# Clinical motion analysis

**STEPHEN VANKOSKI, MS**
**LUCIANO DIAS, MD**

Spring 1999

**THE ROOTS OF MODERN** motion analysis can be traced back to photographer Eadweard Muybridge who used his invention, the zoopraxiscope, to project sequential motions onto a screen so they appeared in motion. At the University of Pennsylvania, he studied animals and human volunteers. To gain insight into uncommon human motion he also recruited patients with physical disabilities from a nearby hospital. **The integration of elegant mathematics and engineering, advances in instrumentation and imaging techniques and the evolution in computer technology have propelled the art and science of human motion analysis beyond basic description towards prominent roles in surgical decision making, rehabilitation, prosthetics, orthotics, ergonomics, and athletic performance.**

---

## GAIT ANALYSIS AT CHILDREN'S MEMORIAL Hospital of Chicago

**Since the Children's Motion Analysis Center opened its doors in 1989, we have examined the pathological gait of more than 2,000 children to direct their surgical, orthotic and therapeutic intervention**. The patients seen in the gait analysis laboratory present with various neuromuscular disorders, but the vast majority of the children carry a diagnosis of cerebral palsy or spina bifida. Gait analysis at Children's includes a complete lower-extremity physical examination, videotaped walking, three-dimensional joint motion or kinematics, joint moments, joint powers, dynamic electromyography, and foot pressure analysis.

The physical exam provides information regarding muscle strength and joint range of motion. Despite the valuable information that is garnered from the physical exam, it is somewhat limited because it is predominantly a horizontal exam. The vertical exam as the patient walks includes the rudimentary observational gait analysis which includes systematically focusing on one body part and then another. Since tasks such as walking are comprised of simultaneous movement of multiple body parts, simple observation is limited. For instance, what appears to be an equinus ankle posture may in fact be a crouch gait in combination with a neutral ankle position. In addition, **events that occur faster than 1/12 of a second cannot be perceived by the human eye**. This can be overcome easily with a videotape and slow motion replay of the events. The **limitation of videotape is that three-dimensional motion is confined to two dimensions, which can be grossly misleading to the clinician**. For example, a patient viewed from the coronal plane with a combination of internal femoral rotation and external tibial rotation may be misinterpreted as having knee valgus.

FIGURE 1. Patient walking through the motion analysis center with reflective markers.

**To assess three-dimensional joint rotations, passive reflective markers are placed on the patient at specific anatomical landmarks** as depicted in *Figure 1*. As the patient walks through the lab, the three-dimensional location of each marker is detected by multiple infrared cameras. A biomechanical model is applied to the marker series to calculate the three-dimensional motion of each body segment. The **processed data generates a graphical representation of each joint in all three planes** and is expressed in terms of the gait cycle (*Figure 2*).

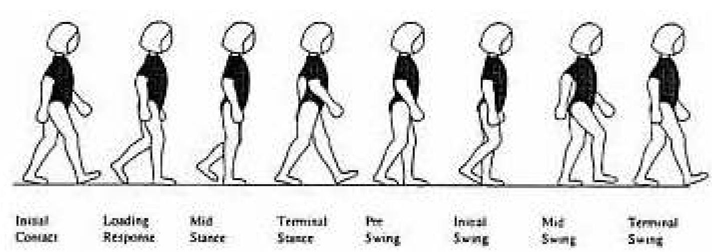


FIGURE 2. The gait cycle broken down into its different phases.

The start of the gait cycle is defined at foot contact with the ground. The end of the gait cycle is defined by the subsequent contact of the same foot. Each gait cycle is divided into two phases: stance and swing. Joint rotations are the easiest to appreciate because the graphical representation can be readily referenced to the observed motion captured on video.

## CAPTURING THE VITAL DATA WE CAN'T ALWAYS SEE

**Sometimes what we can't see, such as joint kinetics and dynamic electromyography (EMG), is just as important or more important than what we can see or think we see. Body segment motion combined with data captured from force platforms can be used to calculate the internal joint moments.** The internal joint moments are created by muscle-tendon complexes, ligaments, and internal joint structures. Each joint can be viewed as a teeter-totter with the combination of internal anatomical structures, external forces, and inertial components acting on each side to yield the net internal joint moment at the state of equilibrium.

Moment analysis has been used for presurgical assessment of candidates for high tibial osteotomy, patients with anterior cruciate ligament deficiency, and children with cerebral palsy and spina bifida. **The joint moments and joint angular velocities can be used to calculate joint power, which has been described as the single most important measure in clinical motion analysis**. Primary power generation occurs at the hip and the ankle during normal level walking. The hip generates 54% of the power, the ankle produces 36% of the power, and the knee only contributes 10% and functions primarily as a power absorber.

Joint power is important because it summarizes a vital role of muscles during movement: the muscle's function as it shortens or lengthens under tension. A concentric contraction, when the muscle shortens under tension, is associated with power generation. An eccentric contraction, when the muscle lengthens under tension, is associated with power absorption. **The muscular activity is monitored using surface electrodes** to determine the timing and relative amplitude of a muscle during walking. **Foot pressure patterns reveal the distribution of pressures and forces under the plantar surface of the foot which are not readily seen**. Custom insoles quantify the peak pressures and contact durations under specific areas of the foot such as the hindfoot, medial midfoot, and first metatarsal head. Quantifying the integrity of the interface between foot and orthoses attenuates the trial and error process often involved in orthotic modifications and surgical interventions.

## GAIT ANALYSIS USED TO BE A GUESSING GAME

Prior to the availability of gait analysis, clinical decision-making for patients with cerebral palsy was a guessing game in which the experience of the pediatric orthopaedic surgeon challenged the complexities of a motor control system disorder complicated by muscle spasticity and skeletal malalignment. The **surgeon and patient were often met with disappointment following surgical intervention** meant to treat the most obvious pathology without regard to more subtle deviations.

*Subsequent treatment of the next abnormality led to multiple interventions*, and the so-called "**birthday syndrome**"—originally dubbed by Dr. Mercer Rang—reflected the yearly (or every other year) series of hospital admissions, recovery, post-op therapy and missed school days.

Gait analysis helps the physician detect the primary problems and differentiate them from secondary or coping mechanisms. For example, the primary problem of external tibial rotation may affect the relationship among the foot, ankle and knee (called the plantar flexion/knee extension couple) and compromise the ability of the patient to extend the knee properly. This secondary knee flexion compromises opposite foot clearance and leads to compensatory hiking of the pelvis to ensure foot clearance.

The primary problem is external tibial torsion. A secondary problem is increased knee flexion, and the tertiary, or coping response, is hip hiking. With gait analysis and consultation with a team of clinicians, the physician can readily identify the problems and not interfere with the compensations that may disappear spontaneously with effective treatment of the primary problem. So the strategy for patients with cerebral palsy, spurred in no small part by gait analysis, has evolved to include an operative plan that addresses all the primary problems at all joint levels simultaneously using a multilevel approach.

## NEW TECHNIQUES HAVE BEEN PROMPTED BY GAIT ANALYSIS

In recent years, **gait analysis has not only altered overall treatment philosophies but has prompted modifications to surgical techniques**. These include iliopsoas lengthening above the iliac crest instead of radical hip flexor release to preserve hip flexor strength and rectus femoris transfer in lieu of rectus femoris release to optimize improvement in swing phase knee flexion in cases of a stiff knee gait pattern (*Figure 3*).

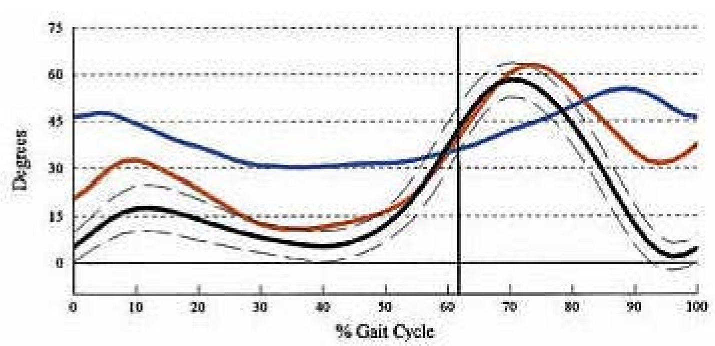


FIGURE 3. Pre-op (blue) and post operative (red) knee flexion-extension curve of a patient with cerebral palsy who underwent hamstring lenghtening and rectur femoris transfer. Normal with standard deviation is also shown as a benchmark (black).

**Further technological enhancements such as musculoskeletal modeling allow estimations of muscle-tendon origin to insertion lengths during gait** (*Figure 4*).

Children's Motion Analysis Center incorporates this recent technology to discern the cause of crouch gait in cerebral palsy in specific patients. Short hamstrings are commonly implicated as the cause of crouch gait. This has been found to be not necessarily always true; many patients with crouch gait have longer than normal hamstring length estimates but shorter than normal hip flexor length. This predicament begs the still unanswered question of which treatment, hamstring lengthening, psoas lengthening or both is appropriate. Surely the answers are individualized to each patient. Technological advances such as this will allow physicians to study principles, challenge old methods and devise new ones to handle the treatment dilemmas presented by patients with cerebral palsy.

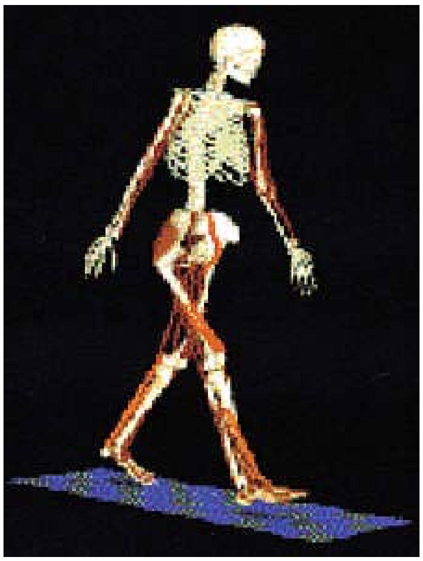

FIGURE 4. Animated character with dynamic muscle origin to insertion lengths.

Much attention has been devoted to the application of clinical gait analysis to the treatment of children with cerebral palsy. **The benefits of gait analysis to these patients has been documented by leading pediatric orthopaedic surgeons, physical therapists and engineers**. This is not surprising since children with cerebral palsy comprise the vast majority of patient volume for many gait laboratories. But with time, a number of established gait labs have been able to accumulate kinematic, kinetic and electromyographic data of patients with other problems—from clubfoot to total joint replacement to rotational alignment of the lower extremity.

## GAIT ANALYSIS IN SPINA BIFIDA

Spina bifida or myelomeningocele was first recognized nearly 4000 years ago and occurs in approximately 1 of 1000 births. Spina bifida results from the failure of the neural tube to close in the developing fetus. The associated neurological impairment generally correlates with the level of the anatomic lesion and ranges from complete paralysis to minimal motor deficit. With improved treatment and intervention for hydrocephalus, these patients, particularly children with low lumbar-level lesions, have a much greater chance of maintaining their level of walking ability into adolescence and adulthood. With the advances in neurological care, these patients are expected to be community ambulators well into adulthood. The challenge to the orthopaedic surgeon to maintain the quality of gait for these children is assisted by gait analysis.

Children with spina bifida present to the orthopaedic surgeon, therapist and orthotist with a wide array of challenges. Some of the orthopaedic problems, such as clubfoot and hip dislocation, are present at birth, but many develop with growth during childhood because of unbalanced muscle groups and unique gait patterns. The muscle imbalance is most evident around the hip because the gluteus maximus and gluteus medius are weak relative to the antagonist flexor and adductor muscle groups.

Neural innervation of the ankle dorsiflexors and plantar flexors also originates from the sacral level of the spinal cord; therefore these muscle groups are typically weak or absent. The muscle weakness induces certain compensatory movements at the pelvis and hip to facilitate forward progression and maintain independent ambulation. This unique gait pattern is characterized by exaggerated dynamic range of pelvic rotation and pelvic obliquity, increased stance phase hip abduction, increased stance phase knee flexion, and increased ankle dorsiflexion.

The recognizable kinematic and temporal parameters have been related to the degree of muscle deficiency around the hip and ankle for children with sacral and low lumbar level lesions. Studies that comprehensively quantify the gait patterns of children with myelomeningocele may augment the typical gait analysis evaluation and subsequent treatment approach to these children. Comparison of pathological gait patterns with normal kinematics and kinetics is common within clinical gait laboratories. Benchmarks are necessary in order to determine the efficacy of surgical treatment, but in some cases comparison to normal may not provide the most meaningful information to guide and evaluate treatment plans. The characteristic gait pattern of children with myelomeningocele offers a reasonably homogeneous pathologic baseline from which comparisons can be drawn. Comparison with the expected pathologic gait pattern for a given level of lesion will allow clinicians to focus on realistic goals and to evaluate the results of surgical, orthotic and therapeutic interventions fairly.

The majority of gait analysis research in myelomeningocele has focused on orthotic intervention. The ankle-foot orthosis (AFO) decreases excessive hip, knee and ankle flexion and muscle activation. As the AFO substitutes for plantar flexor weakness and restrains tibial advancement, the prolonged quadriceps activity ceases earlier during stance due to decreased knee flexion. Gait analysis has documented the profound effect orthotic design can impose on the gait of patients with myelomeningocele. This is important because of the numerous orthotic options available, including knee-ankle-foot orthoses (KAFOs), various crouch-control AFO designs and the classic solid AFO. Many high sacral and low lumbar patients also use crutches for some or all of their walking.

Crutch use is often an issue, particularly with adolescent patients concerned with body image, but gait analysis has been used to demonstrate the benefits of crutch use for many patients with high sacral level lesions. With improving technology, gait analysis will play a vital role in the potential advances in orthotic and assistive device design such as externally powered AFOs, electronically controlled free knee joint KAFOs, and computer-aided design and manufacturing, which ultimately benefit these patients.

Muscle imbalance at the hip in these patients invites hip subluxation and dislocation, and nearly half of all patients with myelomeningocele develop some degree of hip instability during the first ten years of life. Surgeons often debate the efficacy of surgical relocation of the hip in these patients. Complications after surgical intervention such as joint stiffness, pathological fractures, and re-dislocation further fuel the debate. Quantification of the gait pattern and the degree of symmetry of those patients with unilateral hip subluxation have assisted surgical selection. The use of gait analysis at Children’s has shifted the focus from simply the hip status as depicted on x-ray to the quality of gait that is contingent not so much on the hip status but on asymmetrical soft tissue contractures. These contractures are addressed with surgical techniques simpler than the more invasive hip relocation surgery, and at Children's more efforts are directed to avoidance and correction of soft tissue contractures to keep these patients walking throughout their lives.

Williams et al. reported a 24% incidence of late knee pain in patients with lumbosacral-level lesions and described a knee valgus and flexion deformity. Most often this appearance of knee valgus is just that: "apparent" knee valgus that results from a combination of internal pelvic and hip rotation, external tibial rotation, and stance phase knee flexion. Over time, the constant proximal swivel movement of the pelvis and hip over the planted stance foot often induces rotational deformity.

Lim et. al. at Children's Motion Analysis Center documented the possible source of the high incidence of knee pain by showing an excessively high internal knee varus moment related to the magnitude of external tibial torsion in association with increased pelvic rotation and lateral trunk sway. Early attention in these patients is usually directed to the hips and feet, but knee problems may preclude long-term ambulatory status. The use of gait analysis for early detection of abnormal knee moments followed by treatment with tibial derotational osteotomy (*Figure 5*) or KAFO to avoid later knee pain holds promise.

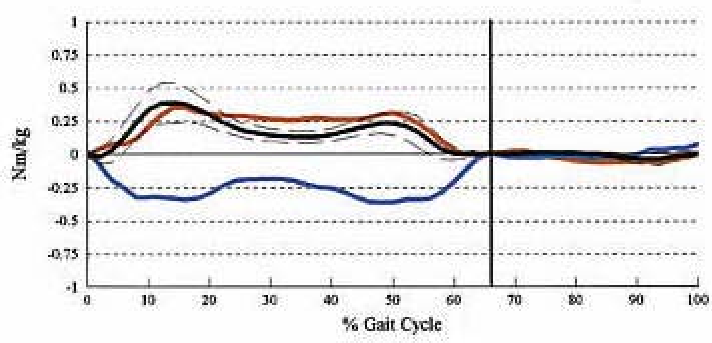


FIGURE 5. Pre-op (blue) and post operative (red) knee moment or torque curve of a patient with spina bifida who underwent internal tibial derotational osteotomy. Normal with standard deviation is also shown as a benchmark (black).

The patients with sacral- and lumbar-level lesions tend to be quite active individuals despite the greater energy demands placed upon them. The functioning muscle mass in children with myelomeningocele is reduced; hence they have a lower aerobic capacity. When this physiological change is compounded with excessive pelvic movements, oxygen consumption during walking is elevated. As energy consumption analysis becomes standard in clinical gait laboratories, more research will be performed on these patients to help direct physical therapy and structured exercise programs to improve long-term walking potential.

**Gait analysis has played a prominent role in the evolution of treatment of patients with cerebral palsy. This has led to selective intramuscular tenotomies to preserve muscle function**, classification of spastic gait patterns to focus treatment plans and **improved surgical planning,** particularly when multilevel simultaneous surgery is considered. The use of gait analysis in the treatment of children with myelomeningocele certainly has progressed more slowly. Nonetheless, its significant influence in cerebral palsy treatment offers much hope for clinicians who treat ambulatory children with spina bifida to address issues such as relocation of subluxed or dislocated hips, rotational abnormalities and efficacy of therapeutic electrical stimulation. This hope will become reality only through well designed, multidisciplinary studies, diligent request for pre and post treatment evaluations, multicenter collaborations now made easier with the information superhighway and as much hard work and motivation as the children demonstrate.

## THE NEXT STEPS

Prevention of disease and clinical outcome measures will take on added importance in the future. Documentation of patient functional status will not only be desirable but necessary as attention shifts from short-term savings to long-term improvement in both cost and quality of treatment. Clinical motion data need to be expressed in an automated, understandable and concise format for clinicians to identify and treat pathological human movement. Interpretation of clinical motion data has been confined to experienced clinicians familiar with the graphical output due in part to the difficulty in visualizing motion and biomechanical parameters.

Advances in computer animation will make it possible to correlate a realistic, anatomically correct, animated human character that depicts actual motion with biomechanical variables, video and descriptive text. The character should be able to be viewed from any angle and manipulated in three-dimensional space. Instead of being inundated with numbers, graphs and charts and comprehending little, this practical, interactive presentation of key results to referring physicians and their patients will allow them to integrate the pertinent gait measurements and observations readily to formulate the treatment plan. Children's Motion Analysis Center is one of the initial testing sites for a program of this kind and will be the first to offer this technological advancement to referring physicians and clients.

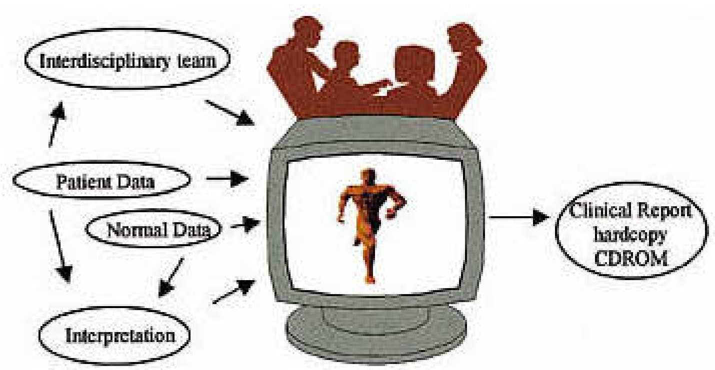


FIGURE 6. The collaborative process of the multidisciplinary team to reach treatment recommendations.

At present there is no universally accepted standard technique for interpretation of clinical motion data. This compromises the ability of professionals in the field to communicate with colleagues in the clinical community. As we reach a consensus, information will be more readily shared among medical centers, immediate physician-physician consult on specific cases will be viable, and the assimilation of larger databases on unique motion disorders will facilitate enhanced treatment. The ultimate goal of motion analysis is to communicate reliable, objective information on which to base clinical decisions, quantify outcomes and ultimately predict the outcomes of various interventions. It is the responsibility of an interdisciplinary team of physicians, engineers and therapists to piece together the multitude of variables, the size and shape of which differ for each child, and to provide a clear course of surgical, orthotic and/or therapeutic treatment.

http://www.childsdoc.org/99Spring/clinicalmotionanalysis.asp

## REFERENCES


1. Delp SL, Arnold AS, Speers RA, Moore CA: Hamstrings and psoas lengths during normal and crouch gait: Implications for muscle tendon surgery. *J Orthop Res* 1996; 14:144–51.

2. DeLuca PA, Davis RB, Ounpuu S, Rose S, Sirkin R: Alterations in surgical decision making in patients with cerebral palsy based on three dimensional gait analysis. *J Pediatr Orthop* 1998; 17:608–14.

3. Gage JR: *Gait Analysis in Cerebral Palsy*, London: MacKeith Press, 1991.

4. Gage JR: Gait Analysis: An essential tool in the treatment of cerebral palsy. *Clin Orthop Rel Res* 1993; 288:126–34.

5. Lim R, Dias L, Vankoski S, Moore C, Marinello M, Sarwark J: Valgus knee stress in lumbosacral myelomeningocele: A gait analysis evaluation *J Pediatr Orthop* 1998; 18:428–33.

6. Ounpuu S, Muik E, Davis RB, Gage JR, DeLuca PA: Rectus femoris transfer surgery in children with cerebral palsy. Part II: a comparison between the effect of transfer and release of the distal rectus femoris on knee motion. *J Pediatr Orthop* 1993;13:331–5.

7. Perry J: *Gait Analysis: Normal and Pathological Function*, New York: McGraw Hill, Inc., 1992.

8. Schafer MF, Dias L: *Myelomeningocele: Orthopaedic Treatment*, Baltimore: Williams & Wilkins, 1983.

9. Vankoski SJ, Sarwark JF, Moore C, Dias L: Characteristic pelvic, hip and knee patterns in children with lumbosacral myelomeningocele. *Gait and Posture* 1995; 3:51–7.

10. Williams JJ, Graham GP, Dunne KB, Menelaus MB: Late knee problems in myelomeningocele. *J Pediatr Orthop* 1993;13:701–3.


TOP