associated with normal aging result in an increase in the amplitude of static postural sway and that increased postural sway is associated with the increased incidence of falling in older adults. Recent scientific investigation does not necessarily support these contentions. Postural sway and measures of static and dynamic measures of postural control were found to be weakly correlated to the ability of healthy older men and women to recover their balance when subjected to large postural perturbations that required stepping responses (3). These findings demonstrate that the association between increased age-related postural sway and the increased incidence of falling in older adults is not entirely causal. In particular, the data generally suggest that the extent to which the subject becomes posturally unstable as a result of a postural insult is independent of whether the stepping response, if required, will be successful.

## Dynamic Posturography

Clinically, it is important to assess the status of the vestibular, visual, and somatosensory components of the postural control system, individually and as an integrated whole. A measurement standard for this purpose is called dynamic posturography (4). Dynamic posturography uses a computer-controlled platform on which the subject stands. A visual surround that provides a consistent visual stimulus to the subject and at the same time visually isolates the subject from the environment encloses the platform. Both the platform on which the subject stands and the visual surround may be moved, under control of the computer. Motion of the platform and the visual surround alters the fidelity of the sensory feedback and thus influences postural stability. Systematic manipulation of the feedback allows derivation of the relative contribution of each feedback system to postural stability.

The sensory organization test (SOT) assesses the three sensory systems that contribute to postural control by manipulating the visual and support surface conditions. There are six conditions in the SOT:

- Eyes open, fixed support surface. During this test, all sensory systems contribute to postural control.
- Eyes closed, fixed support system. During this test the contribution of the visual system to postural control is eliminated.
- Sway-referenced vision, fixed support surface. During this test the contribution of the visual system to postural control is inaccurate.
- Sway-referenced support surface, normal vision. During this test the contribution of the somatosensory system to postural control is inaccurate.
- Eyes closed, sway-referenced support surface. During this test the contribution of the visual and somatosensory systems to postural control are eliminated and inaccurate, respectively.
- Sway-referenced vision and support surface: During this test the contribution of the visual and somatosensory systems to postural control are inaccurate.

An equilibrium quotient (EQ) for each system manipulation is computed and used as an index of postural stability. Systematic reduction of sensory feedback has a substantial effect on the EQ, and age amplifies the effects of the SOT conditions. Diminishing somatosensory feedback (sway referencing) results in a larger reduction of the EQ than does eliminating visual feedback. The largest EQ reduction appears to be elicited when the vestibular system is taxed to the greatest extent.

The balance strategy score (BSS) is also computed for the SOT conditions. The BSS relates to the motor pattern used by a subject to maintain postural stability after a postural perturbation. There are three basic motor strategies for correction of anteroposterior postural perturbations: the ankle strategy, the hip strategy, and the stepping strategy. The specific strategy selected by normal adults depends on the surface upon which the subject is standing and the magnitude of the perturbation. The ankle strategy, which is the most commonly implemented, controls body sway by generating moments about the ankle joint.

The ankle strategy is effective when the support surface is large and firm enough to resist the ankle's movements. Normally the ankle strategy is used to counteract perturbations that are applied slowly and that have low magnitude. An ankle strategy is most useful when the amplitude of body sway does not approach the limit of stability, the point at which a loss of balance is likely. A hip strategy is used in response to larger, more rapidly applied perturbations occurring when the support surface is compliant or smaller than the surfaces of the feet. A hip strategy is employed quite often when a loss of balance is imminent. When neither ankle nor hip strategy can restore postural stability, a stepping response is executed. If executed correctly, the stepping response establishes a new base of support and restores posture stability.

Lastly, dynamic posturography includes a motor coordination test (MCT). During the MCT, large anterior and posterior translations and toes-up and toes-down rotations are applied to the subject. This is achieved by causing the platform on which the subject stands to translate and rotate, respectively. The purpose of the MCT is to assess the activation of the lower extremity and trunk muscles that are stretched by the platform motion and to assess which muscles contribute to the restoration of postural stability. For example, an ankle strategy in response to a perturbation that rotates the subject forward (a backward surface translation) is associated with a distal-to-proximal activation pattern of the posterior ankle, thigh, and trunk muscles. However, a hip strategy associated with a perturbation in the same direction elicits activation of anterior trunk and thigh muscles. Both normal aging and neuromuscular disorders can substantially affect the sequence of muscle activation in response to specific perturbations and the activation latencies (from perturbation to onset of muscle activation).

While dynamic posturography measures postural stability during static upright posture and is considered a gold standard, true measurement of dynamic postural stability is elusive. This is because the easily quantified criterion for static stability (center of pressure within the boundaries of the base of support) is not easily applied to dynamic conditions. For example, during walking, specifically during the swing phase of gait, the center of pressure falls outside of the boundaries of the support foot for up to 80% of the time. A body is considered dynamically stable if active and passive disturbances can be predicted and detected, if responses to the disturbances can be selected, and if the selected responses can be executed. However, unlike static postural stability, dynamic stability has not been defined mathematically. Given that most falls and injuries occur during gait, ascending or descending stairs, or rising from chairs, it seems reasonable, if not expedient, to include dynamic motor tasks in the description of postural stability (1).

The numerous measurement techniques, instruments, and variables confront the exercise practitioner with a problem: the availability of many expedient measurement methods and the inability to generalize from constrained testing conditions to conditions of daily living. Guidelines that are useful in decision making have been developed. The guidelines govern the selection of the task or tasks, perturbation or perturbations, and outcome variables (5). The tasks should represent the normal spectrum of movement and in particular should challenge the postural control system. Similarly, the selection of the perturbation should be based upon the extent to which the system is challenged and to which type of feedback is provided regarding the performance of the postural control system. Outcome variables should be selected according to the ability to identify performance deficits and provide diagnostic information. However, these recommendations represent the ideal and serve as a goal for research. For the exercise professional, they serve as a reminder that effective measurement, interpretation, and application of postural control data are difficult.

## RELATIONSHIPS BETWEEN ECONOMY AND LOCOMOTION BIOMECHANICS

Three major considerations influence the relationship between economy and locomotion biomechanics. These include interindividual variation in movement economy, speed of movement, and stride length and rate. Each of these will be discussed in this section.

### Interindividual Variation in Movement Economy

Economy is measured by the steady-state oxygen consumption for a given submaximal task. This measure of the aerobic demand is typically normalized to the body mass of the individual, particularly for tasks in which upright posture must be maintained and body weight supported by the musculature. This measure is expressed as milliliters of oxygen consumed per unit of body mass (usually in kilograms) per minute of exercise. Occasionally economy is expressed per unit of distance traveled (e.g., milliliters per kilometer per kilogram) when comparing the economy for different speeds of movement, such as different walking or running speeds. Numerous research reports have demonstrated that the economy of motion for a given task tends to vary widely among individuals. It should be stressed that this between-individual variation in economy is independent of neurological and musculoskeletal deficiencies and diseases that may have large deleterious effects on movement economy.

In describing normal variation in economy among a group of young, healthy adults by correlating the aerobic demands observed for one task against those for another task, Daniels et al. noted that individuals clearly were neither economical nor uneconomical for all types of physical activity (6). Economy tends to be task specific and thus may be governed in part by biomechanical factors that define the movement technique used by an individual to perform a certain task.

Despite the commonly held belief that biomechanical factors help to explain economy differences between individuals, the extent to which these differences can be attributed to biomechanics is not well defined. Assuming that selected biomechanical factors are related to movement economy, the subsequent question is whether lasting changes in movement patterns can be produced so that movement economy is improved. The following sections highlight the observed relationships between movement economy and a few selected kinematic, kinetic, and structural factors and the practical implications of these relationships for measuring economy and prescribing exercise. The reader is referred to published reviews for further information on the topic (7–9).

## Speed of Movement

The speed at which an individual moves is one of the simplest and most fundamental biomechanical descriptors of movement. As an example, preferred walking speed is a good indicator of the debilitating effects caused by knee injury and of the general decline in physical performance capabilities of elderly adults (10, 11). Thus, preferred walking speed should not be overlooked as one simple marker that offers insight into the movement capabilities of individuals, especially those whose exercise capacity has been limited by disease, injury, and/or normal aging. The average preferred walking speed of healthy young adults is approximately 1.45 m/second, while that for healthy elderly adults (approximately 70 years of age) is about 1.3 m/second. The preferred walking speed of young and old adults has also been shown to be subtly associated with physical activity status. Individuals pursuing a physically active lifestyle tend to walk slightly faster (approximately 0.1 to 0.2 m/second faster) than sedentary individuals (12).

It is obvious that increasing the speed of movement results in increased rates of oxygen consumption for both walking and running. Altering the speed of walking or running is one of the most common ways of modifying the intensity of the task in exercise evaluations. Many economy comparisons between individuals or groups presented in the research literature have been made at fixed speeds of walking or running, with aerobic demand expressed in milliliters per minute per kilogram. Any confounding effect of speed on economy comparisons is eliminated through use of a common test speed. On the other hand, having subjects walk or run at a preferred speed during an economy or biomechanical evaluation of gait has the appeal of assessing them under exercise conditions that are typical for them and that are within their exercise capabilities.

One problem of using preferred speeds of locomotion during gait evaluations is that there is a speed-related confounder that cannot be ignored. From an economy perspective, a U-shaped speed–economy relationship (Fig. 12.1) for walking exists when aerobic demands for a wide range of walking speeds are expressed relative to distance traveled (milliliters of oxygen per kilogram per kilometer). In other words, there is a speed of walking (approximately 1.25 to 1.35 m/second) for adults that minimizes the aerobic demand required to walk a given distance (12, 13). At walking speeds both higher and lower than this intermediate speed, the cost to traverse a given distance is increased. This effect of speed is most apparent at particularly low and high speeds of walking. For example, Ralston (13) observed that energy expenditure (calories per kilogram per meter) was minimized at approximately 1.25 m/second but that the speed–energy expenditure curve was nearly flat at approximately 1.1 to 1.4 m/second.

Adults (not Children, Teens or Elderly)
Male or Female

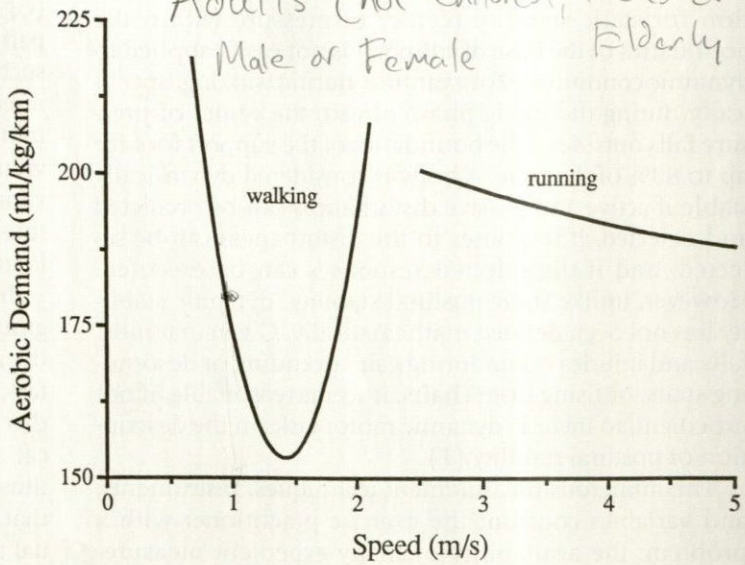


**Figure 12.1.** The aerobic demand to walk a given distance (milliliters per kilogram per kilometer) is affected substantially by walking speed. The most economical walking speed is approximately 1.25 to 1.35 m/second. In contrast, the aerobic demand to run a given distance is affected minimally by speed.

In contrast to walking, the energy cost to run a given distance is reasonably similar for a given individual across a range of running speeds. While Figure 12.1 suggests that there is a subtle decline in the aerobic demand per kilometer traveled as running speed increases, the slope of the speed–economy curve for running can vary somewhat from slightly negative, as shown, to slightly positive, depending on the individual subject, specific subject group, and range of speeds examined. The important point is that the speed confounder is far less of a concern when assessing running economy if the energy demand is met aerobically.

From a biomechanics perspective, comparing gait patterns becomes particularly challenging when comparisons are not being made at a common walking or running speed. The reason for this is that nearly all kinematic and kinetic descriptors of gait are speed dependent. For example, it is well established that as walking speed increases, factors such as stride length, joint angular velocities, peak values for ground reaction forces and net moments about joints of the lower extremity, and activation levels of numerous leg muscles all tend to increase, while other factors, such as stride time and related temporal descriptors of the gait pattern, tend to decrease. Thus, while existing technology and methods offer the potential to describe a wide range of biomechanical characteristics of walking or running patterns, assessing specific deficiencies in gait is compromised or at least substantially complicated by the absence of speed control.

## Stride Length and Rate

Stride length is defined as the distance traveled by the body during one full cycle of motion (e.g., from the instant of left foot contact until the subsequent left foot contact). Stride rate or cadence, which is the reciprocal of stride time, indicates the number of strides completed per unit of time. The average speed or velocity of walking or running is simply the product of stride length and stride rate.

The effect that stride length and rate have on gait economy during steady-state, submaximal exercise lends itself to simple experimental assessment because of this relationship and the ability to control velocity by using a treadmill. The protocol used most frequently entails determining first the preferred stride length and rate for a particular velocity, then the steady-state aerobic demand assessments at a series of stride length and rate combinations that deviate from the preferred condition. This is accomplished by having an individual match the stepping rate to an audible signal so that desired stride rate and stride length are produced. This experimental manipulation produces a curvilinear stride length/rate–economy curve (Fig. 12.2). The aerobic demand of walking or running at a controlled speed tends to increase nonlinearly as optimal (preferred) stride length or rate either increases or decreases (14).

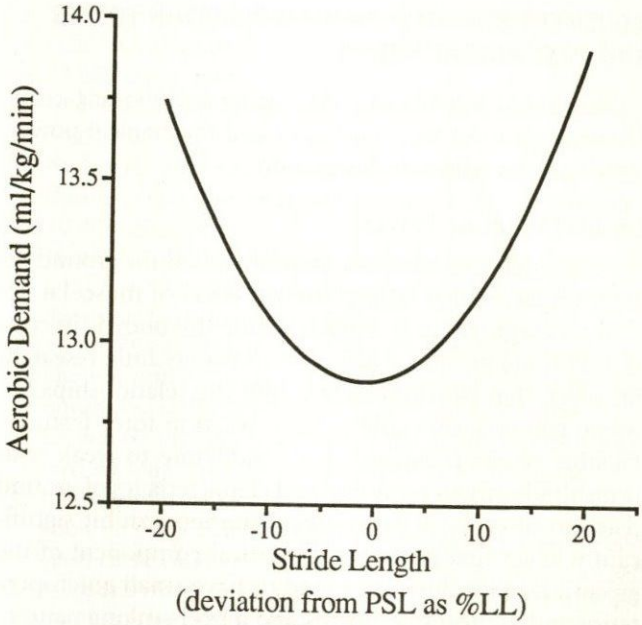


**Figure 12.2.** Stride length and rate strongly affect the aerobic demand for walking (shown here). For most individuals, as stride length either increases or decreases (hence stride rate decreases or increases, respectively) from the preferred stride length (PSL), expressed as a percentage of leg length (%LL), aerobic demand increases.

The preferred and most economical stride length–rate combinations are usually in close agreement with one another, suggesting that most individuals naturally achieve their optimal stride length and rate through some unknown mechanism. One practical implication of this outcome is that a coach is generally ill-advised to manipulate stride length and rate for the purpose of improving economy and running performance unless aerobic demand data specifically confirm an uneconomical running pattern (14, 15). In addition, research suggests that there is no significant relationship between the most economical stride length and leg length, indicating that it is not possible to predict the most economical stride length from physical dimensions.

The reason for the U-shaped stride length/rate–economy response is probably associated with fundamental muscle force– and power-generating capabilities. Fundamental mechanical properties of muscle indicate that the force-generating capacity of muscle falls nonlinearly as the velocity of shortening increases (16). When plotting power (the product of muscle force and the velocity of shortening) as a function of the velocity of shortening, the capacity of muscle to generate power is greatest when muscle fiber velocity is approximately one-third of maximum shortening velocity. Changes in stride length and rate require concomitant changes in the rates of muscle lengthening and shortening, the rate of force development, and the demand for muscular power output, all of which should affect aerobic demand.

## MOVEMENT KINETICS: GROUND REACTION FORCES AND MECHANICAL POWER

Movement kinetics are affected by two major factors. These are ground reaction forces and mechanical power, which are discussed in this section.

### Ground Reaction Forces

Gait specialists have extensively studied the ground reaction force, which reflects the net effect of muscular action and segment accelerations while the body is in contact with the ground. There is surprisingly little research, however, that provides insight into the relationships between gait economy and ground reaction force features. Existing research suggests only moderate to weak relationships between economy and characteristics of ground reaction force (17). Economical runners exhibit significantly lower first peaks in the vertical component of the ground reaction force and tend to have small anteroposterior and vertical peak forces and a heel-striking pattern. It is speculated that the need to provide cushioning during early contact may have an important effect on the demands placed on the muscles, which in turn may affect economy. When landing on the forefoot, a person may need to rely more heavily on musculature to cushion the impact. In contrast, the footwear and skeletal structures of a heel striker may play greater roles in cushioning and supporting the body during early contact.

### Mechanical Power

Aerobic demand represents a global measure of the physiological demand of walking or running. One example of a global estimate of muscular effort from a biomechanics perspective is mechanical power output. Assuming that a substantial portion of the aerobic demand of gait is associated with muscles performing mechanical work (i.e., actively shortening or lengthening), mechanical power should be an effective predictor of gait economy. This is certainly true when the aerobic demand and mechanical power are studied for a wide range of walking or running speeds. As walking or running speed increases, both aerobic demand (milliliters per minute per kilogram) and mechanical power increase in direct proportion to speed. This is not surprising, since both aerobic demand and power output are viewed as markers of exercise intensity. Research has shown, however, that measures of mechanical power explain only a small amount of the interindividual variation in gait economy when examining a single speed of walking or running (18). This may be because a multitude of factors, biomechanical and otherwise, affect gait economy and the relative importance of these factors is likely to vary from individual to individual. In addition, methods of estimating mechanical power output of the body have their own limitations that limit their accuracy as an estimate of muscular effort.

## FLEXIBILITY AND GAIT ECONOMY

One fundamental component of physical fitness is musculoskeletal flexibility. Intuitively, one would speculate that good flexibility, particularly within the trunk and lower extremities, would improve gait economy. This notion is consistent with a widely held view that increasing flexibility is desirable for optimal running performance and may also contribute to reduced incidence of certain types of musculoskeletal injury. Conversely, reduced flexibility may result in a modified gait pattern (e.g., short stride length and high stride rate) that is not economical or in increased muscular effort to produce the same gait pattern because of increased resistance to motion near the extremes of the range of motion (19). This interpretation is compatible with the observations that (*a*) gait economy is known to be adversely affected by advancing age in adults and by lower-extremity orthopaedic pathologies and (*b*) musculoskeletal flexibility tends to decline with old age and joint pathologies.

Interestingly, however, Gleim et al. (20) found that high "non-pathologic musculoskeletal tightness" was modestly related to lower aerobic demands (i.e., better economy) during walking and jogging. The average aerobic demand for the third of the study sample that was determined to be the most flexible was approximately 10% higher than that for the least flexible third of the sample. It was speculated that less flexible individuals may benefit economically from greater elastic energy contributions and a reduced need to use active musculature to neutralize unproductive or undesired movements (19, 20). These rather limited and counterintuitive observations suggest a need for additional research on the specific effects of musculoskeletal flexibility on gait economy in various subject populations.

## MODIFICATION OF ECONOMY THROUGH TRAINING AND MOVEMENT EDUCATION

The preceding discussions should leave the reader with the impression that the association between gait kinematics and kinetics and economy is complex and far less definitive than intuition or common beliefs may suggest. Nevertheless, it is possible through careful testing to identify individuals who display uneconomical gait patterns, such as runners who overstride excessively. From an economy perspective, such individuals may clearly benefit from changes in their pattern of motion. However, there are conflicting findings from studies attempting to describe the effect of training and education on movement economy (15, 21–22). From these limited analyses, it is apparent that the question regarding the ability to make significant improvements in economy through biomechanical training remains unanswered.

## ► SUMMARY

For the exercise professional, biomechanics and physiology are two of the bricks in the foundation of the science of exercise. These two disciplines have considerable overlap relative to postural control and gait. This chapter briefly presents this overlap by first linking the physiology of the postural control system to the mechanics of static and dynamic postural stability and then linking gait economy to the biomechanics of walking and running. Some of the uncertainties associated with each area that affect the utility of the measures for the exercise professional are identified. These uncertainties are related to the technology and models used to collect and analyze research data, the complexity and disparity of human motor performance, and the trade-off between cost and accessibility for various methods of assessment. These uncertainties provide an impetus for continued research and development that ultimately will yield practical applications.

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