

SECTION THREE

Chapter Two

An Overview of the Value of Information Resulting from Instrumented Gait Analysis for the Physical Therapist

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INTRODUCTION

Instrumented gait analysis is frequently used today for clinical applications. Its role has expanded beyond the area of gait analysis to aid in clinical decision making for rehabilitation, surgery, adaptive devices, ergonomics, and athletics. Physical therapists are well trained in the area of gait and movement analysis and are, by definition, movement scientists. The evaluation of gait, locomotion, and balance includes a series of tests described in the *Guide to Physical Therapy Practice* (1). Entry-level didactic requirements include normal gait mechanics and pathological gait for nearly all disabilities. Those in physical therapy training primarily learn observational techniques for clinical gait analysis. In addition, some academic programs provide an introduction to various forms of instrumented gait analysis and their potential to augment the physical therapist's knowledge of gait. Instrumented gait analysis involves information about temporal and linear parameters during gait as well as joint angles, ground reaction forces, and muscle firing patterns.

The purpose of this chapter is to review the scope of quantitative gait analysis (QGA) as it pertains to the practice of physical therapy. A brief background about quantitative gait analysis is followed by a description of how physical therapists evaluate gait. An overview of

gait analysis technology and goals of the information obtained from QGA is discussed. Groups likely to benefit from this information are presented. Limitations of gait lab data and suggestions for improvement are reviewed.

Background

Over the past 10 years, the clinical application of gait analysis has grown rapidly in the United States, as a result of several significant changes. The widespread development of user-friendly software allows the clinician to use instrumented gait analysis more easily. Hardware has also been refined to allow faster data acquisition and computing. These two advances have permitted the clinician to improve his/her understanding and interpretation of information provided by movement analysis technology.

The evaluation of children with spastic paralysis constitutes the onset of movement analysis for the clinical arena and continues to be a large focus of clinical gait analysis. Orthopedic surgeons frequently needed objective information about the success of their surgical interventions, compared to a pre-surgical assessment (2). Other clinical applications of instrumented gait analysis include the assessment of persons with stroke, Parkinson's disease and multiple sclerosis, spinal and orthopedic injuries or disease, and amputations.

Clinical use of the gait data takes the form of an evaluation, ideally before some intervention, followed by a summary of the biomechanical and neuromuscular influences of gait after an intervention. The intervention may be surgery, orthotic or prosthetic applications, and pharmacological or physical therapeutic treatments. The physical therapist can then interpret the clinical significance of the change in gait impairment as a result of such intervention.

METHODS

How Physical Therapists Evaluate Gait

Observational gait analysis (OGA) is defined as the visual inspection of walking. The identification and grading of gait deviations depends on the observer's experience and individual bias (3). The physical therapist observer is trained to see a range of gait events. The gross abnormalities are the most readily observed. Frequently, these are made more pronounced if the therapist asks the subject to walk at a higher velocity or removes some physical or mechanical assistance. The disadvantage of OGA over QGA is the tendency to focus the eye on the gross gait deviations while overlooking more subtle ones.

OGA is a preferable form of gait assessment when considering the ease, time efficiency, and low cost; however, several questions have been raised about its limitations (4–8). Studies evaluating the reliability and validity of OGA unanimously point to only a moderate level of reliability for intra- and interrater assessments (9). However, due to certain design differences in these studies, it is likely too early to eliminate OGA as an important clinical evaluation tool.

Systematic methods of gait analysis have been described by Perry (10) to establish standardization procedures within the field. Perry describes three steps to carry out systematic OGA: 1) organization and classification of the essential gait events, 2) anatomic sequence of observation to sort the multiple events at different joints, and 3) data interpretation for total limb function and for gait cycle differentiation.

Often a physical therapist will start the observation at the foot and assess distally to proximally as the foot hits the ground. Interpretation includes the influence of neuromusculoskeletal and/or behavioral factors that may produce a particular gait pattern, such as spasticity, pain, contracture, or lack of motivation. When OGA provides insufficient information about the etiology of

gait deviations, instrumented gait analysis may be warranted.

Gait Analysis Terminology

There are several terms and definitions commonly used when studying gait analysis: *Gait kinematics* refers to the branch of mechanics that deals with joint angular changes over the gait cycle. Kinematics is evaluated by using external markers that can be observed by cameras. *Gait kinetics* is defined as the forces, moments, and powers that change over the gait cycle. These measurements are captured by the use of force plates embedded in a walkway. *Dynamic electromyography* (EMG) refers to the evaluation of muscle activity throughout the gait cycle. This is accomplished through the use of either surface or needle electrodes.

Gait Measurement Technology

Two-Dimensional versus Three-Dimensional Gait Analysis

Most of the current gait analysis systems today convert the two-dimensional (2-D) data from several cameras into three-dimensional (3-D) data to determine joint centers. This method allows for the measurement of gait when there is out-of-plane movement. Two-dimensional gait analysis is attractive to the clinician because there are fewer markers and cameras needed for data acquisition and processing time is significantly reduced.

When 2-D motion data reduction methods are employed for gait analysis, the assumption must be that the motion is planar. For example, the knee motion for the unimpaired person could be considered to move in a single axis flexion/extension plane. However, if genu valgus, or varus, or femoral, or tibial torsion is present, there is a distortion of the data because the joint plane is no longer parallel to the viewing plane.

Davis et al. (11) evaluated the differences between 2-D and 3-D gait analysis, determining that joint angles for the hip and knee were the most consistent, since these joints represent the smallest out-of-plane movement during normal gait. The ankle, however, had the greatest sensitivity between 2-D and 3-D gait analysis. This is not surprising since the ankle is oriented out of the sagittal plane externally by about 7–10°. Much literature on normal gait over the years must be considered with caution because the conclusions drawn were based on 2-D gait analysis. Davis and colleagues also extend this caution to the kinetic analysis.

Kinematics

The evolution of gait analysis technology has enabled the physical therapist to utilize the resultant data to aid the interpretation of locomotor performance. Since expensive motion analysis equipment is not likely to be present in physical therapy clinics, therapists use other methods of motion analysis, such as videotaping. This method creates a permanent record of gait performance that serves to document progress in therapy but still relies on the therapist's ability to observe gait in a reliable way.

Instrumented gait analysis systems, though not present in most physical therapy clinics, constitute the most prevalent method of motion measurement available to physical therapists. While electrogoniometers and accelerometers require less instrumentation, these devices are more often used in academic or research settings, because they are less user-friendly for the clinician. Clinical gait laboratories are becoming more widely present in hospital settings, and physical therapists can benefit from such quantitative data. For example, physical therapists are able to assess passive and active range of motion (ROM). It may be difficult, however, for the therapist to determine how this available ROM is incorporated into gait. A subject may present with a simple knee-flexion contracture; however, QGA provides the complete knee trajectory throughout the gait cycle to determine whether the subject is using 100 percent of the available ROM. The physical therapist can also determine to what degree the limitation in knee motion has affected hip and ankle motion at simultaneous time intervals. **Figure 1** is an example of the unimpaired and pathological knee flexion/extension trajectory: the right limb demonstrates excessive knee flexion at heel strike (0 percent) and peak knee flexion during the swing phase (80 percent). This pattern is indicative of insufficient quadriceps control or hyperactivity of the hamstrings at heel strike and insufficient dorsiflexion requiring excessive knee flexion for toe clearance during swing. This can be corroborated by examining the dynamic EMG at these intervals.

Ground Reaction Measurement

Force platforms embedded in a walkway provide information about the center of pressure or the point of application of the ground reaction force vector. The ground reaction force is the sum of all the forces of the body segments while the foot is in contact with the ground. Many gait labs are now equipped with foot

pressure systems in addition to force platforms. This technology allows for the determination of how the load is distributed on the plantar surface of the foot. This information can be useful for individuals with orthopedic pathologies from foot/ankle fractures or those relating to disease processes such as diabetic neuropathy. **Figure 2** is an example of the normal ground reaction force during gait.

Another form of kinetic analysis involves the evaluation of joint moments and powers. Joint moments are the forces produced by muscles and ligaments acting at a distance from the joint center. Joint power is the net rate of generating (concentric contraction) or absorbing (eccentric contraction) energy by all muscles crossing a joint, and is the product of the joint moment and its angular velocity. If the calculation of joint moments is required, it is necessary to have a system that can have both kinetics and kinematics. Several investigators have used the examination of external joint moments to predict muscle forces (12).

Temporal and Distance Parameters

Step time and length, stride time and length, and walking velocity and cadence all fall under the definition of temporal and distance parameters of gait. Because physical therapists spend a great deal of time walking close to subjects to either provide verbal or physical assistance, they have a keen awareness of length and timing parameters, particularly when they are asymmetrical. There is a variety of easy methods for determining timing parameters when force platforms are not available. These include the use of a stop watch to determine walking velocity (distance over time), counting the number of steps per minute (cadence) over a known distance, chalking the soles of shoes or walking on carbon impregnated paper to determine step and stride lengths, or heel switches to determine step and stride time intervals. The greatest challenge to using heel switches is their placement when the subject does not achieve heel strike during gait. In this case, the distance parameters are distorted because the heel does not strike the ground first, thereby lengthening the step length parameter by a factor proportional to the length of the hindfoot.

However, these methods pose clinical challenges; namely, the clinician must have the time to obtain these measurements. A laboratory staff experienced in data collection and processing can provide the easiest method to obtain QGA results. The physical therapist can then be instrumental in the interpretation of

parameters such as asymmetry in joint trajectories and their etiologies. The therapist also receives feedback on how gait parameters change as a result of rehabilitation techniques. For example, although the therapist may be keenly aware of the impairments limiting asymmetry in the temporal and linear components of gait, it may not be obvious as to how much symmetry should be sought during treatment and what rate of treatment progression achieves the most efficient gait. Repeated measurements of the temporal and distance parameters from QGA may relate to a particular progression of gait training and may provide insight into optimal clinical practice guidelines. These studies are sorely needed to validate many interventions in the field of rehabilitation.

Dynamic Electromyography (EMG)

Voltage potentials detected by surface or wire electrodes provide information about the timing and intensity of the muscle contraction. Physical therapists know when muscle groups responsible for locomotion should be active, but it is most difficult to observe anything but gross muscle activity during gait; therefore, dynamic EMG can provide useful information unavailable by observation. Timing of muscle activity is the most frequently used parameter obtained from dynamic EMG. Weakness or spasticity of one or two joint muscles produces visible gait deviations, but it is difficult to observe whether the activity is present at the appropriate times. Neurological subjects who exhibit spasticity walk with a stiff-legged gait, and QGA provides information about which muscles are spastic and when they are misfiring (13).

The intensity of muscle contraction obtained from dynamic EMG is more controversial, because it must be normalized for some maximal effort, such as a maximal voluntary contraction. Instrumentation requires certain dynamic EMG systems to have gain settings that may alter the interpretation of the magnitude of the EMG signal. If the subject demonstrates spasticity, the maximal contraction is an abnormal response to voluntary contraction, making relative submaximal comparisons of muscle activity difficult.

Goals of Quantitative Gait Analysis

Comparisons to the Disabled Populations

Probably the most common use of instrumented gait analysis is the comparison of gait data from the disabled population to that of the nondisabled. An occasion where this normative external standard may be most useful is when there is an expectation for normal

performance (2). The limitations of such comparisons include issues of age, gender, walking velocity, and anthropomorphic differences between the two groups. For example, comparisons of data from subjects who walk at different velocities from the normative standards have limited validity. Walking velocity is often drastically reduced in disability, and the normative data are most often collected at self-selected and faster-paced speeds. The effect of speed may explain a large portion of the group differences (14). We also know that men walk differently from women of similar height and

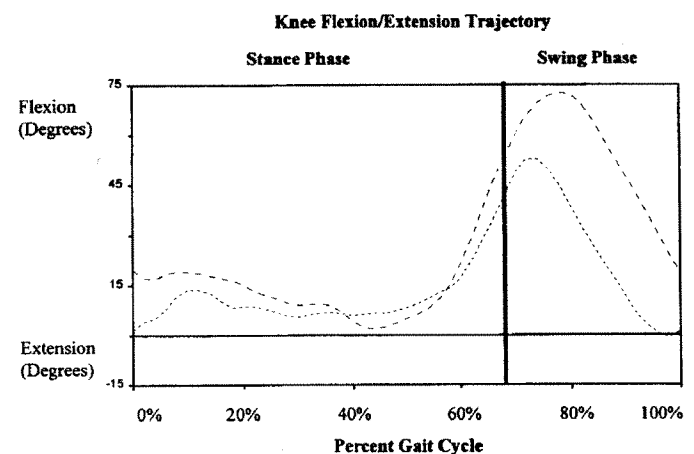


Figure 1.

Knee flexion and extension trajectory of a neurological subject during level walking at self-selected walking speeds. Pathological (.....), Normal (-----).

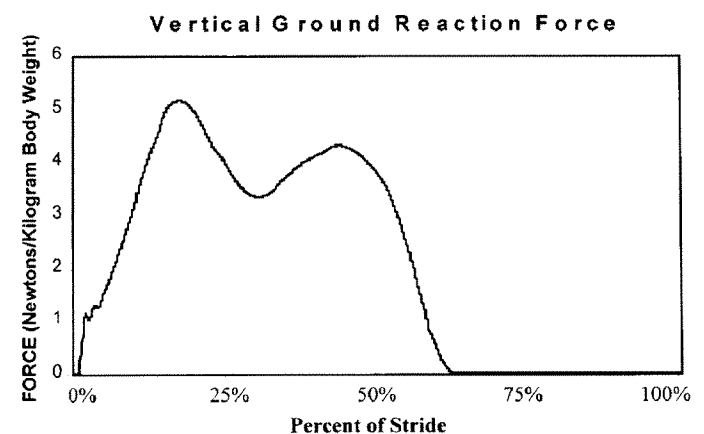


Figure 2.

Force output over a stride length (heel strike to heel strike on the same side) of a 45.36 kg female striking the force plate with the left limb while walking at a self-selected walking speed. Forces have been normalized by dividing by the body weight. Time base is normalized to 100% with toe-off at 60%.

weight and that age and maturation affect walking patterns (15). Therefore, caution must be used when making comparisons of disabled walking patterns to normative databases.

Identification of Disability Levels

As our healthcare environment is more often requiring outcomes that are quantitative, gait analysis can be useful in identifying levels of disability or functional loss. While therapists use measures of impairment to plan and implement treatment (16), it is important to relate these impairment measures to disability levels. QGA is well suited to provide information about the impact of impairments during a functional movement. This is an important service, as physical therapists make very well defined impairment measures in a "static" position but have to interpret how these impairments relate to functional problems in walking.

Several studies have begun to address the identification of disability levels using QGA. Knutsson (17) used dynamic EMG to classify subjects with hemiplegia through the assessment of spasticity patterns. Delitto et al. (18) classified those with low back pain, and Richards et al. (19) classified the recovery stage of persons who had suffered a stroke, based on their walking velocity. These studies effectively relate the gait impairments to the disability outcome and make comparisons within a very homogeneous group rather than comparing the data with those of a normative database.

Efficacy of Interventions

Currently, there is a great demand to shorten the length of hospital stay and a concomitant demand to increase function: these demands require practitioners to seek the most effective treatment interventions. Physical therapists have many treatment paradigms at their disposal, but there is little information available regarding the intensity and duration of treatment. Gait analysis can be a valuable tool to determine the benefit of mobility treatments and their transference to the functional task of walking. QGA comparisons made before and after treatment can aid in the determination of the intensity and duration of treatment, and when the effect of a treatment has reached a plateau. For example, using QGA, conclusions may be drawn about which surgical or physical rehabilitation techniques for the person with anterior cruciate ligament deficiency (ACL D) are beneficial. Sinkjaer and colleagues studied muscle coordi-

nation of ACL D subjects and classified those who were good versus those who were poor compensators during walking (20). These differences have important clinical treatment implications but would not have been identified with a less sophisticated form of analysis.

Performance Enhancement

Physical therapists often render treatment to improve normal performance, as is the case with athletes. Williams et al. (21) conducted a study using gait analysis coupled with oxygen consumption measurements to compare recreational and elite runners. These authors reported that gait analysis proved to be more useful than the assessment of running efficiency. Therefore, gait analysis may be a useful tool to predict the incidence of injury in athletes. This predictive information is extremely desirable to third party payers and helps to justify prophylactic physical therapy treatments and the promotion of wellness in the athletic population.

Mechanisms of Gait Deviations

A major challenge for physical therapists in the evaluation of gait is the determination of which deviations are primary and which compensatory. Observational gait analysis provides one answer to the trained observer; however, these judgments need to be corroborated by quantitative measures. For example, the contribution of muscles to measured motion versus passive movement during the gait cycle has been evaluated. A study by Sutherland et al. (22) indicated that the plantar flexors are accelerators, but only in 40–50 percent of the gait cycle and not at terminal stance as was originally thought. From a therapeutic point of view, it is quite possible to observe sufficient plantar flexion that may be occurring later in the stance phase (60 percent and beyond). This observation may lead the physical therapist to decide that there is sufficient plantar flexion power, not realizing that the plantar flexion is occurring late in the gait cycle and is likely a result of the passive extension at pre-swing due to a rapid unloading of the limb. Once the source of a gait deviation is determined to be primary, a physical therapist is better able to tackle the deficiency more directly.

Groups Potentially to Benefit

Anterior Cruciate Ligament Injury

The literature suggests that gait analysis might be helpful to physical therapists in determining whether an

individual is a candidate for a knee orthosis, rehabilitation, or surgery. Berchuck et al. (23) describe the gait pattern of persons with ACLD, which condition resulted in drastic changes in knee joint kinetics during level walking in the absence of serious kinematic differences. These researchers determined that a “quadriceps avoidance” pattern was evident. Kadaba et al. (24), on the other hand, describe the same phenomenon as increased-stance knee flexion that was balanced by quadriceps muscle activity. This activity was described as a positive adaptation due to the absence of the ACL. However, it becomes even more crucial when an anterior cruciate reconstruction fails over time. If physical therapists could receive feedback from kinetic analysis of the knee joint forces during weight-bearing exercises, alterations could be made in the treatment strategy to avoid overstretching a reconstructed ACL, and they could educate the patient as to proper functional activities to avoid reinjury.

Geriatric

Understanding the mobility problems in the elderly can point to rehabilitation strategies. Patla et al. (25) describe methods for classification and characterization of mobility performance, such as walking over a variety of terrains. Gait analysis can be useful in determining whether there are problems with the locomotor apparatus. The aging process is multifactorial; therefore, sensory and visual systems must be screened as well. Matching subjective reports with quantitative gait results may aid the physical therapist in determining which factors are the most limiting. For example, if pain is perceived during the stance phase and is correlated with reduction in force output of the quadriceps muscles or reduced knee moments and powers, the physical therapist can be guided by this information as to which impairments to address first in the rehabilitation program.

Pediatrics

Spastic paralysis often requires surgical intervention for the lengthening of spastic muscles and their tendons in an attempt to reduce muscle contractures and abnormal skeletal alignment. Without the knowledge of abnormalities of muscle function, floor reaction forces, and 3-D movements, functional outcomes had been disappointing. With the advent of clinical gait analysis, the American Academy for Cerebral Palsy and Developmental Medicine was the first to apply the results in the care of these persons (26).

Stroke and Head Injury

Central nervous system disorders can produce a mixture of spasticity, impaired motor control, and primitive reflexes, all of which can result in contracture. It is difficult to discern inappropriate muscle action during gait, because of the mass firing patterns and the compensatory efforts to control the limbs. Herein lies an extremely powerful benefit to the output from QGA for the physical therapist. The major muscle groups firing for extended periods are usually obvious to the skilled gait observer, but the relative contributions of muscles crossing the pelvis, hip, knee, and ankle are harder to determine. Dynamic EMG can clarify this relationship and guide the therapist in emphasizing manual interventions and gait training to reduce spasticity.

Gait EMG of spastic muscles has also helped in the clinical decision making for pharmaceutical interventions (27) such as Botulinum Toxin A (BTX). BTX paralyzes muscles firing at inappropriate times during gait and allows for strengthening of the antagonist muscle group and gait training without the influence of spasticity on the biomechanics of gait. The equinovarus deformity is a good example of the difficulty in differentiating the primary offending muscle during gait. The cause may be premature activity or contracture of the soleus, while tibial muscles display normal function. A blocking agent, such as BTX, used in a sequential fashion can help tease out the cause. The common assumption is that the tibialis posterior is the cause, but Wills et al. (28) discovered that this muscle was the primary cause in only 25 percent of the cases, while the tibialis anterior was the more frequent cause (45 percent) in 50 children with spastic paralysis. The physical therapist can use this diagnostic information to improve the balance of the firing patterns between the agonist and antagonist through neuromuscular re-education, biofeedback, and/or strengthening.

Fatigue (Post-polio and Chronic Fatigue Syndromes)

Persons who have functioned well for 20–30 years since polio, are now experiencing disabling symptoms that are most often attributed to overuse, but the mechanisms are unclear (29). These individuals spontaneously substitute alternate muscles for the weak or absent musculature. Persons who have post-polio syndrome are primarily hampered by fatigue; therefore, an understanding of the intensity and firing pattern of the lower limb muscles is more appropriate than joint angle profiles. Typically, the firing patterns of muscle activity in these people are prolonged in order to avoid

instability during gait. The physical therapist who is aware of which muscles are particularly susceptible, will educate the subject about paced activity and provide gait-training techniques that incorporate as many alternate strategies as possible. Only one study has been conducted in the area of gait abnormalities in Chronic Fatigue Syndrome (30). This study identified gait abnormalities compared with sedentary healthy controls. However, the authors were not able to identify the causal factors for this apparent difference but hypothesized them to be due to balance problems, muscle weakness, or central nervous system dysfunction. Gait analysis has begun to characterize movement dysfunction in this population, but further work is needed to compare these deficits over prolonged exercise where the influence of fatigue may be more pronounced.

Prosthetics

Several studies have evaluated the effectiveness of prosthetic feet (31,32), many of which are designed to conserve energy. A study by Gitter and colleagues (32) indicated an improvement in energy efficiency of approximately 30–40 percent with the energy-storing feet over the standard SACH foot for persons with transtibial amputation walking at normal speed. However, the authors found that despite this greater mechanical performance, there were no significant differences in the knee and hip powers for the two feet. Typically, physical therapists and prosthetists will recommend the latest prosthetic components to enhance prosthetic gait, but may be unable to determine different energy requirements for walking with each component. Since physical therapists have an opportunity to assess energy requirements from subjective reports during prosthetic gait training, corroboration for this perceived decreased energy requirement from the use of sophisticated prosthetic components might be obtained from QGA. Torburn et al. (33) indicated that while the kinematic and kinetic patterns implied reduced energy expenditure during gait, oxygen consumption increased due to the increased intensity and duration of muscle firing. Dynamic EMG coupled with kinematic and kinetic gait analysis allows for a teasing out of discrete components incorporated into gait. A physical therapist is equipped to utilize this information to guide the treatment program and provide input for optimal prosthetic equipment.

Orthotics

Physical therapists commonly evaluate the appropriateness or effectiveness of an orthosis, particularly when an individual is in the acute recovery phase of rehabilitation. QGA, with and without the orthosis, reveals the degree to which an orthosis may help through the evaluation of temporal and linear parameters and kinematic trajectories. The physical therapist must include in the interpretation the physical constraints of the orthosis in evaluating the kinematic trajectories. For example, an ankle-foot orthosis may prohibit plantar flexion at heel strike but provide sufficient clearance during swing phase. The ankle trajectories will appear abnormal, due to this physical constraint. The decision about orthosis effectiveness might be better based on ambulation speed or temporal symmetry than on ankle trajectory that would appear abnormal from the QGA results. Therefore, while QGA provides information about gait performance, the interpretation of these findings is critical. The physical therapist can offer a therapeutic perspective as to prioritization of the gait parameters to which the subject is capable of adjusting during rehabilitation.

Limitations of Gait Lab Data

Improvement is needed in the quality of the data collected in gait laboratories. For example, if there is excessive soft tissue movement under the reflective markers, information about joint angle profiles may contain excessive variability that is not part of the movement pattern. This error of measurement is magnified when mathematical derivations are made to calculate velocity and acceleration. Further work is needed to improve the quality control efforts in practicing laboratories. Greater efforts must be made to standardize marker placement and terminology across gait laboratories to communicate effectively between clinical groups. There must be a better understanding of the underlying gait models utilized by commercial software, so that the interpretation of gait data considers the proper assumptions made by gait models.

Finally, normalization procedures need to be standardized to optimize across subject comparisons, in addition to the need for normative databases for homogeneous disabled groups. A common clinical use of gait analysis is to compare the performance of an individual with normative data to describe how the disabled gait differs from the “normal.” We know that

certain anthropomorphic factors, such as weight and leg length, can vary the walking performance in nondisabled individuals. However, varying anthropomorphic features are not available in existing databases; if they were, the gait pattern of a subject of a specific stature could then be compared to a larger sample of persons with similar physical characteristics.

More definitive research that determines the utility of gait analysis in the clinical setting is needed. In most cases, OGA suits the clinician well for gross gait deviations. Even 2-D gait analysis may give sufficient information about gait performance with less complexity than is needed for 3-D analysis. Nevertheless, the system of analysis depends on the kind of clinical judgment the user intends to base on the data. If the physical therapist requires discrete unobservable information about walking performance, QGA will be needed. Currently, this situation would require a referral to a center where this level of analysis is performed, since it is impractical for most clinical settings. However, the more practitioners define a need for QGA, the more gait laboratories will be driven to provide information useful to the clinician in a timely manner. Clinicians seek to be successful with the patients under their care; therefore, whatever information aids in the planning of rehabilitation strategies will prove beneficial to them.

CONCLUSIONS

As all diagnostic and treatment methods will be under scrutiny during the medical economic readjustments currently underway, gait laboratories will have similar obligations. Clinical gait analysis will be obliged to relate objective findings to functional measures and outcomes. More importantly, in order for gait laboratories to survive in this arena, they will have to address how treatment progression can be guided by gait analysis. Physical therapists routinely address functional outcomes and are well equipped to assess the effectiveness of guided treatment as a result of quantitative findings about gait and movement analysis.

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