ACTA
ORTHOPAEDICA
et
TRAUMATOLOGICA
TURCICA

Acta Orthop Traumatol Turc 2009;43(2):94-101
doi:10.3944/AOTT.2009.94

Three-dimensional quantitative gait analysis

Üçboyutlu niceliksel yürüme analizi

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Gait analysis is one of the essential steps of clinical examination in musculoskeletal medicine. Gait can be measured by various qualitative and quantitative techniques. In this article, the advantages and limitations of three-dimensional quantitative gait analysis will be discussed.

Key words: Biomechanics; cerebral palsy; gait.

Yürüme analizi iskelet-kas sisteminde klinik incelemenin temel aşamalarından biridir. Yürüme çeşitli niteliksel ve niceliksel tekniklerle ölçülebilir. Bu yazıda yürümenin üçboyutlu niceliksel analizinin avantajları ve kısıtlılıkları tartışıldı.

Anahtar sözcükler: Biyomekanik; beyin felci; yürüme.

Normal gait is the end product of a healthy neuromusculoskeletal system. For walking normally, central and peripheral nervous system (locomotor generator), muscles and skeletal levers should integrate with each other as well as visual, proprioceptive, cognitive and cardiovascular systems. Any impairment in these body structures and functions may cause a pathological gait pattern. Individuals preserve their ability to walk by compensatory mechanisms, to the extent their selective control allows. Alternative movement patterns and muscle activations are used to overcome the limitations imposed by the primary pathology. The ultimate walking pattern is a mixture of primary deficit and compensatory substitutions including but not limited to inadequate, excessive, inappropriately timed, or out-of-phase muscle action.[1-8]

Gait analysis is one of the fundamental steps of musculoskeletal examination. Surgical, orthopedic, and therapeutic recommendations are commonly based on clinical examination and observational gait analysis. Various pathologies may cause similar gait patterns and observational gait analysis may be disappointing in terms of treatment outcome. Although observational gait analysis has been used for many years in our daily practice, there are multiple reasons why it may not be adequate for the identification of more complex gait parameters. Complexity of gait makes it difficult to assess visually. A human eye cannot perceive an event happening faster than 1/12 of a second (83 msec) and cannot differentiate movement on different planes at the same time. This makes difficult to differentiate primary gait dysfunctions from compensatory movements such as the femoral internal rotation with knee flexion observed only in the coronal plane which may be misinterpreted as knee valgus. In addition, observational acuity varies from individual to individual, and success in observational gait analysis relies highly on expertise. If observational analysis is not sufficient, videotaping the patient and observing the tape several times in slow motion or frame by frame may be sufficient to evaluate the gait pattern.

A more objective evaluation can be provided by the use of three-dimensional (3D) quantitative gait analysis.[6] The advance of 3D quantitative gait analysis, which includes kinematic, kinetic, and dynamic electromyographic assessment, has enabled clinicians

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Submitted / *Başvuru tarihi:* 20.01.2009 **Accepted / *Kabul tarihi:*** 10.03.2009

to differentiate gait deviations objectively and understand the primary problem behind a complex disorder more accurately than observational analysis. It serves not only as a measure of treatment outcome, but also as a useful tool in planning ongoing interventions by quantifying functional limitations. A detailed history and physical examination of the patient combined with the gait data and the expertise of the team help clinical decision-making in terms of antispastic drugs, orthotics, and surgery.[1-8]

Kawamura et al.[9] compared observational assessment to 3D quantitative gait analysis of 50 patients with spastic diplegic cerebral palsy (CP) in a retrospective study. They reported that only knee flexion at initial contact and pelvic obliquity at mid stance appeared to be reliably evaluated on a visual basis alone. Visual observation was inadequate for the evaluation of hip flexion at terminal stance; knee extension at terminal stance; knee flexion at initial swing; ankle dorsiflexion at initial contact; hip adduction at loading response; pelvic rotation; hip rotation at mid stance and foot progression angle, all of which require some form of quantitative assessment.

Three-dimensional quantitative gait analysis

Gait disorders in children with CP are heterogeneous and require invasive treatments. The use of gait analysis to characterize a child's walking pattern may improve the understanding of complex gait abnormalities. Desloovere et al.[10] examined the correlation between gait analysis data and clinical measurements including range of motion, spasticity, strength and selectivity measurements, and evaluated the combined predictive value of static and dynamic clinical measurements on gait data of 200 children with CP. Their findings revealed that, despite overall poor correlation coefficients, clinical measurements of strength and selectivity had the highest degree of significant correlation with gait analysis data compared to the range of motion and spasticity measurements. They concluded that gait analysis data could not be sufficiently predicted by a combination of clinical measurements. They explained their results in several ways such as different behavior of bi-articular muscles while walking, compensation mechanisms, co-contractions, muscle synergies, and interactions of multiple limitations as well as changes in velocity during walking. They suggested that, as intra-limb and inter-limb coordination, balance problems and interactions across planes and levels could not be estimated by only clinical measurements, subsets of clinical examination and gait analysis data considered together might prove to be the best method in clinical decision-making for children with CP.

A three-dimensional quantitative gait analysis laboratory (Fig. 1) consists of three primary components: kinematic, kinetic, and dynamic electromyographic assessment. Typically, it takes approximately 1-2 hours for the acquisition of data and 1-2 hours for interpretation of the gait analysis. Patients should be at a height of at least 1 meter and able to walk the length of the laboratory 5 or 10 times. In addition, patients should have sufficient cognitive ability to follow the direction of the examiner to perform the evaluation. A typical 3D quantitative gait analysis session starts with subject preparation and followed by data recording and data analysis. During subject preparation, anthropometric data including height, weight, leg length and joint width of the knee and ankle are collected. One of the pre-selected standard clinical gait analysis protocols is used and for modelling of the body, passively reflective markers are placed on specific anatomical landmarks such as the sacrum, bilateral anterior superior iliac spine, middle thigh, lateral knee (directly lateral to the axis of rotation), middle shank (the middle point between the knee marker and the lateral malleoli), lateral malleoli, heel, and forefoot (between the second and third metatarsal head). These positions and measurements are validated.[11]

After the subjects are instrumented with retroreflective markers, they walk barefoot or with shoes

Fig. 1. A three-dimensional quantitative gait analysis laboratory.

together with walking aids (if they need), at a self-selected pace, a number of times, over a 10-meter long walkway during which time data collection is completed. Three to nine cameras record the quantitative spatial location of each marker as the subject walks. The trial in which all the markers are automatically and clearly identified by the system is determined as the best data. Some laboratories average the trials they have collected. Three components of the ground reaction force (GRF) are collected by forceplates as the subject steps on them. Ground reaction forces and kinematic data are combined with inverse dynamics to predict joint moments and powers of the hip, knee, and ankle joints in three dimensions. The recorded data are then processed for interpretation. The clinically validated biomechanical model combines the movement, force plate, and EMG data with patient specific measurements to calculate the joint center locations, segment orientations, three-dimensional joint angles and moments.

Table 1. Time-distance parameters of gait

Cadence (steps/minute)
Walking velocity (meter/second)
Stride time (second)
Step time (second)
Single support (%)
Double support (%)
Stride length (meter)
Step length (meter)

Time-distance parameters

Time distance parameters of gait are presented in Table 1. Documentation of treatment effects using time-distance measurements provides useful information concerning the patient's walking ability, which

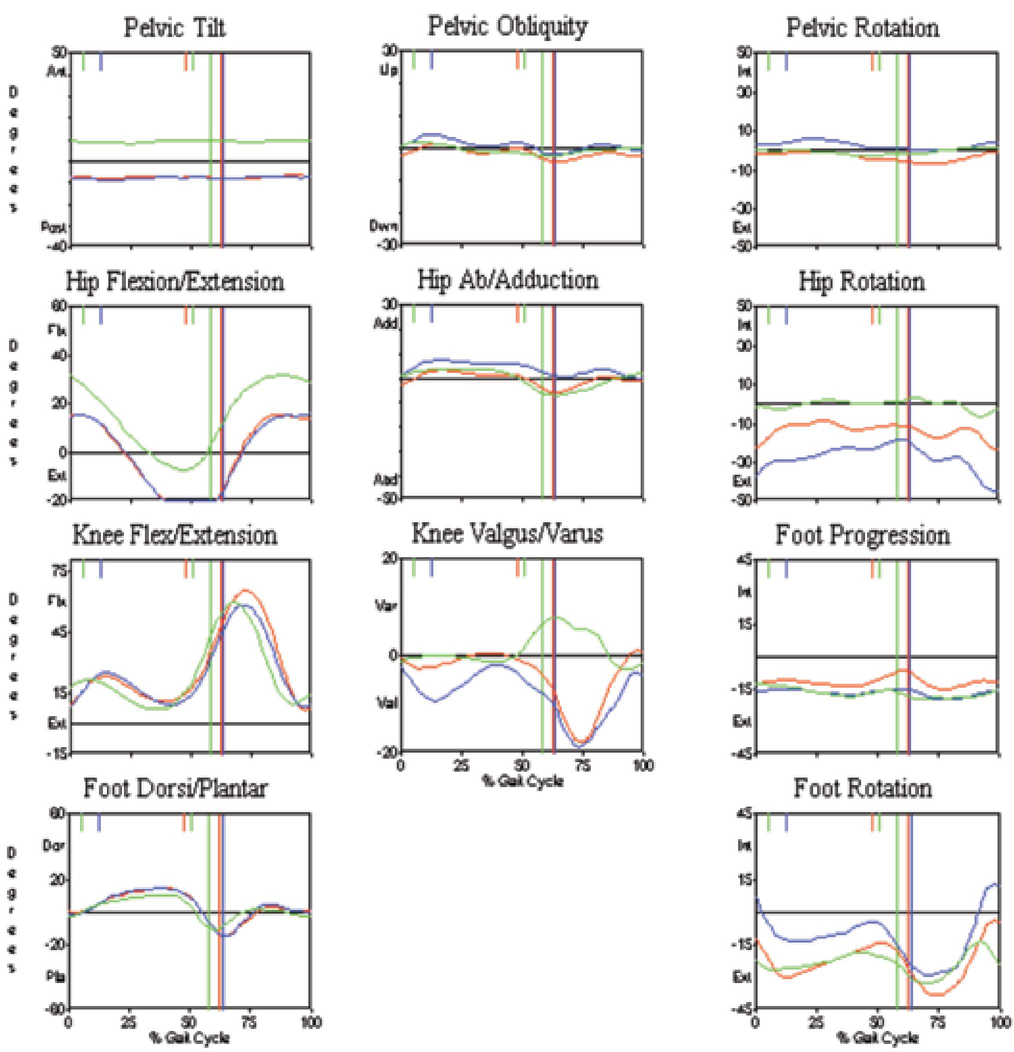

Fig. 2. Joint kinematic graphs in all three planes during gait.

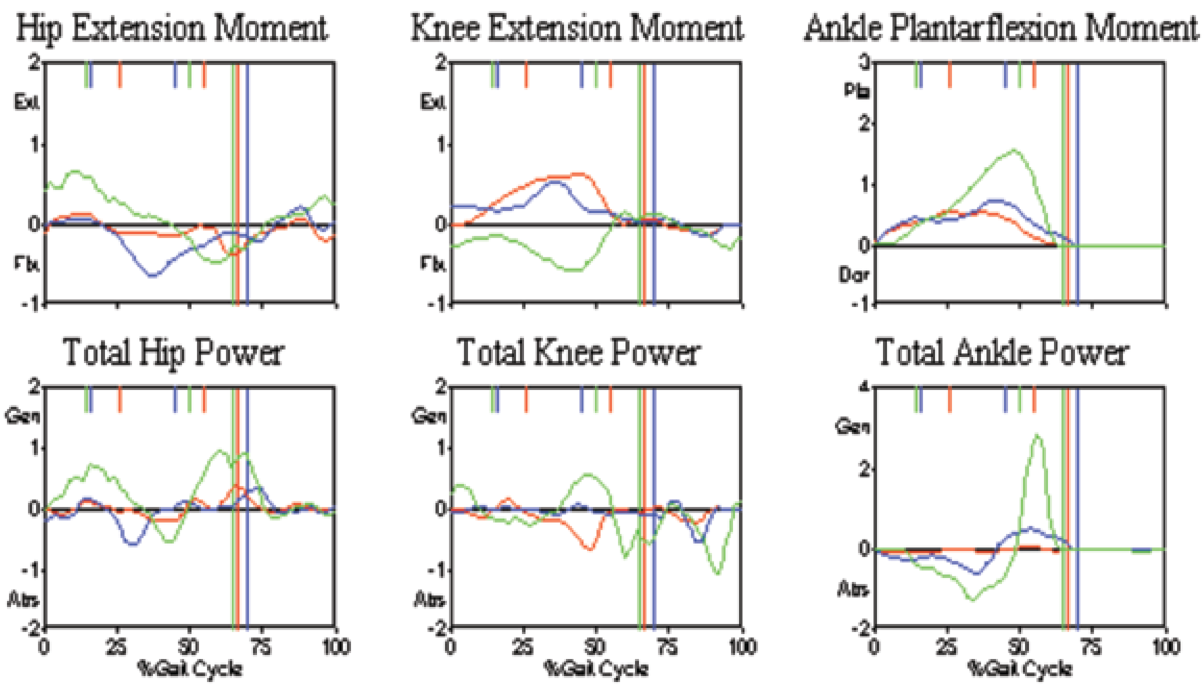

Fig. 3. Joint moment and power graphs in sagittal plane during gait.

objectively complements and reinforces the clinical evaluation and patient impressions of the procedure. However, time-distance measurements are only end products of a complicated motion pattern that neither explain a gait pattern nor distinguish between the primary gait fault and compensation.

Kinematics

Kinematics describes limb segment and joint motion. Kinematic data describes movement of joints and body segments - linear and angular displacement, velocity and accelerations, but do not reflect the causes of the movement. Electrogoniometers, gait "mats", magnetic systems, and optical systems are used for measuring kinematics. The method most commonly used by current gait laboratories to measure kinematics involves a sophisticated computerized video camera apparatus known as an optoelectronic system to assess the motion of each limb segment and joint in all three planes during gait (Fig. 2). In kinematic graphs, range of motion, baseline shift, timings of peak and valleys, and pattern of the line are evaluated, whereas for kinetic graphs, amplitude is less important and we mainly focus on timing of peak and valleys and pattern of the line.

Interpretation of pelvic kinematics is useful to differentiate compensatory movements of the trunk. An abnormally large pelvic rotation is often seen as a compensation to increase reach in patients with a short step due to hip or knee problems. Excessive motion of the pelvis and upper body is a compensation for weakness as well as a "motor" to assist in forward progression. Control of pelvic motion is critical to the maintenance of total body balance since the weight of the head, arms and trunk acts downward through the pelvis. Kinematic and kinetic studies of upper-body motion in the frontal plane have shown that the trunk is precisely controlled and highly dependent upon the motion of the pelvis. The more decrease in function of lower extremities, the more increase in motion of pelvis and upper body.

Kinetics

Kinetics describes the measurements of joint moment and power. Joint moment and power are calculated by using the GRF data obtained from the embedded force plates. The force plates are placed along the walkway on which the subject walks, and ground reaction forces are recorded by means of piezoelectric or strain gauge transducers. The vertical ground reaction forces vary above and below the body weight because of vertical upward and downward movement of the centre of gravity, most often determined by walking velocity.

Joint moments and powers are further calculated from the GRF data in combination with kinematic information such as joint and body segment position,

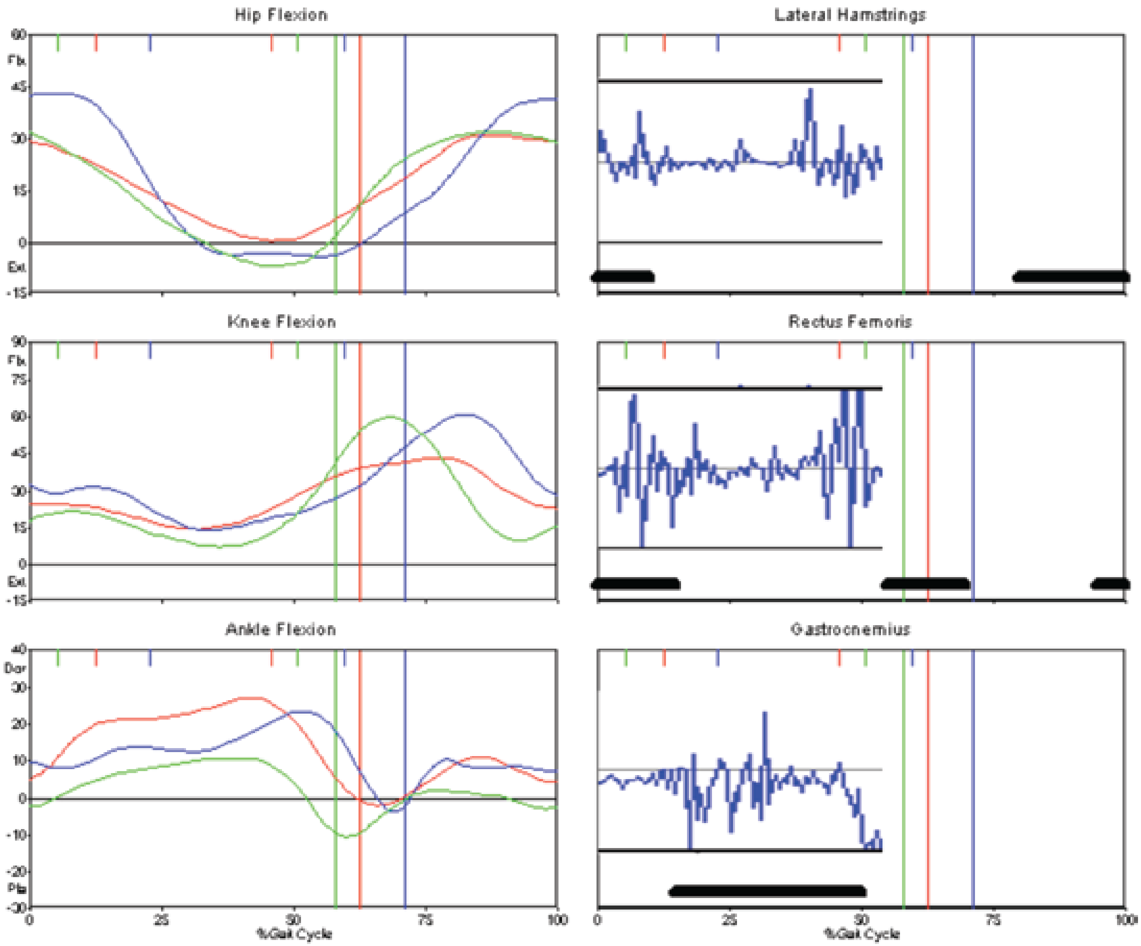

Fig. 4. Dynamic electromyographic recordings during gait.

velocity, acceleration at each instant in time, estimates of body segment masses, and moments of inertia (Fig. 3). Inverse dynamics physics and simplified models of the musculoskeletal system are used for calculations. An external joint moment (Nm/kg) refers to a net external load applied to the joint (ground reaction forces, segmental weight and inertia), and an internal joint moment is the result of the sum of all muscle activity acting about the joint in a given direction (forces from muscles, ligaments, and joint capsules). Net joint moment shows which muscle is dominant but also includes the contribution of passive structures and muscle contracture. With co-contraction joint kinetics indicates dominance, which is important to balance treatment of both agonists and antagonists. The joint moment tells us which muscles are acting at any given time, but it does not tell us why. We combine the joint moment with the joint angular velocity to derive the mechanical power. The net power (= net joint moment x angular velocity W/kg) absorbed refers to eccentric muscular contraction, and net power generated refers to concentric muscular contraction. Abduction moment of the hip, flexor moment of the knee (quadriceps avoidance pattern), adduction moment of the knee (knee osteoarthritis), plantar flexion moment of the ankle (double bump) are the most commonly used parameters to assess outcome of various interventions.[12-28] Weight bearing ability can be reliably measured by force plates in terms of vertical ground reaction forces and used as an outcome measure in stroke patients.[21,27]

Dynamic electromyography (EMG)

Dynamic electromyographic recordings provide information about the timing and duration of muscle activity during gait (Fig. 4). The electrical muscle activity can be recorded by the surface electrodes or fine-wire electrodes. This activity is then transmitted to a computer by cable or radio wave telemetry after appropriate amplification. With dynamic EMG, we measure the electrical signal associated with the voluntary or involuntary activation of a muscle which could be eccentric, concentric, or isometric in nature. Dynamic EMG data have a role in joint kinetic data interpretation as an indicator of the source of a joint moment (muscles, joint capsule, or ligaments) and can be used to document the relative contribution of agonist and antagonist muscles. Most major muscle groups are active around the beginning and ending of the stance and swing phases of walking (transition times). During mid stance and mid swing, most muscles are electrically silent (except for the muscles controlling ankle motion). The EMG signal is the summation of the motor unit action potential within the pick-up area of the electrodes. Timing of the muscle contraction, duration of the activity and onset-to-peak activity are documented in a dynamic EMG report. Dynamic EMG is useful to determine *(i)* relative contribution of each muscle to moment; *(ii)* co-contraction - where net moment may be zero; *(iii)* timing of muscle contraction - inappropriate or premature activity (spasticity); *(iv)* fatigue - from spectral analysis (Fast Fourier Transform): mean power frequency (MPF) falls with fatigue; *(v)* diagnosis - muscle disorders such as Duchenne dystrophy, myasthenia gravis, Lou Gherig's disease; *(vi)* information during selective dorsal rhizotomy. Muscle force cannot be estimated directly from the relative intensity of the signal. Electromyographic amplitude is associated with, but not equal to muscle force.[1,2,4]

Interpretation of the data

Interpretation of the data is the most challenging part of gait analysis. Although computerized gait analysis generates precise, objective data regarding gait parameters, the interpretation of that data is (as with many diagnostic procedures) subjective and therefore variable. All software used in different gait labs gives very colorful and attractive print-outs and the team working in the lab is asked to interpret the data and comment on which intervention would be better for the patient. A detailed history and physical examination of the patient, combined with the gait data and the expertise of the team, may help clinical decision-making. Additional functional assessment questionnaires may help integrate the laboratory outcome to functional outcome.

Limitations of 3D quantitative gait analysis

Main limitations and demands of gait analysis are the artificiality of gait with all markers and electrodes on short walkways in a laboratory, intensive labor, high cost, and the necessity of a well trained team.[7] Team members should be extremely careful with data collection, analysis, and interpretation, and aware of the numerous potential sources of error. Potential sources of error are the type, size and placement of electrodes and markers, the effects of age, body structure, growth and stress on gait data, system errors, artifact and calibration errors as well as evaluator bias: errors resulting from carelessness or poor training. Reliability of the measurements depends on daily calibration of the cameras, extra attention to marker placement, regular training of the team, and update of the system. Steinwender et al.[29] reported lower repeatability of gait analysis data in spastic children compared to normal children. We demonstrated repeatability of our gait data in normal adults[30] and patients with stroke.[31] In order to minimize errors, one should pay attention to daily calibration of the cameras, to marker placement, to minimize possible obstructions of the markers with clothing and to minimize surface (skin) motion. Before interpretation of the data, we have to pay attention to plotting conventions of the graphs (as they differ from lab-to-lab), to stride-to-stride consistency and walking velocity of the subject (walking velocity changes peak moment and power amplitudes). It is advised to look for velocity differences, especially when right- and left-side data are taken from different walking trials or if the data are collected on different days, while making pre- and post-treatment, or barefoot versus orthotics comparisons. Every lab should have their specific normative data to compare with the patients'.

There are no generally accepted standards and comparison of results from different laboratories. Better training of clinicians in the complexities of the kinematic, kinetic, and motor control features of gait, and standardization of terminology may improve already limited understanding of the data. Guidelines for selecting and applying specific gait analysis techniques in evaluating and treating different gait abnormalities are needed. If one considers setting up a clinical gait analysis laboratory, the mission of the laboratory (clinical or research or both, to which population), equipment (time-distance data, motion measurements, force platforms, EMG, foot pressure measurement) and minimum staff (data collector/technology keeper/interpreter) should be discussed in advance. The expectations in future are to provide a reliable, global evaluation technique for those providing treatment; to save for the health care system, and for patients and their families; to show the efficacy for clinical and research purposes and the standardization of terminology to improve communication.

In conclusion, through descriptive and experimental studies, 3D quantitative gait analysis has advanced our understanding of normal gait, identified and quantified the biomechanical and motor control abnormalities of pathologic gait, and documented the usefulness of various therapeutic interventions. Further research are needed to show how gait analysis can improve patient care, and to provide more evidence that 3D quantitative gait analysis studies can aid in the diagnosis and determination of the pathomechanics of some gait abnormalities.

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