CHAPTER 5 Gait Analysis

Observing a child's gait, whether in a sophisticated computerized laboratory or simply in the hallway of a clinic, is an integral part of the orthopaedic examination. A systematic approach to gait analysis—that is, looking at the trunk and each joint moving in all three planes (sagittal, coronal, and transverse)—can yield valuable information about the patient's condition and help in establishing a treatment plan. For a child's gait to be properly examined, the patient needs to be as unclothed as deemed appropriate. The physician should observe from the level of the child, for example, sitting while examining the gait of small children. A thorough evaluation of the head, trunk, upper extremities, hips, knees, and ankles, with the child viewed from the front and from the side, should be completed. Whenever possible, the child should also be asked to run. There should be adequate space for the child to walk comfortably and naturally.

Phases of Gait

The gait cycle is divided into two phases—stance and swing (Fig. 5–1). *Stance phase* is defined as the time during which the limb is in contact with the ground and supporting the weight of the body. Conversely, *swing phase* is the time when the limb is advancing forward off the ground. During swing phase, the advancing limb is not in contact with the ground and body weight is supported by the contralateral limb. Stance phase occupies 60 percent of the gait cycle and swing phase occupies 40 percent. Both phases can be further subdivided.

STANCE PHASE

Stance phase can be divided into single-limb support and double-limb support phases. There are two periods of double-limb support, when both legs are in contact with the ground at the same time. The first period occurs when the foot makes contact with the ground at the beginning of stance phase and the weight of the body is accepted. Previously known as *heel strike,* this period is now more appropriately termed *initial contact.* The second period of double-limb support occurs at the end of stance phase just prior to swing phase, as the body weight is shifted onto the other limb and the heel rises from the floor in preparation for *push-off.*

SWING PHASE

Swing phase encompasses three separate periods—initial swing, midswing, and deceleration. *Initial swing* begins with *toe-off* and continues as the foot is raised from the ground and the limb moves forward. *Midswing* starts as the swing limb advances past the contralateral stance limb, the knee extends, and the foot travels in a forward-swinging arc. *Deceleration,* or *terminal swing,* occurs at the end of swing phase as the musculature of the forward-moving swing limb smoothly stops the limb, initial contact is made with the ground, and the gait cycle is completed.

TIME SPENT IN EACH PHASE

The percentage of time spent in each phase of gait is consistent between individuals. As the speed at which a person walks increases, the amount of time that is spent in double-limb support decreases. During running, double-limb support disappears and is replaced by *double-limb float,* a period during which neither leg is in contact with the ground.[30]

Temporal Parameters

Distance and time measurements calculated during gait analysis are referred to as *cadence parameters* (Table 5–1). *Step length* is defined as the distance between the two feet during double-limb support and is measured from the heel of one foot to the heel of the contralateral foot. Step length can differ between right and left sides. *Stride length* is the distance one limb travels during the stance and swing phases. It is measured from the point of foot contact at the beginning of stance phase to the point of contact by the same foot at the end of swing phase. *Step time* is the amount of time used to complete one step length. *Cadence* is the number

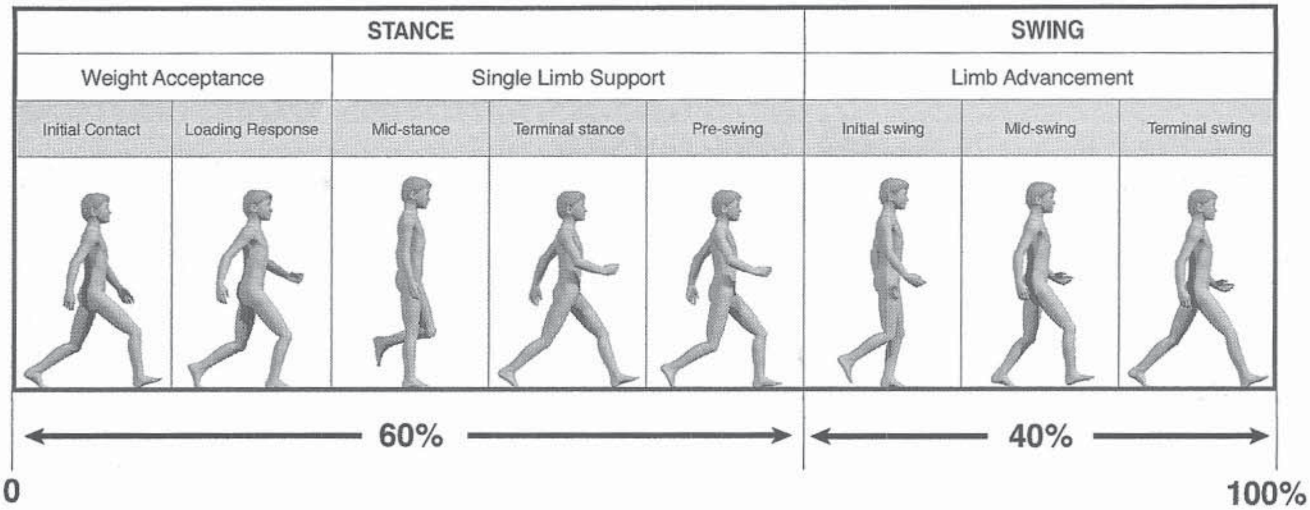

FIGURE 5–1 The gait cycle for the right leg. In *stance phase* the foot is in contact with the ground and the limb supports the weight of the body; in *swing phase* the limb advances forward off the ground.

of steps taken per minute. *Walking velocity* is the distance traveled per time (usually measured in meters per second). Normal values matched for age are available for these cadence parameters.[42]

Small children walk with increased cadence but decreased step and stride lengths, resulting in many quick, small steps. As children grow, their step and stride lengths increase and cadence decreases.[3,38,42] Step length increases linearly with increasing leg length.[42] Nomograms have been constructed to determine normal cadence parameters for children based on their height.[43]

Neurologic Control of Gait

The entire neurologic system plays a role in gait. Most of the muscular actions that occur during gait are programmed as involuntary reflex arcs involving all areas of the brain and spinal cord. The extrapyramidal tracts are responsible for most complex, unconscious pathways. Miller and Scott proposed the concept of the "spinal locomotor generator," designated neurons within the spinal cord that are responsible for reflex stepping movements.[28] Golgi tendon units, muscle spindles, and joint receptors produce neurologic feedback and serve as dampening devices for the coordination of gait. Voluntary modulation of gait (e.g., altering speed, stepping over an obstacle, changing direction) is made possible through interaction of the motor cortex.[19] The cerebellum is important in controlling balance.

A child's gait changes as the neurologic system matures.[27] Infants normally walk with greater hip and knee flexion, flexed arms, and a wider base of gait than older children. As the neurologic system continues to develop in a cephalocaudal direction, the efficiency and smoothness of gait increase.[38] However, when the neurologic system is abnormal (e.g., in cerebral palsy), the delicate control of gait is disturbed, leading to pathologic reflexes and abnormal movements.

TABLE 5–1 **Cadence Parameters**

Step length: Distance between two feet during double-limb support
Stride length: Distance one limb travels during stance and swing phases
Step time: Time needed to complete one step length
Cadence: Number of steps per minute
Walking velocity: Distance traveled per time (meters/sec)

Function of Gait

The simplest function of gait is to travel from one point to another. Normal ambulation is likened to a controlled forward fall. The swing limb comes forward to stop the fall and accept the weight of the body. The joint motions inherent in normal gait serve this purpose. Body weight is transferred from one limb to the other in a smooth fashion, and the forward momentum of the body is sustained.

Gait Energy

Although gait is designed to be energy efficient, bipedal gait is inherently unstable and inefficient. Quadripeds (e.g., dogs) run faster than humans regardless of size. Their center of gravity is suspended between the four limbs on the ground, and the vertebral and trunk muscles act to augment stride. In human gait, the center of gravity is not balanced between the limbs, nor do the trunk and spinal muscles play a significant role in walking.

To conserve energy, movement of the joints of the lower extremities minimizes the rise and fall of the center of gravity, located just anterior to the second sacral vertebra.[17] Muscular activity during gait is coordinated, and very few

TABLE 5–2 **Six Determinants of Gait**

Determinant	Strategy
Pelvic rotation	Decreases angle between limbs and ground, flattens arc of pathway of center of gravity, allowing stride to lengthen without increasing drop of center of gravity at point of initial contact
Pelvic tilt	Decreases vertical displacement of center of gravity by approximately 50 percent and shortens pendulum of limb by knee flexion in swing phase
Knee flexion after initial contact in stance phase	Reduces vertical displacement of center of gravity as weight of body is carried foward over stance limb
Foot and ankle motion	Smooths out path of center of gravity when coupled with knee motion
Knee motion	Smooths out path of center of gravity when coupled with foot and ankle motion
Lateral displacement of pelvis	Reduces lateral movement of center of gravity toward stance foot during gait cycle

concentric contractions of the muscles are required during normal ambulation. Inertia is used to its fullest advantage to lessen the work of walking.

Abnormal deviations in gait can have significant physiologic costs and substantially increase the energy required to walk. Deviations such as a weak muscle, a contracted joint, or the impediment of a cast may change gait enough to increase the metabolic requirements, thereby causing the individual to tire easily. The amount of energy required to walk can be measured by quantifying oxygen consumption and oxygen cost.[5] An indirect measure of energy expenditure is heart rate, which rises as oxygen consumption increases.[34] The physiologic cost index is calculated using the child's heart rate and walking speed, and varies little in normal children.[4] Oxygen uptake and oxygen cost during walking are greater in children less than 12 years of age than in teenagers.[44]

In 1953, Saunders, Inman, and Eberhart described the six determinants of gait by which the body reduces the amount of energy required to ambulate (Table 5–2).[35] These six "strategies" work in harmony to minimize the rise and fall of the center of gravity (vertical displacement) and the side-to-side motion of the pelvis (horizontal displacement). The end result is the establishment of a smooth pathway for the forward progression of the body's center of gravity during gait. The center of gravity displaces an average of one-eighth inch during gait, with the lowest point at 50 percent of the gait cycle during double-limb support.[35]

An example of these determinants in action is flexion of the knee coupled to ankle joint motion in stance phase. If one imagines how much rise and fall is felt when walking with a cylinder cast with knee extension, the contribution of knee flexion in stance phase (the third determinant) to minimizing energy required for walking is easily appreciated.

Kinematics

Kinematics is defined as the study of the angular rotations of each joint during movement. In simpler terms, kinematics denotes the motions observed and measured at the pelvis, hip, knee, and ankle during stance and swing phases of gait (Fig. 5–2). Kinematics can be observed in three planes: the sagittal plane (flexion and extension), the coronal plane (hip abduction and adduction), and the transverse plane (rotation of the hips, tibiae, or feet). Normal kinematics[12] for each plane are briefly described below.

SAGITTAL PLANE

In the sagittal plane, the pelvis is tilted approximately 15 degrees (Fig. 5–2A). There is minimal motion of the anterior tilt as each leg is advanced forward. Alterations in pelvic tilt can occur when there are contractures of muscles around the hip. For example, if the hamstrings are tight, the pelvis typically assumes a more posterior tilt.

The hip is flexed at initial contact and then extends fully during stance phase, as the body advances over the planted foot (Fig. 5–2B). At heel rise and push-off, the hip flexes rapidly to pull the stance phase limb off the ground. The hip continues to flex during swing phase.

The knee exhibits a more complex pattern (Fig. 5–2C). At initial contact, the knee flexes approximately 15 degrees, thereby buffering the acceptance of body weight through knee flexion. The knee then extends during stance phase to neutral position or minimal flexion. At heel rise, the knee begins to flex again, reaching maximal flexion in early swing phase to allow the foot to clear the ground as the limb advances. During the remainder of swing phase, the knee extends passively, using forward momentum. The normal kinematics of the knee are disturbed in crouch gait secondary to spasticity. Deviations range from hyperextension of the knee in stance phase if the heel cord is tight, to flexion in stance phase due to tight hamstrings, to inability to flex the knee in swing phase due to inappropriate rectus femoris action.[14]

Ankle sagittal plane kinematics start with a neutral ankle at initial contact, when the heel normally strikes the ground (Fig. 5–2D). The ankle then plantar flexes 5 to 10 degrees as the forefoot comes to rest on the ground. This plantar flexion is known as *first rocker.* The ankle dorsiflexes throughout midstance as the tibia moves forward over the plantigrade foot (*second rocker*). During *third rocker,* the ankle plantar flexes and the heel rises to prepare for push-off (Fig. 5–3). Dorsiflexion of the ankle back to a neutral position is seen during swing phase to allow for clearing of the foot. In patients with peroneal nerve palsies and foot drops, dorsiflexion during swing phase is impaired. The individual compensates by hyperflexing the knee and hip in swing phase to avoid dragging the toes, a pattern called *steppage gait.*

CORONAL PLANE

Pelvic obliquity is observed in the coronal plane (Fig. 5–2E). Each hemipelvis rises slightly during swing phase to augment the ability to advance the swing limb. Pelvic rise must be accompanied by a contralateral fall, so the stance phase hemipelvis drops slightly. Accentuated pelvic obliquity may be seen in patients with limb length discrepancy, and accen-

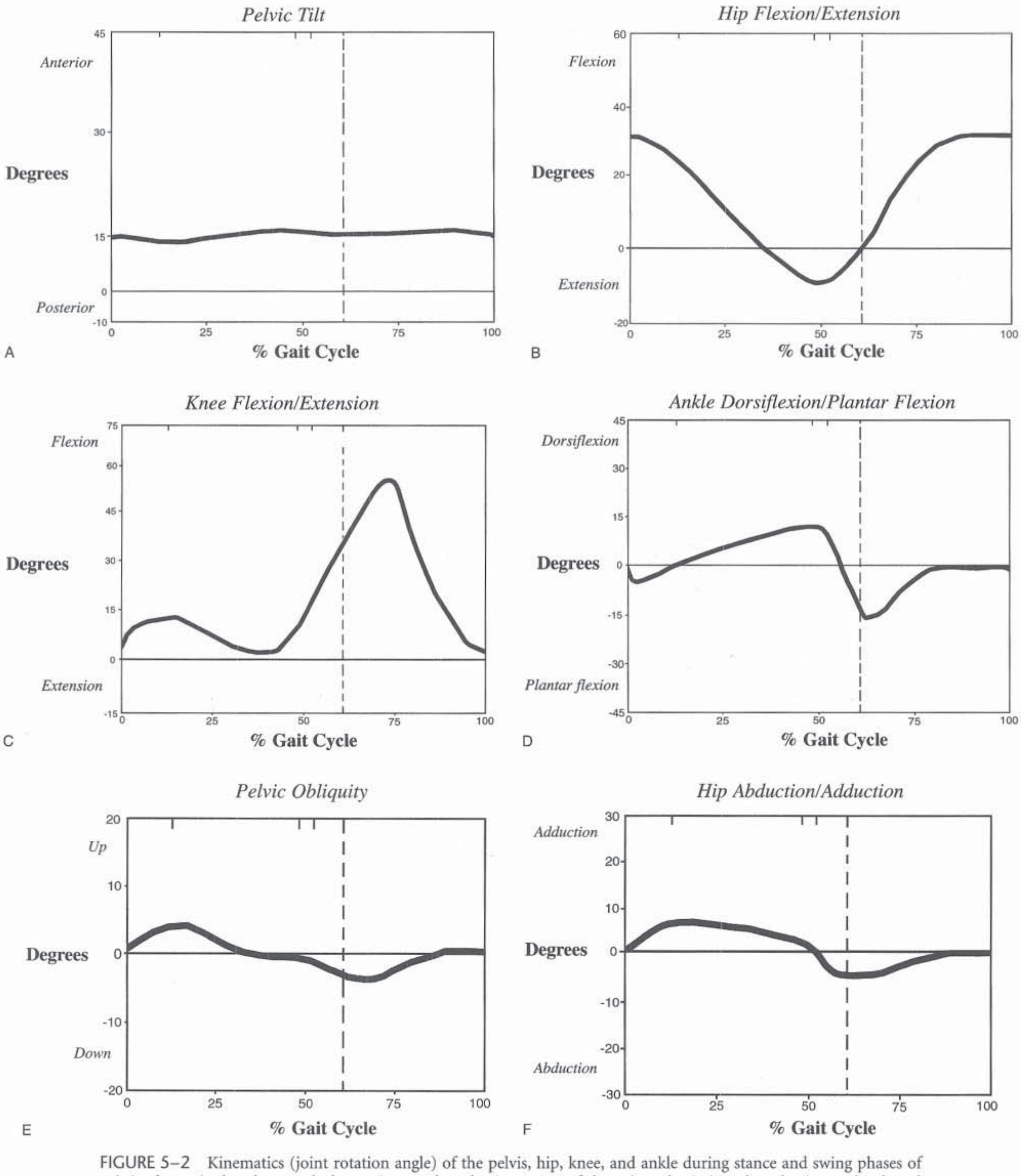

FIGURE 5–2 Kinematics (joint rotation angle) of the pelvis, hip, knee, and ankle during stance and swing phases of gait in the sagittal and coronal planes. Stance phase begins at 0% of the gait cycle. Swing phase begins at the dotted vertical line. **A,** Anterior tilt of the pelvis; **B,** hip flexion and extension; **C,** knee flexion and extension; **D,** ankle plantar flexion and dorsiflexion; **E,** pelvic obliquity rise and fall; and **F,** hip adduction and abduction.

tuated pelvic drop in swing phase is seen in patients with abductor lurches or *Trendelenburg gait* (e.g., patients with myelomeningocele).

Minimal hip motion in the coronal plane occurs during normal gait (Fig. 5–2F). Each hip slightly adducts during stance phase and abducts during swing phase. If a patient has a scissoring gait, as is often seen in cerebral palsy, the adduction is more extreme and may occur throughout the gait cycle, leading to difficulty advancing the swing limb.

TRANSVERSE PLANE

In the transverse plane, kinematic data measure rotation. The pelvis and hips rotate minimally during gait. The tibiae

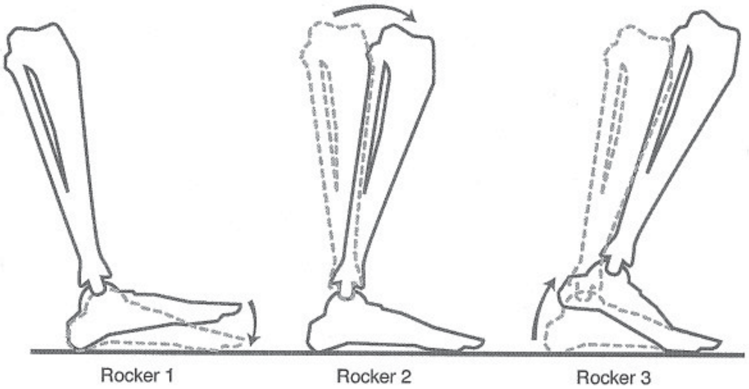

FIGURE 5–3 Kinematics of the ankle in the sagittal plane: *First rocker*—ankle plantar flexes 5 to 10 degrees as the forefoot comes to rest on the ground; *second rocker*—ankle then dorsiflexes throughout midstance as the tibia moves forward over the plantigrade foot; *third rocker*—ankle then plantar flexes and the heel rises to prepare for push-off.

should not exhibit a range of motion but, instead, have a mild fixed external rotation. The *foot-progression angle* is the angle the foot makes with the path the subject is walking, which can be likened to footprints in the sand at the beach. The normal foot-progression angle is approximately 10 to 15 degrees external (Fig. 5–4).

Muscle Activity

The source of the energy required to begin walking is provided by muscle activity (Table 5–3). Once started, the transition of the body to a steady gait pattern is accomplished in approximately three steps.[26] Gait is maintained by a combination of gravity, momentum, and muscle contraction. The presence of electrical activity in the muscles of the lower extremity is recorded via electrodes, which are applied to the skin surface for superficial muscles or inserted into the muscle as fine wire electrodes for deeper muscles such as the posterior tibialis.[21,48] There are set patterns to muscle activity observed on electromyography in normal children during gait (Fig. 5–5),[47] and these patterns vary with walking velocity.[37] Deviations from these normal patterns are seen in pathologic gait, such as the gait exhibited by patients with cerebral palsy.[32]

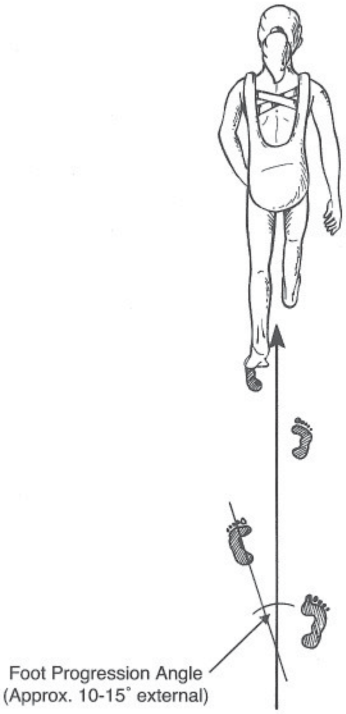

FIGURE 5–4 Illustration of the foot-progression angle, the angle the foot makes with the path the subject is walking (often likened to "footprints in the sand"). The normal foot-progression angle is approximately 10 to 15 degrees external.

TYPES OF MUSCLE CONTRACTION

Two types of muscle contractions occur during gait. A concentric contraction occurs when the muscle shortens, thereby generating power. An eccentric contraction occurs when the muscle lengthens despite electrical contraction. Concentric contractions generate power and accelerate the body forward. Eccentric contractions slow down and stabilize joint motions during gait, thereby minimizing energy requirements. Muscles undergoing eccentric contractions outnumber those with concentric contractions during gait.

CONCENTRIC CONTRACTIONS

Two concentric contractions occur at terminal stance. The gastrocsoleus contracts to lift the heel off the ground and push-off. The iliopsoas muscle also contracts concentrically, flexing the hip and pulling the stance phase limb off the ground at terminal stance and early swing. The gastrocsoleus and iliopsoas muscles are believed to be the two primary accelerators of gait, although controversy exists as to which muscle contributes the most toward forward propulsion of the body.[33,40,45]

ECCENTRIC CONTRACTIONS

Eccentric contractions slow down and smooth joint motions. The anterior tibialis muscle contracts eccentrically at

TABLE 5–3 **Muscle Activity During Gait**

Types of muscle contraction
Concentric—generates power and accelerates body forward
Eccentric—slows down and stabilizes joint motions during gait
Stance phase: Muscles of leg and foot work to stabilize plantigrade foot
Swing phase: Momentum generated by gastrocsoleus and hip flexors at terminal stance carries leg forward

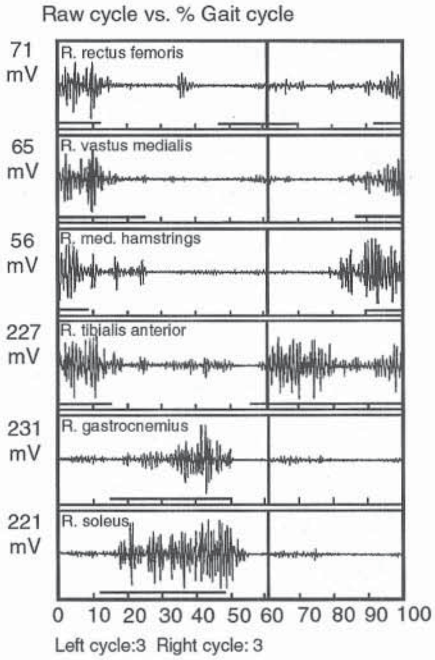

FIGURE 5–5 Normal electromyographic patterns of muscle activity during gait.

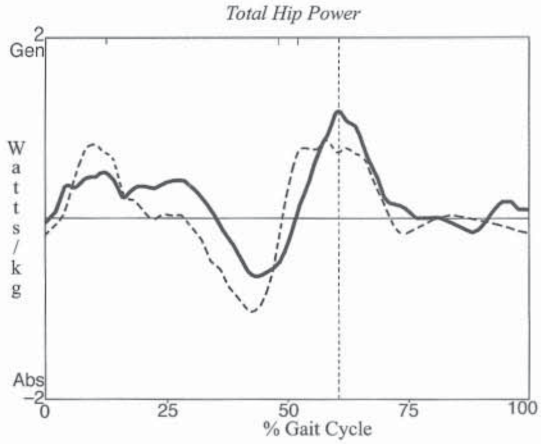

FIGURE 5–7 Kinetic graph of hip power (measured in watts/kg; Gen, generation (+); Abs, absorption (−)). Note the burst of power generation at terminal stance as the iliopsoas pulls the leg off the ground.

initial contact, firing during plantar flexion of the ankle as the foot is lowered to the ground. In doing so, the foot is gently lowered to the floor and acceptance of body weight can occur gradually. If the anterior tibialis muscle does not fire, the foot "slaps" to the floor at initial contact. The gastrocsoleus contracts eccentrically throughout the second rocker of stance phase, controlling the rate of dorsiflexion of the ankle as the tibia advances forward over the plantigrade foot.[41] In the absence of normal gastrocsoleus strength, the ankle dorsiflexes excessively, resulting in poor push-off and calcaneus gait.[22,36]

A powerful eccentric contraction occurring during weight acceptance in stance phase is that of the hip abductors. The abductors of the stance phase limb fire in order to limit contralateral pelvic drop as the swing limb comes off the ground. Meanwhile, the stance limb hip adducts slightly. If the gluteal muscles are weak, they cannot generate a sufficient eccentric contraction and the hemipelvis of the swing limb drops, resulting in a Trendelenburg gait. The trunk can compensate for the pelvic drop by swaying over the stance limb. This brings the center of gravity over the affected hip and lessens the pelvic drop. Patients with Trendelenburg gait use more energy to walk.

MUSCLE ACTIVITY DURING STANCE AND SWING PHASES

More muscle activity occurs during stance phase than during swing phase. During stance phase, the muscles of the leg and foot work to stabilize the plantigrade foot. In swing phase, momentum generated by the gastrocsoleus and hip flexors at terminal stance carries the leg forward. The main

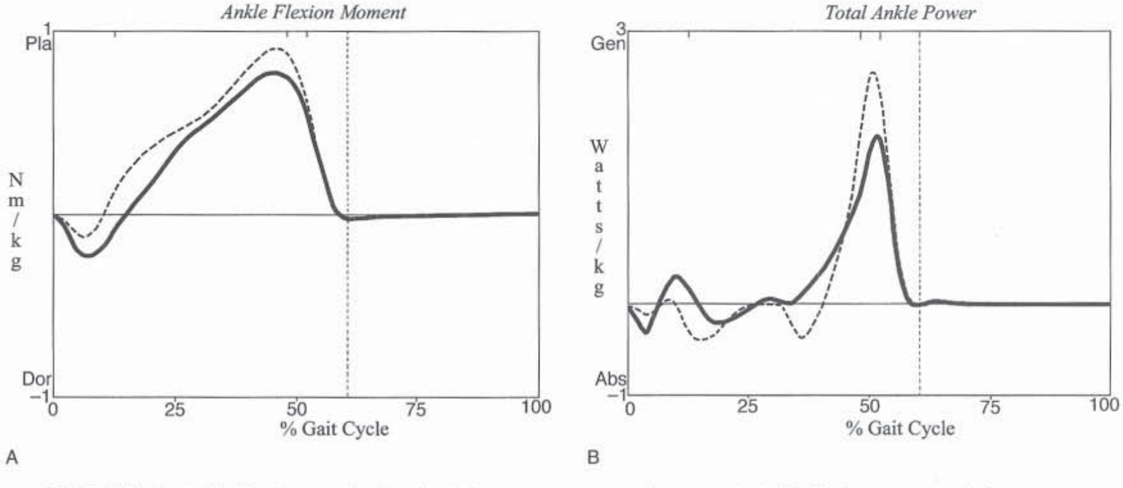

FIGURE 5–6 Ankle kinetics graphs showing joint net moments and powers. **A,** Ankle flexion moment during stance (measured in newton · meter/kg, or Nm/kg). **B,** Total ankle power (measured in watts/kg; Gen, generation (+); Abs, absorption (−)). Note the burst of power at terminal stance due to the concentric contraction of the gastrocsoleus and the short period of power absorption at initial contact.

concentric contraction that occurs during swing phase is that of the anterior tibialis, which dorsiflexes the foot for easier clearance during swing and pre-positions the foot for initial contact.

Kinetics

Kinetics is the study of the forces generated by the joints during gait. Kinetic data are reported as moments (forces acting about a center of rotation) and powers. These forces can be measured from force plates in a gait analysis laboratory. If one knows the motion occurring kinematically at a joint and which muscles are active during that period, the kinetic forces can be better understood.

For example, the anterior tibialis fires at initial contact while the ankle is plantar flexing to lower the foot to the ground. The result of this eccentric contraction is power absorption, the magnitude of which can be measured in the laboratory (Fig. 5–6). The gastrocsoleus fires at terminal stance as the ankle plantar flexes at push-off. This concentric contraction leads to power generation. There are characteristic patterns of power generation and absorption at each joint (Fig. 5–7).[20,31] Kinetics is dependent on walking velocity.[8,45] An adult pattern of kinetics is probably reached by 5 years of age.[31]

Pathologic Gait

Deviations from normal gait occur in a variety of orthopaedic conditions. Disorders that result in muscle weakness (e.g., spina bifida, muscular dystrophy), spasticity (e.g., cerebral palsy), or contractures (e.g., arthrogryposis) lead to abnormalities in gait.[6,7] Pathologic gaits are described in greater detail in their respective neuromuscular chapters.

Gait Analysis Laboratories

The study of gait in a laboratory dates back to 1957, when Inman began evaluating joint motion.[17] From that start, gait analysis was used primarily to document neuromuscular gait, first in patients with poliomyelitis, then in those with cerebral palsy and myelomeningocele. Over time, computer software has been developed that allows three-dimensional analysis. Although most software measures motion at the pelvis, hip, knee, and ankle, models have recently been developed to assess motion in smaller joints (i.e., segments of the foot) and in the trunk.

Gait analysis is most often used for preoperative planning and for documentation of postoperative outcome in patients with cerebral palsy (Fig. 5–8).[6,10,11,13,25,46] Motion analysis now is also being applied to spinal deformity,[23] and it has been

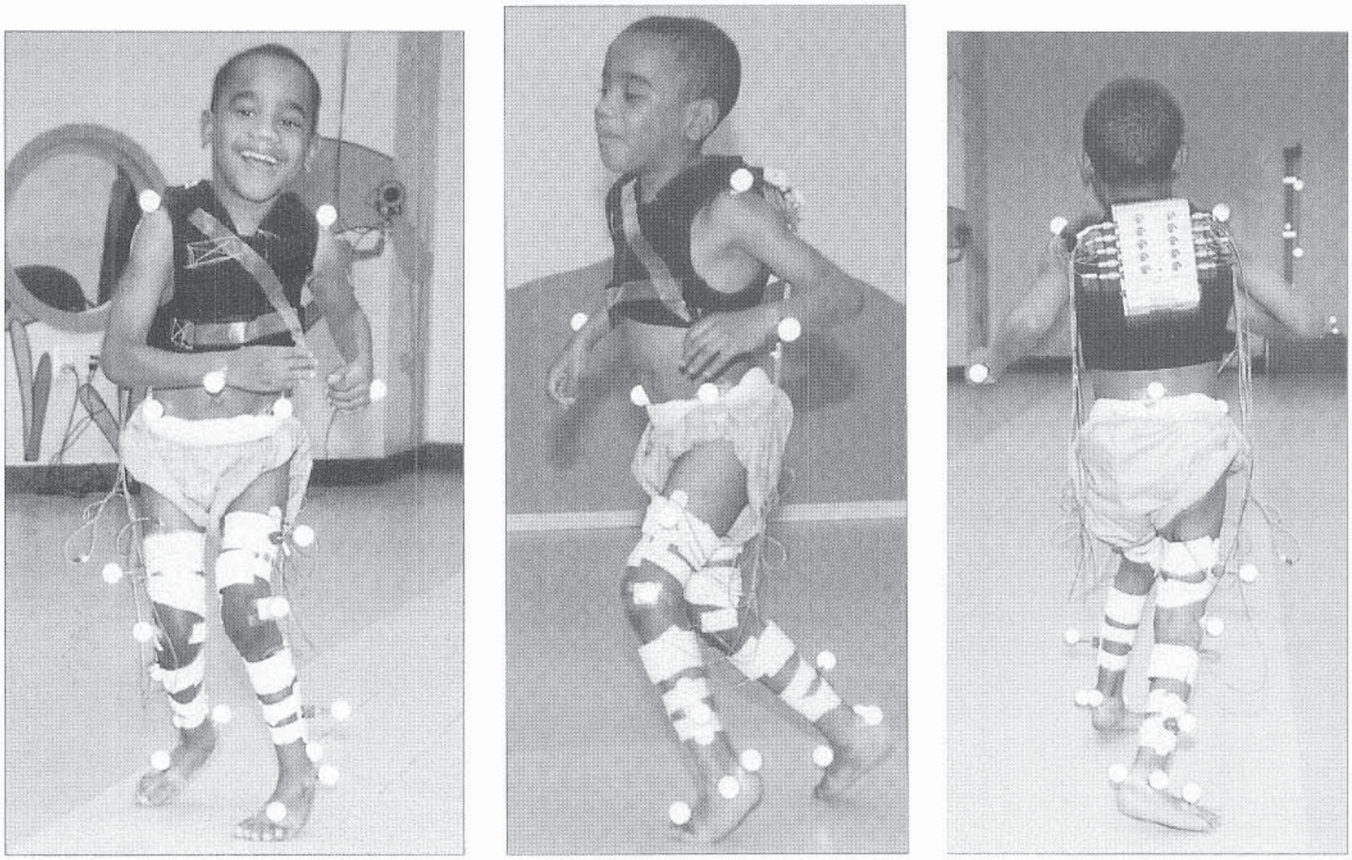

FIGURE 5–8 Six-year-old boy with spastic diplegia undergoing gait analysis. Markers are used to collect kinematic data; electromyographic data are being simultaneously gathered.

used as an outcome measurement for evaluating surgical treatment of nonneurologic orthopaedic conditions such as clubfeet, fractures, and degenerative joint arthritis.[2,9,15,22,24,29,39] Research in motion analysis continues in the fields of arthroplasty, prosthetics,[1] and orthotics,[16] stimulating development of newer products and lending a scientific basis to new and innovative designs.

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