Optimization of Walking Ability of Children with Cerebral Palsy

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In the last fifteen years, a new paradigm has emerged for orthopaedic clinical decision-making to optimize the walking ability of children with cerebral palsy. This paradigm is based on the biomechanics of normal gait, pathologic gait, and gait disruptions associated with distinct clinical disease processes as well as on a greater understanding of the anatomy and physiology of the muscle-tendon unit and the importance of skeletal alignment.

Normal gait has been studied, and with current technology we are now able to quantitatively measure the normal movements associated with gait (kinematics) and to objectively assess the principal applied moments acting about the joints (kinetics) during the gait cycle. This information, coupled with the electrical potentials generated by individual muscles during the gait cycle (dynamic electromyography), has documented the maturation of normal gait in children and led to the development of age-matched normal profiles for walking.

Careful quantitative analysis of pathologic gait and gait disruption associated with a variety of clinical disease processes has led to the development of classification schemes for gait deviations and to the recognition of common pathologic gait patterns. It has become clear that the pathomechanics of various gait deviations are often disease-specific, and therefore the underlying causes and appropriate treatments of similar gait deviations in children with poliomyelitis, cerebral palsy, myelodysplasia, or a spinal cord injury are distinct.

Investigation of the anatomy and physiology of the muscle-tendon unit has revealed numerous variables that can influence the unit’s ability to generate a moment about a joint during the gait cycle. These variables include aspects of myoarchitecture such as muscle mass, fiber length, and pennation angle, which are used to determine the physiological cross-sectional area, a value that is a predictor of the maximum force that can be generated by the muscle-tendon unit. Skeletal alignment affects the function of the muscle-tendon unit because the ability of a muscle to generate a moment (moment = force × distance) is related to the distance from the joint center about which the force is applied. Skeletal malalignment generally shortens the available lever arm, placing the muscle-tendon unit at a biomechanical disadvantage and compromising its ability to generate an optimal moment.

This quantitative, biomechanically based approach has been accepted as a research and teaching tool and as an instrument of outcome assessment. The clinical orthopaedic community has not fully embraced this new paradigm, and its role in clinical decision-making remains controversial, with critics expressing concerns about expense and about accuracy and repeatability. The goals of this review are to: (1) describe this new paradigm and its application to orthopaedic clinical decision-making for children with cerebral palsy and (2) present the current indications for the most common orthopaedic operations performed to optimize the walking ability of children with cerebral palsy.

Clinical Decision-Making

Orthopaedic clinical decision-making to optimize the walking ability of children with cerebral palsy should be based on five sources of information (Fig. 1).

Clinical History

The clinical history is obtained by reviewing the patient’s medical record and interviewing the child and his or her care providers. The medical history identifies associated medical problems and all previous treatments. The social history assesses the family dynamics and support resources required to undertake the arduous rehabilitation that is required after musculoskeletal surgery. A functional assessment of both the cognitive and the motor neurode-
development is performed. Finally, the child’s and care providers’ perceived functional problems and goals for interventions to improve gait should be identified.

**Physical Examination**

The physical examination begins with observing the patient’s gait. This should be done in a systematic fashion in two planes. The ranges of motion of all major joints from the pelvis to the foot are measured. The accuracy and repeatability of these measurements are improved by using standardized techniques of limb-segment manipulation and using a goniometer and an angle guide. Skeletal alignment in the transverse, coronal, and sagittal planes is assessed in a similar systematic fashion. A neurological examination is performed to identify any deficits of selective control of muscle activation, muscle strength, and balance.

**Diagnostic Imaging**

Diagnostic imaging is used to better assess skeletal alignment. It is most valuable for evaluation of the foot and ankle and for assessment of the alignment of the lower extremity in the coronal and sagittal planes. It is best to make these radiographs while the patient is standing. Common patterns of malalignment of the foot and ankle include ankle valgus, pes equinus, pes planovalgus, and pes equinovarus. Rotational malalign-

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**Fig. 2-A** Sagittal plane view of a subject walking with a crouch gait pattern. Note the greatly increased hip flexion, anterior pelvic tilt, and anterior trunk tilt. **Fig. 2-B** Sagittal plane view of the same subject performing high kneel walking. Note the greatly improved alignment of the hips, pelvis, and trunk. This improvement suggests that these deviations are compensatory in nature.
ments, which are common in the femur and tibia, cannot be evaluated well on plain radiographs. The value of computerized tomography in the assessment of rotational malalignment of the femur and tibia is more controversial. Concerns about the accuracy of this measurement technique are related to the difficulty in defining and determining the axis of the proximal part of the femur, the femoral neck, and the femoral head.

Quantitative Gait Analysis

Quantitative gait analysis utilizes high-speed motion-picture cameras, retro-reflective markers on the surface of the skin aligned with palpable skeletal landmarks, and force platforms to measure various aspects of gait.

Kinematic data, presented as a waveform, describe the motion occurring simultaneously in three planes. Kinetic data (moments and powers), also presented as a waveform, define the motion occurring about the joints during the gait cycle. Analysis of kinetic data provides a biomechanical basis for the understanding of pathologic gait and helps to provide a rationale for the selection of various orthopaedic, neurosurgical, and orthotic interventions.

Dynamic electromyography documents the timing of individual muscle activation during the gait cycle. Other modalities that may be used include pedobarography (dynamic assessment of foot pressure distribution and progression) and energetics (dynamic assessment of oxygen consumption, reflecting the physiologic costs associated with walking).

Interpretation of these data is improved by understanding the technologies and techniques used to measure movement. Kinematic calculations assume a constant relationship between the skin surface marker and the underlying skeletal landmark. Concerns about the accuracy of this measurement technique are related to the difficulty in defining and determining the axis of the proximal part of the femur, the femoral neck, and the femoral head.

Fig. 3-A

Fig. 3-B

Figs. 3-A, 3-B, and 3-C Findings on quantitative gait analysis that serve as indicators for iliopsoas recession at the pelvic brim. The normal ranges of the kinematic and kinetic data for the pelvis and hip are indicated by the gray band on each plot. Fig. 3-A Kinematic analysis of pelvic tilt in the sagittal plane. Note the anterior tilt with a “double bump” waveform pattern during stance phase (arrows). Fig. 3-B Kinematic analysis of hip flexion-extension in the sagittal plane shows diminished extension in terminal stance (arrow), with a decreased dynamic range throughout the gait cycle.

Fig. 3-C

Kinetic analysis of hip moment in the sagittal plane shows an increased internal extension moment in midstance (arrow 1), with delayed crossover to an internal flexion moment in midstance or terminal stance (arrow 2).
The effects of hip joint pathoanatomy and skin-surface-marker motion artifact on kinetic calculations have not been systematically established.

Dynamic electromyography measures the electrical potential generated by a muscle when it is activated. The magnitude of the electrical signal is related to the force being generated by the muscle. This relationship can be determined when the magnitude of that potential can be normalized to that associated with a maximum manual muscle contraction. However, children with cerebral palsy may have impaired selective control of muscle activation, compromising the ability to assess a maximum manual muscle contraction. However, children with cerebral palsy may have impaired selective control of muscle activation, compromising the ability to assess a maximum manual muscle contraction. In such a situation, the dynamic electromyography data can be normalized to the maximum value occurring during the gait cycle, or more commonly presented as a raw signal. In this circumstance, the dynamic electromyography data can provide valuable information concerning the timing of muscle activation but cannot indicate relative muscle strength or weakness. An appreciation of these limitations greatly enhances the critical and correct application of the quantitative data to the clinical decision-making process.

Quantitative analysis of normal gait has identified four important components or prerequisites: (1) stability of the limb in stance phase, (2) clearance of the limb in swing phase, (3) effective shifts of the limb from stance to swing and from swing to stance phases, and (4) occurrence of these components in a fashion that promotes maximum efficiency of energy expenditure.

In pathologic gait, these four components are disrupted to varying degrees and in varying combinations. Gait deficits or deviations, as identified by quantitative gait analysis, associated with the pathologic gait of children with cerebral palsy may be classified as primary, secondary, or tertiary. Primary deficits are directly related to the underlying disorder of the central nervous system and include spasticity, impaired balance, and impaired motor control. In general, orthopaedic interventions do not directly address these primary deficits. Secondary deficits or deviations occur as a consequence of growth and development of the musculoskeletal system and are generally sequential and progressive over time. Such deficits result in greater disability as children grow into young adults. Examples include the progression of deformity of muscle-tendon units from completely dynamic deformity (overactivity with no fixed shortening) in early childhood to myostatic deformity (fixed or structural shortening or contracture) seen in later childhood and preadolescence. The same sequential progression is true for skeletal deformities, in which flexible and passively correctable segmental malalignment at the foot and ankle is followed in time by rigid skeletal deformity. Finally, the interpretation of quantitative gait data is facilitated by the recognition of common patterns of pathologic gait of children with cerebral palsy. The most common patterns—jump gait, crouch gait, stiff gait, recurvatum gait, and intoeing or outtoeing gait—have distinct kinematic and kinetic profiles.

**Examination Under Anesthesia**

The clinical assessment of whether a muscle-tendon unit deformity is dynamic or myostatic is best performed when the child is examined under general anesthesia. When the child is awake, the presence of spasticity can limit the distinction between dynamic overactivity and fixed shortening of the muscle-tendon unit. Spasticity is not present under general anesthesia, so that any limitation of range of motion is due to a myostatic deformity (contracture) of the muscle-tendon unit or intra-articular pathology such as adhesions or bone deformity.

**The Diagnostic Matrix**

Clinical decision-making with use of the diagnostic matrix is best carried out at an interpretation session attended by clinical and technical members of the motion analysis laboratory team. The certainty of selecting the best intervention is proportional to the consistency of the data within the diagnostic matrix. The selection and results of a specific treatment are optimized when the problems being considered are common and the data from all sources are consistent. It is not possible to be as confident about the selection of intervention or its results when the problems are unusual and the data within the matrix are not consistent. This inconsistency may be a consequence of attempts to classify the continuous spectrum of a clinical disease process into a categorical framework and/or deficiencies in the technology and techniques of quantitative gait analysis. Sorting out these inconsistencies frequently involves the input of members of both the clinical and the technical team. For example, discrepancies concerning motion about the hip and pelvis...
between observational gait analysis and quantitative gait analysis are generally resolved by giving greater weight to the quantitative data. This is done because visual assessment of the movement about the hip and pelvis during the gait cycle is difficult and frequently misleading, whereas the accuracy of the kinematic assessment is much greater in all three planes\(^{24,35,42,45,46}\). On the other hand, discrepancies among the clinical examination, diagnostic imaging, and quantitative gait analysis data about the foot and ankle should be resolved in favor of the data derived from the clinical examination and diagnostic imaging. The reason for this is that the foot and ankle model used in quantitative gait analysis is simplistic\(^{35,47-49}\). For example, ankle dorsiflexion is defined by the relative alignment of the shank and foot axes in the sagittal plane, and the foot axis is defined by a single marker over the forefoot that combines the movements occurring through multiple foot segments into a single measure. With a major skeletal segmental malalignment, such as pes planovalgus, the model overestimates the amount of ankle dorsiflexion occurring during midstance, giving inaccurate kinematic data.

**Current Indications for Common Musculoskeletal Surgical Interventions**

With use of the diagnostic matrix, it is possible to identify the indications for the selection of specific musculoskeletal surgical interventions to optimize the gait of children with cerebral palsy.

**Iliopsoas Recession**

**Clinical history:** The most common symptom indicating the need for this procedure is the inability to stand straight and walk with the upper body erect.

**Physical examination:** A hip flexion contracture (\(>30\)°) is an indication for iliopsoas resection. The patient should be examined in the supine position (Thomas test) and the prone position (Staheli test)\(^{29}\). The magnitude of a hip flexion contracture is frequently overestimated by...
these techniques because of the difficulty in stabilizing the pelvis, and the measurements are inconsistent because of variability in pelvic positioning. The current recommendation is to position the pelvis so that the line connecting the anterior superior and posterior superior iliac spines is vertical50. This technique facilitates more consistent positioning of the pelvis and ensures that the angle measured during the clinical examination is the same as that used in the kinematic model in gait analysis for the calculation of hip motion in the sagittal plane. Observing the child while he or she walks in a “high kneel” pattern (i.e., walks on the knees) removes the influence of tight hamstrings on pelvic alignment (Figs. 2-A and 2-B). This will unmask any tightness of the hip flexors.

Diagnostic imaging: No imaging studies are required.

Quantitative gait analysis: With this analysis, which identifies kinematic and kinetic indicators (Figs. 3-A, 3-B, and 3-C), pelvic motion in the sagittal plane shows an anterior tilt with a “double bump” waveform pattern during stance phase. Hip motion in the sagittal plane shows diminished extension in terminal stance, with a decreased dynamic range throughout the gait cycle. Kinetic analysis of the hip moment in the sagittal plane shows an increased internal flexion moment in midstance or terminal stance.

Examination with the patient under anesthesia: This is frequently required to resolve the roles of dynamic and myostatic deformities of the hip flexor muscles.

Management: There is considerable controversy concerning the appropriate indications for iliopsoas recession to improve gait in children with cerebral palsy40,50-56. A better understanding of the biomechanics of hip, pelvic, and trunk motion is needed to clarify the indications for this procedure in these children. When hip flexion contractures are present, they are seldom an important problem for a child with cerebral palsy who is able to walk. In addition, these contractures are frequently overestimated on clinical examination. The kinematic and kinetic variables identified as indications for this procedure are frequently the consequence of other primary gait deficits, such as weakness of the abdominal and hip extensor muscles and impaired balance and position senses. Similar quantitative profiles may be seen as tertiary or compensatory deviations, such as in a severe crouch gait due to insufficiency of the ankle plantar flexors and overactivity of the knee flexors. These disorders increase hip flexion and possibly anterior pelvic tilt, shifting the body’s center of gravity forward relative to the hip center, increasing the external hip flexor moment and delaying the flexor-to-extensor moment crossover in stance phase. Such compensatory gait patterns resolve spontaneously following correction of the underlying primary or secondary deficits.

Femoral Rotation Osteotomy
Clinical history: Candidates for this procedure, or their parents, report intoeing, knee knocking, and tripping.

Physical examination: The patient has increased femoral anteverision, which is best appreciated when he or she is examined in the prone position with the hip in full extension. Hip rotation is abnormal, with increased internal rotation and limited external rotation, indicating increased femoral anteverision42,55. The value of another physical examination maneuver, the
trochanteric prominence angle test, has recently been shown to be limited by obesity, scarring associated with previous surgery, and variable alignment of the greater trochanter with respect to the axis of the femoral neck. Observational gait analysis may reveal internal rotation of the patella relative to the line of progression when the child walks. This visual assessment is often confounded by increased, asymmetric pelvic rotation during the gait cycle.

Diagnostic imaging: Computerized tomography scans may be utilized to assess femoral anteversion when the findings of the clinical examination are compromised or confusing. The most widely accepted techniques are performed in either two-dimensional or three-dimensional (volumetric reconstruction) formats.

Quantitative gait analysis: Kinematic data reveal increased internal hip rotation throughout the gait cycle. Examination with the patient under anesthesia: Anesthesia may be necessary to evaluate a patient with suspected femoral anteversion. Relative internal-external rotation of the hip is tested as described above, and when necessary the examination can be augmented by the use of fluoroscopy to visualize the alignment of the femoral head and neck.

Management: There is a relationship between increased femoral anteversion (a static, structural skeletal deformity) and increased internal hip rotation (a dynamic gait deviation). The latter occurs as a compensation to restore the lever arm available for the hip abductor muscles, which is diminished by the former. When both are present, surgical correction of the increased femoral anteversion will result in resolution of the gait deviation and normalization of hip rotation during walking. Not all children with cerebral palsy and increased femoral anteversion exhibit increased internal hip rotation when walking, and not all children with cerebral palsy and increased internal hip rotation during the gait cycle have increased femoral anteversion.

Medial Hamstring Lengthening
Clinical history: The patient or parents may complain that the child cannot stand up straight, walks with the knees bent, and has anterior knee pain with fatigue when walking a distance.

Physical examination: Straight-leg raising is limited (<60°), the popliteal angle is diminished (<130°) when mea-
The hamstring muscles cross both the hip and the knee joint, and appropriate medial hamstring lengthening will improve knee extension at initial contact and in terminal swing. Increased anterior pelvic tilt is not seen following unilateral or bilateral medial hamstring lengthening. Lateral hamstring lengthening is necessary only in teenagers with a severe crouch gait (>40° of knee flexion in stance) and should otherwise be avoided to minimize the risk of excessive weakness following surgery. Severe hamstring tightness may cause posterior pelvic tilt. In this situation, the increased anterior pelvic tilt that may occur following bilateral medial and lateral hamstring lengthening is not harmful. Knee flexion contractures that exist following hamstring lengthening are best corrected by the use of serial casts in the postoperative period.

**Rectus Femoris Transfer**

**Clinical history:** The patient or parents complain that the child has stiff knees, toe dragging, and tripping.

**Physical examination:** The patient has a positive prone rectus test (Duncan–Ely test). The child is placed in the prone position with the hips and knees fully extended. The test is considered positive when the pelvis elevates (as a result of hip flexion) as the knee is slowly passively flexed and/or there is a “catch” on rapid passive knee flexion.

**Diagnostic imaging:** No imaging studies are required.

**Quantitative gait analysis:** Kine- matic and dynamic electromyographic data are useful (Figs. 6-A and 6-B). Knee motion in the sagittal plane shows a diminished dynamic range of motion (<80% of normal), delayed and diminished peak flexion in swing phase, and a blunting of the flexion wave in swing phase. Dynamic electromyography shows an inappropriate midswing phase of the rectus femoris. Coactivation of the vastus lateralis in midswing may or may not be present and does not seem to affect the outcome of a rectus femoris transfer.

**Examination with the patient under anesthesia:** No additional information is gained from an examination under anesthesia.

**Management:** Diminished and delayed peak knee flexion in swing phase may be the consequence of decreased velocity and diminished stride length. In addition, a combination of factors occurring during stance phase, at the stance-to-swing interval, as well as abnormal activity of the rectus femoris in midswing can all contribute to the disruption of knee flexion in swing phase. Currently, the rectus femoris transfer is indicated to maintain or improve the magnitude and timing of peak knee flexion in swing phase when hamstring lengthening is being performed. The rectus femoris transfer is best performed at the time of hamstring lengthening, but it may also be done following inappropriate isolated hamstring lengthening that has resulted in a stiff knee gait pattern. Although it is considered a component of the quadriceps femoris muscle group, the rectus femoris is actually a two-joint muscle (the other three components are single-joint muscles) whose activation timing and functional importance during the gait cycle are distinct from those of the remainder of the quadriceps. For this reason, transfer of the rectus femoris does not compromise knee extensor function in stance phase.

**Gastrocnemius Lengthening**

**Clinical history:** Patients and their families report toe walking, toe dragging, tripping, and intoeing.

**Physical examination:** The patient has a diminished passive range of ankle dorsiflexion, a sustained spastic response to an applied fast stretch of the gastrocnemius muscle (clonus), and an increased deep tendon reflex at the ankle. It is helpful to consider the foot and ankle as consisting of three segments (hindfoot, midfoot, and forefoot) and
two columns (medial and lateral). The alignment of each segment is described relative to the adjacent proximal segment. The three most common patterns of segmental malalignment of the foot and ankle in children with cerebral palsy are equinus (seen most commonly in younger children), planovalgus (seen most commonly in children with spastic diplegia), and equinovarus (seen most commonly in children with spastic hemiplegia). Equinus malalignment consists of plantar flexion deformity of the hindfoot, with the other segments in normal alignment and the columns having an appropriate length. Planovalgus malalignment consists of hindfoot plantar flexion and eversion, midfoot pronation, and forefoot supination. The lateral column is functionally shorter than the medial column. Equinovarus malalignment consists of hindfoot equinus and inversion, midfoot supination, and forefoot pronation. The lateral column is functionally longer than the medial column.

Diagnostic imaging: Weight-bearing plain radiographs of the foot and ankle are routinely utilized. When malalignment is found on physical examination, it is evaluated further on the radiographs, with the investigator looking for structural abnormalities.

Quantitative gait analysis: Kinematic, kinetic, and dynamic electromyographic data are routinely obtained (Figs. 7-A through 7-D). Ankle motion in the sagittal plane shows excessive plantar flexion in stance and swing phases. All three ankle rockers in stance phase are disrupted, with an absence of the first (or heel) rocker, flattening or inversion of the second (or ankle) rocker, and a premature, diminished third (or forefoot) rocker. The ankle moment in the sagittal plane shows an absence of the internal dorsiflexion moment in the loading response, an increased internal plantar flexion moment in midstance (the double bump pattern), and a decreased internal plantar flexion moment in terminal stance. The ankle power in the sagittal plane shows premature power generation in midstance and diminished power generation in terminal stance. Dynamic electromyography of the gastrocnemius is notable for premature activation of the stance-phase burst, beginning at initial contact or in terminal swing.

Examination with the patient under anesthesia: The relative contributions of the gastrocnemius and soleus muscles to tightness of the ankle plantar flexors are best determined with an examination under anesthesia. These contributions are assessed by measuring ankle dorsiflexion with the knee flexed (which relaxes the gastrocnemius and allows evaluation of the soleus) and extended (greater reduction in ankle dorsiflexion motion with the knee extended, compared with the motion when the knee is flexed, is attributed to myo-static deformity of the gastrocnemius).

Management: Discrepancies between the passive range of motion of the ankle noted on physical examination and the dynamic ankle motion measured during gait may be the consequence of (1) an increased spastic response following the disrupted first rocker, which further limits the dynamic range of motion at the ankle in the second rocker; (2) the fact that the external forces applied about the ankle during gait (particularly in adolescence and the teenage years, primarily as a result of increased body weight) are greater than those that can be applied by the examiner during the clinical assessment; or (3) the fact that foot and ankle segmental alignment during the clinical examination may not be consistent with dynamic foot and ankle segmental alignment during gait (because of variable lever arm alignment). Discrepancies between the findings of observational gait analysis and those of quantitative gait analysis at the foot and ankle may be the result of the assumption that a toe strike at initial contact, easily appreciated visually, implies increased or excessive ankle plantar flexion. However, increased knee flexion with neutral ankle alignment, also results in a toe-strike pattern at initial contact. Quantitative gait analysis (kinematic data) effectively documents the absence or presence of excessive ankle plantar flexion in this situation.

Overview and the Future

The acceptance and integration of quantitative gait analysis into clinical decision-making for children with cerebral palsy will occur as pediatric orthopaedic surgeons move away from opinion-based practices toward evidence-based medicine. Good clinical practice involves the interpretation of evidence from a variety of sources, with application of the results of population-based studies to the individual patient. With technological improvements and greater clinical experience with their applications, issues related to the accuracy and reliability of quantitative gait analysis will be resolved, greatly facilitating the collaboration required for multicenter studies. Comprehensive assessment of outcome in multiple domains (technical, functional, patient satisfaction, and cost) will determine the true costs of performing the correct (or incorrect) surgery to improve walking for children with cerebral palsy.

Utilization of a diagnostic matrix that includes quantitative gait analysis will play a central role in the incorporation of an evidence-based-medicine paradigm for clinical decision-making to optimize the walking ability of children with cerebral palsy.
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