Abstract

The act of walking involves the complex interaction of muscle forces on bones, rotations through multiple joints, and physical forces that act on the body. Walking also requires motor control and motor coordination. Many orthopaedic surgical procedures are designed to improve ambulation by optimizing joint forces, thereby alleviating or preventing pain and improving energy conservation. Gait analysis, accomplished by either simple observation or three-dimensional analysis with measurement of joint angles (kinematics), joint forces (kinetics), muscular activity, foot pressure, and energetics (measurement of energy utilized during an activity), allows the physician to design procedures tailored to the individual needs of patients. Motion analysis, in particular gait analysis, provides objective preoperative and postoperative data for outcome assessment. Including gait analysis data in treatment plans has resulted in changes in surgical recommendations and in postoperative treatment. Use of these data also has contributed to the development of orthotics and new surgical techniques.

Characteristics of Gait

The Gait Cycle

A complete gait cycle is defined as the movement from one foot strike to the successive foot strike on the same side (Fig. 1). The stance phase, which begins with foot strike and ends with toe-off, usually lasts for about 62% of the cycle; the swing phase, which begins with toe-off and ends with foot strike, lasts for the final 38%. During each cycle, a regular sequence of events occurs. Expressing each event as a percentage of the whole normalizes the gait cycle. Initial foot strike, or initial contact, is designated as 0%; the successive foot strike of the same limb is designated as 100%.

The events of the gait cycle, which define the functional periods and phases of the cycle, are foot strike, opposed toe-off, reversal of fore shear to aft shear, opposite foot strike, toe-off, foot clearance, tibia vertical, and successive foot strike (Tables 1 and 2). The older terms “heel strike” and “foot flat” should not be used because these events may be absent in subjects with pathologic gait. The stance phase is divided into three major periods: initial double-limb support, or load-
ing response; single-limb stance; and second double-limb support, or preswing (Fig. 1). The defining events for initial double-limb support are foot strike and opposite toe-off. The defining events for single-limb stance are opposite toe-off and opposite foot strike. Single-limb stance is further divided by the event of reversal of fore to aft shear into midstance and terminal stance. Terminal stance refers to terminal single-limb stance and should not be confused with second double-limb support.

The swing phase is divided into initial swing, midswing, and terminal swing. The defining sequential events for initial swing are toe-off and foot clearance. Midswing begins with foot clearance and ends with tibia vertical. Terminal swing begins with tibia vertical and ends with foot strike.

**Temporal Parameters**

Temporal (time-distance) parameters include velocity, which is reported in centimeters per second or meters per minute (mean normal for a 7-year-old child, 114 cm/s) and cadence, or number of steps per minute (mean normal for a 7-year-old child, 143 steps/min). Mean velocity for adults more than 40 years of age is 123 cm/s; mean cadence is 114 steps/min. Step length is the distance from the foot strike of one foot to the foot strike of the contralateral foot. Stride length is the distance from one foot strike to the next foot strike by the same foot. Thus, each stride length comprises one right and one left step length.

**Force**

Gait is an alternation between loss of balance and recovery of balance, with the center of mass of the body shifting constantly. As the person pushes forward on the weight-bearing limb, the center of mass (COM) of the body shifts forward, causing the body to fall forward. The fall is stopped by the non-weight-bearing limb, which swings into its new position just in time.

The forces that act on and modify the human body in forward motion are gravity, counteraction of the floor (ground-reaction force), muscular forces, and momentum. The pathway of the COM of the body is a smooth, regular curve that moves up and down in the vertical plane with an average rise and fall of about 4 cm. The low point is reached at double-limb support, when both feet are on the ground; the high point occurs at midstance. The COM is also displaced laterally in the horizontal plane during locomotion, with a total side-to-side dis-
distance traveled of about 5 cm. The motion is toward the weight-bearing limb and reaches its lateral limits in midstance. The combined vertical and horizontal motions of the COM of the body describe a double sinusoidal curve.

Determinants of Gait
Saunders et al. defined six basic determinants of gait. Absence of or impairment of these movements directly affects the smoothness of the pathway of the COM. The six determinants are pelvic rotation, pelvic list (pelvic obliquity), knee flexion in stance, foot and ankle motion, lateral displacement of the pelvis, and axial rotations of the lower extremities. Loss or compromise of two or more of these determinants produces uncompensated and thus inefficient gait.

Perry described four prerequisites of normal gait: stability of the weight-bearing foot throughout the stance phase, clearance of the non-weight-bearing foot during swing phase, appropriate pre-positioning during terminal swing of the foot for the next gait cycle, and adequate step length. Gage et al. added energy conservation as the fifth prerequisite of normal gait.

Gait Analysis
Initially, a complete physical examination that includes measuring the range of motion of at least the hip, knee, and ankle joints should be performed on all patients with gait problems. The presence of any muscle or joint contractures, spasticity, extrapyramidal motions, muscle weakness, or pain should be determined and charted in a systematic way. Any abnormal neurologic signs also should be documented because these can contribute to gait abnormalities. Radiographically documented abnormalities of the lumbar spine, pelvis, or lower extremities, including rotational malalignment, should be documented.

Effective evaluation of a patient’s gait requires a systematic approach to the observation of the gait. First, to assess for coronal plane abnormalities such as trunk sway, pelvic obliquity, hip adduction/abduction, and possibly rotation, the patient should be asked to walk both

### Table 1
Gait Cycle: Events, Periods, and Phases

<table>
<thead>
<tr>
<th>Event</th>
<th>% Cycle</th>
<th>Period</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foot strike</td>
<td>0</td>
<td>Initial double-limb</td>
<td>Stance, 62% of cycle</td>
</tr>
<tr>
<td>Opposite toe-off</td>
<td>12</td>
<td>Single-limb stance</td>
<td></td>
</tr>
<tr>
<td>Opposite foot strike</td>
<td>50</td>
<td>Second double-limb</td>
<td></td>
</tr>
<tr>
<td>Toe-off</td>
<td>62</td>
<td>Initial swing</td>
<td></td>
</tr>
<tr>
<td>Foot clearance</td>
<td>75</td>
<td>Midswing</td>
<td></td>
</tr>
<tr>
<td>Tibia vertical</td>
<td>85</td>
<td>Terminal swing</td>
<td></td>
</tr>
<tr>
<td>Second foot strike</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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### Table 2
Gait Cycle: Periods and Functions

<table>
<thead>
<tr>
<th>Period</th>
<th>% Cycle</th>
<th>Function</th>
<th>Contralateral Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial double-limb</td>
<td>0-12</td>
<td>Loading, weight transfer</td>
<td>Unloading and preparing for</td>
</tr>
<tr>
<td>support</td>
<td></td>
<td></td>
<td>swing (preswing)</td>
</tr>
<tr>
<td>Single-limb stance</td>
<td>12-50</td>
<td>Support of entire body weight; center of mass moving forward</td>
<td>Swing</td>
</tr>
<tr>
<td>Second double-limb</td>
<td>50-62</td>
<td>Unloading and preparing for swing (preswing)</td>
<td>Loading, weight transfer</td>
</tr>
<tr>
<td>support</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial swing</td>
<td>62-75</td>
<td>Foot clearance</td>
<td>Single-limb stance</td>
</tr>
<tr>
<td>Midswing</td>
<td>75-85</td>
<td>Limb advances in front of body</td>
<td>Single-limb stance</td>
</tr>
<tr>
<td>Terminal swing</td>
<td>85-100</td>
<td>Limb deceleration, preparation for weight transfer</td>
<td>Single-limb stance</td>
</tr>
</tbody>
</table>

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toward and away from the observer. Each segment (trunk, thigh, leg, and foot) should be observed while the patient walks each way, and any abnormalities should be charted. The patient should then walk back and forth in front of the observer to allow evaluation of sagittal plane abnormalities such as pelvic tilt and flexion and extension of the hip, knee, and ankle. Axial or rotational abnormalities are difficult to quantify by simply watching the patient walk. If such abnormalities are suspected, the patient should be videotaped from the front and from the side. This facilitates analysis because the videotape can be slowed or stopped for closer observation.

Typical observations in a child with an antalgic gait would include a limp in which the time spent on the affected limb is disproportionately short. In the coronal plane, a trunk lean away from the painful side might be noted. In the sagittal plane, decreased trunk motion as the patient tries to decrease the motion in a particular joint may be apparent, as well as decreased step length and diminished time spent on the affected limb. In a child with Trendelenburg gait, one would note in the coronal plane that the child leans over the affected hip to compensate for ipsilateral abductor weakness. On the sagittal view, disproportionate time spent on the affected limb is often noted.

**Gait Analysis in the Motion Analysis Laboratory**

Observational gait analysis is limited because it cannot determine the biomechanical causes of an abnormal gait. Although one can infer causation, without measurements of kinetics or of muscular activity by dynamic electromyography (EMG), one can rarely be sure of the etiology of a problem. For example, using observational gait analysis and a good physical examination, the physician might determine that a child with an equinovarus foot demonstrates swing-phase varus and recommend a procedure such as a split posterior tendon transfer. However, the same gait pattern can have other etiologies, such as tibialis anterior spasticity with a normal tibialis posterior pattern. The gait laboratory can provide much more information, such as EMG, force plate, foot pressure, and kinetic data, which may clarify the picture. It is often difficult in a short clinical examination to determine the amount of extrapyramidal activity (for example, athetosis, ataxia, or dystonia) that is present. This is much easier to determine by using the tools of the motion analysis laboratory than by simple observation.

**Kinematics**

Kinematics measures the dynamic range of motion of a joint (or segment). On simple observation, rotational abnormalities in the transverse plane may be confused with sagittal or coronal problems. For example, a child with severe femoral anteversion may appear to have increased adduction or knee valgus when viewed from the front. Three-dimensional motion analysis helps eliminate some of this ambiguity of visual analysis.

In the motion analysis laboratory, standardized reflecting skin markers or markers mounted on wands are captured by charge-coupled device (CCD) cameras while the patient walks down a walkway (Fig. 2). These cameras are positioned so that they yield information that can be subjected to three-dimensional data analysis. The images are then processed by a computer to derive the graphs of the kinematics. The same joint range of motion that was observed on visual inspection can then be quantified and plotted. The data can be compared with age-specific normal values and different conditions of walking (eg, barefoot, with braces, with shoes). They can also be easily compared with previous gait studies, such as those done preoperatively. The three-dimensional data permit the assessment of dynamic rotational problems that cannot be assessed through routine observation. Stride-to-stride differences can be assessed and plotted to determine the variability of the gait. The gait of a patient with athetosis or ataxia will be markedly variable, which may be missed in the clinical setting.

**Kinetics**

Kinetics describes the forces acting on a moving body. The net moment is determined by the ground reaction force, the center of rotation of each joint, and the center of mass, acceleration, and angular velocity of each segment. These joint moments and forces are derived from force plate measurements and kinetic data. Also required are anthropometric data (eg, leg length, foot length). The patient is instructed to walk on a surface that contains...
one or more force plates. The transducers are set up such that vertical force, fore-aft shear, medial-lateral shear, and torque can be measured and compared with normal values. When these data are combined with the kinematic and anthropometric data, a representation of the force at each joint (joint moment) can be determined.

Kinetics parameters can be reported as internal moments, in which the force at a joint is assumed to be secondary to muscle activity. Other factors such as ligament stretch, joint morphology, or contractures also may contribute to the moment. Kinetics parameters also can be described as external moments, in which the force acting on a joint is thought to be a response to the ground-reaction force. External and internal moments have the same numeric value but are opposite in sign (positive or negative).

Three-dimensional moments are particularly helpful in evaluating patients who have joint problems such as osteoarthritis, genu varum, or contractures. They also may help in the evaluation of prosthetic problems in amputees. Shoes and orthotics can be designed to decrease forces at joints or pressure areas in children with cerebral palsy and in patients with rheumatoid arthritis or diabetes. Kinetic measurements such as these are helpful in the design and evaluation of many of the new biomechanically based orthopaedic surgical procedures.

Muscle Activity

Although the action of the muscles can be inferred from watching a patient walk, it is often difficult to determine whether a muscle is active or inactive during a particular motion. This knowledge is sometimes very important in determining which therapeutic intervention will correct the problem, and it is critical in helping to determine which muscles should be used as a “motor” in a muscle transfer. For example, the stiff-knee gait in a child with cerebral palsy may have several different etiologies. The EMG may be used to determine if the child has swing-phase rectus femoris activity, indicating that the child might benefit from a rectus femoris–to–hamstring muscle transfer. If the child were to have swing phase activity of the other quadriceps muscles or cocontraction of the hamstring muscles, the outcome of the rectus femoris transfer would not be as predictable.

Surface or fine-wire EMG is used to measure the muscle impulses. Surface electrodes suffice to measure the activity of muscle groups such as the gastrocnemius-soleus or the adductors. Cross-talk from adjacent muscles can be a problem, but this usually does not alter clinical decisions. In deep, buried muscles (eg, tibialis posterior or flexor digitorum profundus), however, fine-wire electrodes must be placed to get meaningful information. The information gained from fine-wire EMG must be weighed against the minimal discomfort this procedure causes the patient. Young children often are not able to cooperate with this procedure, which is also somewhat technically demanding.

Foot switches or similar timing devices are used to time the EMG data to the gait cycle. The raw data obtained may be presented as such or averaged. When EMG data are combined with the kinematic and kinetic data, a more complete understanding of the patient’s gait can be obtained.

Fine-wire EMG has been shown to be useful in evaluating some of the muscles of the lower extremities, such as the iliacus, rectus femoris, tibialis anterior, posterior tibialis, and flexor hallucis longus. It is almost always required for the muscles of the upper extremity because these small muscles have significant cross-talk.

Foot Pressure

The measurement of foot pressure is helpful with subtle valgus foot deformities and with conditions that cause increased pressure at certain points, such as diabetes or Charcot foot. Measurement of foot pressure can be used both to define the problem and to determine if the treatment (eg, an orthotic, shoe modification, or surgery) has improved the pressure concentration.

There are two main types of foot pressure measurement systems, those in which the forced transducers are placed in the patient’s shoes and those in which the patient steps on a force plate transducer. Both have advantages and disadvantages, but they provide similar information. The resulting data are usually charted on a colored grid in which different colors represent different pressure concentrations.

Energetics

The main disadvantage of gait abnormalities from any cause is that they force the patient to expend more energy. The goals of achieving a normal gait therefore are not only to decrease the stresses on muscles and joints but also, most importantly, to decrease the energy required to move from place to place. Energetics is the measurement of energy expenditure. Several methods are used to measure energy expenditure. One method is to collect and measure the carbon dioxide and oxygen expired during ambulation. Another method is to take the patient’s pulse when a steady state has been achieved while walking. A third option is to use force plate data to determine the mechanical cost of work done by the patient while walking.

The first method involves collecting expired gases as the patient exercises. The collection apparatus may be a metabolic cart that is propelled by a technician who walks next to
the subject, or it may be a portable apparatus that is worn as a backpack or waist belt. Using mathematical conversion models, energy utilization can be determined. Limitations of this method include the artificiality of having a breathing apparatus in place and the fact that oxygen consumption may vary throughout the exercise trial, throughout the day, or from day to day.

The heart rate method has the advantage that the pulse is easily measured but the disadvantage of being rather imprecise. Also, as with the oxygen-measurement method, anxiety or other factors such as ambient room temperature, variability in body temperature, and training effects can affect the heart rate and therefore decrease the utility of the results.

In the third method, work is calculated using force plate data and the translation of the body's COM. This method does not suffer from the same disadvantages as the meta-

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**Figure 3** Preoperative temporal parameters and kinematics for a boy aged 4 years 5 months (dashed lines) who presented with bilateral toe-walking and internal rotation of the limbs, compared with those of a normal 4-year-old child (solid lines). The vertical lines indicate toe-off. The percentage of the gait cycle to the left of this line represents the stance phase, and the percentage of the gait cycle to the right of this line represents the swing phase.
bolic methods because the mechanical work is measured directly. However, it remains to be demonstrated that the results are reproducible in a clinical setting.

Despite the limitations of these methods, assessment of energy expenditure is an excellent outcome measurement. If the goal of a procedure is a more efficient gait, then measuring the energy expenditure before and after the procedure is a valid way to determine success.

**Case Study**

A boy aged 4 years 5 months presented with bilateral toe-walking and internal rotation of the limbs. He wore bilateral ankle-foot orthoses but was falling up to 20 times per day. He was able to ride a tricycle and climb stairs and had an endurance of about one half mile. The experienced referring orthopaedic surgeon thought that the boy should have bilateral heel cord lengthenings. The physical examination demonstrated mild hip flexion contractures and an increase in femoral internal rotation of 70° bilaterally. The popliteal angle was 150° (30°). The boy also had plantar flexion contractures at the ankle of 15°, hyperreflexia, and a positive Duncan-Ely test suggestive of rectus femoris spasticity.

The kinematic data demonstrated coronal plane abnormalities included increased pelvic obliquity in stance phase and increased adduction throughout the cycle. Sagittal plane abnormalities included increased anterior pelvic tilt, minimally increased flexion of the hip, diminished and delayed peak knee flexion in swing, and a marked increase in ankle plantar flexion throughout the gait cycle. Transverse plane abnormalities included normal pelvic rotation; increased femoral rotation; tibial rotation, which followed the femoral rotation; and an internal foot progression angle (Fig. 3).

The EMG data showed full-cycle activity of the rectus femoris but, most importantly, increased activity in swing phase; full-cycle activity of the vastus lateralis; minimal but out-of-phase activity of the hip adductors; mostly stance-phase activity of the gastrocnemius-soleus; and full-cycle activity of the tibialis anterior (Fig. 4).

Based on the physical examination, a review of the videotape, and integration of the gait data, the following procedures were recommended: bilateral derotational osteotomies of the femurs, psoas lengthening at the pelvic brim, adductor longus recession, distal medial hamstring lengthening, rectus to semitendinosus transfer, and Strayer gastrocnemius recession. Some of these procedures could have been predicted by a meticulous examination of the child, but others may have been missed. For example, the recommendation for the rectus transfer was based on kinematic and EMG data.

One year after the surgery, the boy was no longer falling. He was also playing soccer and learning inline skating. Kinematic plots showed that the parameters had all returned nearly to normal (Fig. 5).

**Applications of Gait Analysis**

**Developmental Disabilities**

The most common use for clinical gait laboratories in the United States is for evaluating children with developmental disabilities, particularly those due to cerebral palsy and myelomeningocele. These children have very complex gait problems combined with the underlying neurologic insult. Complete evaluation of these patients in a clinical setting is often very difficult, and gait analysis has been helpful in formulating treatment plans. DeLuca et al reviewed 91 patients who had been recommended for surgery by experienced physicians; they then compared the recommendations based on gait analysis. They found that the addition of gait analysis data resulted in changes in surgical recommendations in 52% of the patients, with an associated reduction in the cost of surgery (as well as the effect on the patients from avoiding...
The development of new surgical technique and orthotics has benefited from research performed in motion analysis laboratories. Clinicians often must decide whether an orthotic is needed and how to determine the appropriate orthotic. Several studies that have evaluated the efficacy of various orthotics in the management of children with developmental disabilities have practical applications for patient management.

**Total Joint Arthroplasty**

Total joint replacement for arthritic hips and ankles has been evaluated extensively for patient satisfaction, biomechanical properties, and longevity. Additionally, studies also have evaluated the effect of these procedures on gait using objective

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**Figure 5** Postoperative temporal parameters and kinematics for the 6-year-old patient described in Fig. 3 (dashed line) compared with those of a normal 6-year-old child (solid line).
gait analysis. Cruciate-sparing and cruciate-retaining total knee arthroplasties showed important differences in stability and forces across the knee joint, which may have implications for patient satisfaction as well as longevity of the prosthesis. New designs have taken gait analysis data into consideration. The effect of staging for bilateral knee arthroplasties was evaluated by Borden et al, who found that whether the procedure was done unilaterally or bilaterally had little effect on the biomechanical outcome.

Amputations

The gait laboratory can be used to evaluate the gait of patients with lower extremity amputations as well as the upper extremity function in upper extremity amputees. Problems with prosthesis fitting and with primary and compensatory gait deviations also can be easily documented with a complete gait study. Energy expenditure and gait efficiency for various levels of amputation and different prostheses have been well documented using gait analysis. The design of new prostheses also has been aided.

Sports Medicine

Gait laboratories with high-speed cameras and high-resolution video systems can evaluate any sports activity that can be performed within the capture area of the system. Overhand and underhand throwing activities have been evaluated, and the resultant data have been used to recommend more efficient motions as well as to prevent injuries. The batting motion in baseball has also been studied. Other sports, such as tennis, golf, running, and bicycling, also have been studied, and the results are used to enhance the performance of athletes.

Several studies have evaluated the effect of anterior cruciate ligament injuries and reconstructions on gait. Andriacchi and Bira have demonstrated the muscle substitution patterns about the knee after anterior cruciate ligament injuries. Torry et al found that knee effusion, even without an injury, can lead to gait changes involving the entire lower extremity.

The Future of Gait Analysis

Kaufman has listed several aspects of gait analysis that could make it an even more clinically useful tool in the future. He foresees that advances in computer power, data acquisition systems, and visualization of human motion via patient-specific computer animation will provide clinically useful information in almost real time, such as information gained from a computed tomography scan or magnetic resonance imaging. If artificial intelligence becomes a reality, its application could help standardize the interpretation of the vast amounts of data obtained in three-dimensional motion studies. Using data derived from gait analysis, modeling of the body can be used to evaluate clinical problems as well as possible solutions. As gait analysis becomes more accepted throughout the orthopaedic field, standardization of techniques and the ability to communicate between laboratories and across different platforms are needed. The efforts currently being made will improve the efficacy of gait analysis even further.

The entertainment industry has embraced the concept of three-dimensional motion analysis for music videos, video games, Internet applications, computer animation, and even computer-generated actors. Application of this technology to medicine by combining three-dimensional images with gait analysis data may provide a patient-specific virtual reality experience that can predict the outcome of surgeries.

Summary

Gait analysis ranges from simple observation of a walking patient to computerized measurements of kinematics, kinetics, muscular activity, foot pressure, and energetics done in the motion analysis laboratory. Including these data in treatment plans helps in deciding on the most appropriate intervention as well as in making informed recommendations for postoperative treatment. Advances in computer-based data acquisition systems and standardization of analysis techniques likely will further improve the efficacy and application of gait analysis.

References