Comparison of functional outcomes from orthopedic and neurosurgical interventions in spastic diplegia

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Selective dorsal rhizotomy (SDR) and orthopedic surgery, in the form of muscle-tendon (MT) lengthening surgery are commonly performed in ambulatory children with spastic diplegia to improve their level of motor function. This investigation is a post hoc comparison of the functional effects from each of these surgical options in 30 patients with spastic diplegia who underwent one of these interventions as their initial surgical procedure. Sixteen children underwent SDR and 14 underwent MT surgery in two separate prospective clinical trials. The same functional outcome measures preoperatively and approximately 1 year postoperatively were used in both studies including temporospatial parameters from three-dimensional gait analysis, the total score, and score on each of the five dimensions of the Gross Motor Function Measure (GMFM). Comparisons indicate that patients who underwent SDR had significant improvements in GMFM Dimensions 2, 4, and 5 as well as in total score, although 63% of those studied had a 10% or more reduction in gait velocity. Gait was more predictably improved in the MT group, with only 21% demonstrating reductions in velocity. Conversely, the change in GMFM scores in the MT group was not as pervasive and skewed toward higher skills with only GMFM Dimension 5 and total score improved significantly. Several important hypotheses are derived from these comparisons. Multicenter clinical trials are needed to define more clearly the indications for and to assess more comprehensively the outcomes from each intervention.

Key Words * cerebral palsy * spastic diplegia * orthopedic surgery * selective dorsal rhizotomy * gait * outcome measures

Cerebral palsy (CP) is a group of disorders in which the common underlying disease is a nonprogressive lesion to a developing nervous system. Although many patients with CP may have associated cognitive or sensory impairments, the hallmark of this disorder is motor dysfunction. The incidence of CP has remained fairly steady at approximately one to three per 1000 live births,[11,27] but the etiology and epidemiology of this disorder have changed somewhat in recent decades. Spastic diplegia is now the most prevalent type of CP, occurring in more than 50% of cases.[14]

Nearly all children with spastic diplegia have deficits at the foot and ankle and, as severity increases, the

ability to exert control at the knee and hip joint is compromised.[1] Despite bilateral lower-extremity involvement, the majority of children with spastic diplegia have the capability to ambulate, albeit at a later age and with less proficiency than normally developing peers.[3,4,22] Joint excursions, cadence, and walking speed decrease as a function of severity.[6] The parents and caregivers of children with spastic diplegia put a major emphasis on motor development and walking in early childhood years.[4] Consequently, the majority of interventions provided to these children are designed to facilitate, improve, or maintain walking skills. Orthopedic surgery, in the form of muscle-tendon (MT) lengthening surgery and selective dorsal rhizotomy (SDR) are two invasive strategies used to treat the mobility deficits in spastic diplegia.

Muscle-tendon lengthening surgery has played a central role in the treatment of deformity caused by CP.[5,12,23,26] Indications for orthopedic surgery in spastic CP include dynamic or static joint contractures that interfere with ambulation or lead to joint instability. It has been demonstrated in numerous studies that MT surgery will increase passive and active joint motion and alter limb alignment in gait.[10,32] The effects on overall motor function are less clear.

Since 1984, SDR has become popular in the management of motor dysfunction in patients with spastic diplegia.[8,9,23,24] Selective dorsal rhizotomy is a neurosurgical procedure that involves partial deafferentation of the lumbosacral dorsal roots to attenuate the spinal stretch reflex of lower-extremity MT units. The reduction in spasticity is intended to facilitate gait and motor function. The evidence is clear that spasticity, as measured by the Ashworth Scale or other more objective techniques, is reduced following this procedure, but the impact on motor function as determined by randomized clinical trials is more controversial.[17,29]

Although the primary pathophysiological mechanism addressed by each of these two surgical approaches may differ, considerable overlap exists in their respective indications, with the reality that many patients with spastic diplegia are candidates for either and perhaps both procedures. Each procedure may improve limited joint mobility and dynamic movement abnormalities,[18] but their comparative effect on gait and overall motor function have not been previously investigated. The purpose of this study is to develop hypotheses regarding the relative functional effects of orthopedic surgery and SDR in ambulatory patients with spastic diplegia. Two independently conducted prospective investigations in which the same outcome measures were used are combined for post hoc analyses to compare changes in gait and overall gross-motor function approximately 1 year following MT surgery and SDR. Our ultimate goal is to understand better the magnitude and quality of change in motor function that can be expected from these two approaches for managing spastic diplegia and to design the studies necessary to document their relative merits.

CLINICAL MATERIAL AND METHODS

Patient Selection Criteria and Groups

Each of the two groups of patients described below was enrolled in a prospective trial at a different institution. For purposes of this comparison, inclusion criteria specified that all children who had complete preoperative and postoperative datasets consisting of Gross Motor Function Measure (GMFM) dimensions and temporospatial gait parameters and who had not undergone prior orthopedic or neurological surgery were to be included in the analysis. Five of the 21 children in the SDR group and 16 of 30 children in the MT group failed to meet these criteria and were therefore excluded. Table 1 lists the age and preoperative functional status of the two surgical groups. Ambulatory status was rated either as a

"limited ambulator" defined as one who can take steps at home or in the community with external assistance or as an "independent ambulator" who walks freely in the community with no assistance needed.

TABLE 1 PREOPERATIVE FUNCTIONAL STATUS OF PATIENTS UNDERGOING TREATMENT FOR CP WITH SDR OR MT SURGERY*		
Parameter	Group 1 SDR (16 patients)	Group 2 MT Surgery (14 patients)
age at surgery (yrs)	5.86 ± 2.24 (3.2–12.7)	5.88 ± 1.92 (3.7–10.9)
ambulatory status		
limited	11	8
independent	5	6
velocity (m/sec)	0.55 ± 0.32	0.68 ± 0.32
cadence (steps/min)	113 ± 39.5	132.9 ± 42.9
stride length (m)	0.56 ± 0.20	0.59 ± 0.20
GMFM total score (%)	71.9 ± 13.4	76.3 ± 14.6
*All values, except ambulatory status, are expressed as the mean ± standard deviation.		

Group 1 consisted of 16 of 21 patients with spastic diplegia who were in the surgical arm of a randomized clinical trial at the Children's Hospital and Regional Medical Center in Seattle, Washington, comparing SDR plus physical therapy (PT) to PT alone.[17] For inclusion in the original protocol from which this subset was derived, children needed to be at least 3 years of age, demonstrate spasticity without concomitant athetosis or ataxia, and be ambulatory or have the potential to ambulate.[15,20] Any child with active hip subluxation or significant static contractures of lower-extremity joints was excluded from participation.

Group 2 consisted of 14 of 30 patients with spastic diplegia who participated in a prospective analysis of MT surgery at the Kluge Children's Rehabilitation Center of the University of Virginia (Table 2).[2] All patients were scheduled for MT surgery for the correction of dynamic and/or static contractures. For inclusion in the original protocol, children needed to be able to ambulate a minimum distance of 10 m with or without hand-held aids. Exclusion criteria consisted of the following: nonambulatory, moderate-to-severe mental retardation, or a concurrent medical condition that required medications that might affect motor function (for example, anticonvulsant or antispasmodic drugs). In addition, any patient with torsional deformities severe enough to warrant osteotomy was not included because of the prolonged recovery time after the procedure. Six of the patients were independently ambulatory without aids and eight required hand-held aids for ambulation.

Case No.	No. MT Units Lengthened	Procedures†
1	2	gastroc recess
2	8	adductor longus, prox gracilis, semitendinosus release gastroc recess
3	6	gastroc recess, med & lat hamstring lengthening, subtalar stapling
4	2	gastroc recess, subtalar stapling
5	6	adductor longus, prox gracilis release, gastroc recess
6	6	adductor longus, prox gracilis release, gastroc recess
7	13	adductor longus, prox gracilis, rt adductor brevis release, med & lat hamstring lengthening, semitendinosus release, gastroc recess
8	6	semitendinosus release, rectus femoris transfer to semimembranosus, calcaneal osteotomy, gastroc recess
9	2	gastroc recess
10	8	adductor longus, prox gracilis, semitendinosus release, gastroc recess
11	2	gastroc recess
12	6	med hamstring lengthening
13	12	adductor longus release, prox gracilis release, med & lat hamstring lengthening, gastroc recess
14	6	adductor longus, prox gracilis release, gastroc recess

* Gastroc = gastrocnemius; lat = lateral; med = medial; prox = proximal; recess = recession.
† All procedures were bilateral unless otherwise indicated.

Operative Technique and Postoperative Management

A consistent operative technique was used for all patients in Group 1.[16,17] The patients received general anesthesia without neuromuscular blockade so that electromyographic responses would not be suppressed. A narrow laminectomy was performed at each level from T-12 to S-2, and intraoperative dorsal root stimulation was performed at each level to identify possibly abnormal electromyographic responses. A mean of 26% of all rootlets were sectioned (range 20-56%). Postoperative management consisted of continuous infusion of narcotic agents for pain and benzodiazepines for muscle spasms as needed for 3 to 5 days, with discharge in approximately 8 days. Physical therapy was initiated 4 days after surgery. For the first 4 weeks, each child received PT 2 hours per day for 5 days each week. During the next 5 months, all children were scheduled to receive 4 to 5 hours of PT per week in their home communities. Children received 1 to 4 hours of PT per week during the last 6 months of the study period.[17]

A standard approach for the MT surgery was used as previously reported.[19] Muscle-tendon units having a broad aponeurotic expansion at the MT junction were lengthened by transection of this aponeurosis (recession), followed by manual stretching until the desired joint position was achieved. Typically a 1- to 3-cm gap in the aponeurosis resulted while continuity of the muscle was maintained. Muscle-tendon structures conducive to aponeurotic lengthening included the semimembranosus, biceps femoris, gastrocnemius, and iliopsoas. Muscle-tendon release was performed at the muscle origin for the adductor longus and gracilis and distally for the semitendinosus (tenotomy). A mean of 6 MT units were recessed or released per patient. The standard postoperative protocol included using an abduction pillow while supine and long leg casts (ambulatory) for 3 weeks. Ambulation was begun on the 1st postoperative day and recommended two to three times daily while at home. All patients were released from the hospital after a therapy session on the 1st postoperative day. At 3 weeks postoperatively, casts were replaced with ankle-foot orthoses for ambulation. Physical therapy was prescribed two to three times per week for 12 weeks to regain strength and promote ambulation. The patient's preoperative

therapy regimen was resumed after 3 months.

Procedures

All patients were evaluated preoperatively within 10 days prior to SDR and a mean of 2.3 months prior to MT surgery and postoperatively within a mean of 12.2 months after SDR and 11.3 months after MT surgery. All patients underwent three-dimensional gait analysis while walking barefoot at a freely selected speed. A five-camera Motion Analysis System (Orthotrak, Santa Rosa, CA) was used in the SDR group and a six-camera Vicon 370 System (Vicon Clinical Manager software, Version 1.21, Tustin, CA) was used in the MT surgery group. Temporal gait parameters such as velocity, stride length, and cadence, which have been shown to be good indicators of gait and general motor function were compared pre- and postoperatively in all patients.[6] In addition, the GMFM, a validated evaluative measure of motor function, was administered pre- and postoperatively.[28] The GMFM includes 88 items within five progressively more difficult dimensions; a score can be obtained for each dimension as well as a total score. Scores are expressed as a percentage, with 100% being the highest score attainable and the expected score for a normally developing 5-year-old child. Therapists at each institution who had met the interrater reliability criteria set by the test developers performed all of the GMFM assessments.

Data Analysis

The change in temporospatial gait parameters and in GMFM scores as a result of surgery was examined within groups by using the Wilcoxon signed ranks test. The magnitudes of change within each parameter across surgical groups were compared with a Mann-Whitney U-test. A probability value of less than 0.05 was considered statistically significant.

RESULTS

Within-Group Comparisons

Group 1: SDR. No significant changes were noted in gait velocity, stride length, or cadence following SDR. Improvements were noted in the GMFM Dimensions 2, 4, and 5 as well as the total score (Table 3).

TABLE 3 COMPARISON OF PRE- AND POSTOPERATIVE DIFFERENCES BETWEEN FUNCTIONAL OUTCOME MEASURES WITHIN EACH SURGICAL GROUP USING THE WILCOXON SIGNED RANKS TEST						
	Group 1 SDR			Group 2 MT Surgery		
	Preop	Postop	p Value	Preop	Postop	p Value
velocity (m/sec)	0.56	0.55	0.64	0.68	0.75	0.22
stride length (m)	0.56	0.62	0.20	0.59	0.67	0.06
cadence (steps/min)	113.0	98.8	0.13	127.5	127.1	0.95
GMFM 1 (%)	97.9	98	0.99	98.7	99.2	0.18
GMFM 2 (%)	94.7*	97.8*	0.03*	95.5	96.6	0.17
GMFM 3 (%)	88.5	91.1	0.33	90.3	89.5	0.75
GMFM 4 (%)	55.5*	66.2*	0.05*	57.2	62.3	0.13
GMFM 5 (%)	33.6*	42.9*	0.003*	39.6*	43.8*	0.007*
GMFM total (%)	71.9*	76.9*	0.007*	76.3*	78.3*	0.02*
* Indicates significance of test at p < 0.05.						

Group 2: MT Surgery. No significant changes were noted in gait velocity, stride length, and cadence following MT surgery. The GMFM Dimension 5 score, and consequently the total score, improved with

no appreciable change in the first four dimensions. Although the mean change in GMFM Dimension 4 for this group was greater than that seen in Dimension 5, the change in this parameter was more variable and therefore did not reach significance.

Comparison Between Groups

None of the preoperative gait parameters or GMFM scores differed statistically between groups. Postoperatively, the magnitude of change in any of the outcome measures did not differ between groups; however, cadence was now significantly lower in the SDR group as compared with the MT surgery group ($p = 0.038$).

Fig. 1. Graphs showing the postoperative change in GMFM total score for individual patients in the MT surgery group (upper) and SDR group (lower).

Figure 1 shows the percentage change of GMFM total scores for the individual children in the MT surgery and SDR groups. Appreciable deterioration in GMFM total score for individual children was not seen in either group (only one child per group had a greater than 4% decrease in total score). For the GMFM total score, a greater than 4% increase occurred in 63% of the SDR group and 50% of the MT surgery group.

Fig. 2. Graphs showing the postoperative change in the velocity and stride length for individual patients in the MT surgery group (upper) and SDR group (lower).

Figure 2 shows the percentage of change in velocity and stride length for the individual children in the MT surgery and SDR groups. A decrease of more than 10% in gait velocity was observed for 10 (63%) of 16 children in the SDR group and three (21%) of 14 in the orthopedic surgery group. No statistically significant differences were found between groups in the magnitudes of change postoperatively. However, the disparity in the statistical changes within groups and in the percentage of children who improved or deteriorated in velocity and GMFM total score suggest that relative differences across procedures may exist. This is shown in Fig. 3, which depicts the magnitude of mean change in GMFM scores for the two groups.

Fig. 3. Graph showing the magnitude of postoperative change for the two surgical groups on each of the five dimensions of the GMFM and the total score.

DISCUSSION

The results of this investigation suggest that different patterns of functional change may follow MT surgery and SDR. Selective dorsal rhizotomy seemed to produce a more generalized effect, as reflected by significant changes in more dimensions of the GMFM, whereas orthopedic surgery had a significant effect only on the highest dimension of the GMFM, which was also reflected in a significant change seen in the total score. A greater percentage of patients improved in gait function after MT surgery, whereas SDR was seen to have a potentially negative effect on gait parameters with 63% of patients showing a 10% or greater decrease in velocity postoperatively. These patterns of functional change may be partly explained by examining the mechanisms of the procedures and the differences in subject profiles. The procedures themselves varied between patients as well with respect to the location and percentage of rootlets sectioned in the SDR group and with the numbers and types of procedures performed in the MT surgery group. Postoperative management between procedures may also substantially affect ultimate outcomes.

Changes in functional outcome measures must be considered against the natural history of functional change in untreated patients with CP of similar age and severity. The mean age of the two groups was virtually identical with a similar range, which minimizes the potential confounding factor of differential rates of developmental change across groups. Patients in the SDR group had lower mean velocities, primarily due to slower cadences rather than shorter strides. Both treatment groups consisted of patients with mild-to-moderate spastic diplegia, based on their GMFM scores. The expected change in total GMFM score over a 12-month period for a 6-year-old child with mild-to-moderate spastic diplegia is approximately 4 to 5%,[28] which was reached in the SDR group but not in the MT group. Postoperative management also differed significantly across groups with the most obvious difference being a greater intensity and frequency of PT in the SDR as compared with the MT group. In fact, in the PT-only arm of the randomized trial reported here, functional improvements were similar to those reported in the SDR plus PT group, implying that PT alone or motivational effects may be responsible for many of the

positive outcomes seen.[17]

Gait analysis provides a detailed evaluation of one skill, walking. Normal children begin to reach a plateau in walking velocity by late adolescence when mature stature has been attained.[21,30] The average increase in velocity is approximately 4% per year between the age of 7 years and maturity. The steady increase in velocity occurs because increases in stride length exceed a slight decline in the step frequency or cadence. In contrast to normally developing children, velocity in children with CP does not increase as rapidly with age,[20] particularly in the absence of surgical intervention.[13] Selective dorsal rhizotomy did little to alter the natural history of gait in most patients, whereas the majority of patients in the MT group exceeded the expected change based on both the natural history of CP and on normal developmental rates.

Perhaps the most crucial factor in accounting for the differences across procedures is the primary pathophysiological mechanism that each addresses. Selective dorsal rhizotomy has been shown conclusively to reduce tone.[16,24,29,31] However, spasticity reduction may compromise antigravity control in those patients who use this while standing and walking,[25] thus accounting in part for its variable effects on gait velocity in the sample studied here. More patients with severe diplegia appear to be the most vulnerable to the effects of tone reduction on gait following SDR.[31] Rhizotomy, however, may actually enhance other functions such as sitting, crawling, and transitional movements that can be hampered by excessive antigravity muscle tone, as suggested here. As further evidence, Steinbok and colleagues[29] demonstrated clinically significant changes in the lower dimensions of the GMFM following SDR in a cohort of patients having severe spastic diplegia (mean preoperative total GMFM score 60.7).

The more pervasive changes in gross motor function after SDR seem logical given its more diffuse effect on a greater number of lower-extremity muscles, as compared with MT surgery, which directly influences only those MT units addressed and the joints spanned by them. Although altering one joint position by MT surgery may propagate positive effects to joints proximal and distal as adjustments are made to keep the body center balanced over the foot, the effects are still confined primarily to improving lower-extremity alignment and function. Consequently, MT surgery has its greatest positive effects on the GMFM dimensions that relate most closely to upright posture and mobility. It is also possible that MT surgery improves higher order skills (such as athletics) not measured by the GMFM that stop at the equivalent of a 5-year-old skill level.

In summary, MT surgery and SDR have different modes of action, and neither addresses the primary brain defect causing spastic diplegia. The magnitude of functional change is likely to be modest with either intervention. The quality of movement may be altered with SDR and this aspect of the intervention is not adequately assessed with the GMFM or other available tools. Specific details regarding SDR such as the optimum number of rootlets to cut or the overall effect as a function of initial severity are not known. As with SDR, considerable variability exists in the indications for lengthening a specific MT unit. Reduced excursions and joint contractures are certainly due to spastic tone; thus, recurrent joint deformity is a potential problem with MT surgery. Adjunctive bracing and PT may be necessary to minimize risk of recurrence or maximize the surgical outcome of either procedure. In some patients a surgical procedure such as MT lengthening or SDR may not be warranted at all, and in those patients other forms of therapy such as strength training may be more appropriate.[7] Patient selection and choice of procedure are still based largely on clinical judgment and availability of resources.

This post hoc data analysis suggests a number of useful hypotheses for further study. The first hypothesis is that MT surgery will more reliably result in more robust changes in walking than SDR. This improvement will be due to the mechanism of the MT intervention and will be measurable using gait and energy cost outcomes. A second hypothesis is that SDR will reliably result in more global changes in overall independent mobility and health-related quality of life and will be measurable with energy cost and more comprehensive functional health outcomes. The third hypothesis is that MT surgery and SDR are complementary procedures with additional benefits. The effect magnitude will be substantially greater than that expected from either procedure alone or that associated with motivation, development, or other concurrent therapies. These hypotheses are all testable by using prospective randomized controlled trials, with multicenter designs offering the additional advantages of more rapid accrual of patients and greater generalizability of results.

References

1. Abel MF, Damiano DL: Strategies for increasing walking speed in diplegic cerebral palsy. **J Pediatr Orthop** **16**:753-758, 1996
2. Abel MF, Damiano DL, Pannunzio M, et al: Role of multiple muscle-tendon recessions and releases to improve motor function in diplegic cerebral palsy. **Dev Med Child Neurol** **39 (Suppl 75)**:16, 1997 (Abstract)
3. Bleck EE: Locomotor prognosis in cerebral palsy. **Dev Med Child Neurol** **17**:18-25, 1975
4. Bleck EE: **Orthopedic Management in Cerebral Palsy**. Philadelphia: MacKeith, 1987, pp 142-212
5. Bleck EE: **Orthopedic Management in Cerebral Palsy**. Philadelphia: MacKeith, 1987, pp 282-392
6. Damiano DL, Abel MF: Relationship of gait analysis to gross motor function in cerebral palsy. **Dev Med Child Neurol** **38**:389-396, 1996
7. Damiano DL, Vaughan CL, Abel MF: Muscle response to heavy resistance exercise in children with spastic cerebral palsy. **Dev Med Child Neurol** **37**:731-739, 1995
8. Fasano VA, Broggi G, Barolat-Romana G, et al: Surgical treatment of spasticity in cerebral palsy. **Childs Brain** **4**:289-305, 1978
9. Foerster O: On the indications and results of the excision of posterior spinal nerve roots in men. **Surg Gynecol Obstet** **16**:463-474, 1913
10. Gage JR, Fabian D, Hicks R, et al: Pre- and postoperative gait analysis in patients with spastic diplegia: a preliminary report. **J Pediatr Orthop** **4**:715-725, 1984
11. Grether JK, Cummins SK, Nelson KB: The California Cerebral Palsy Project. **Paediatr Perinat Epidemiol** **6**:339-351, 1992
12. Hoffer MM, Rinsky L, Root L, et al: Symposium: management of cerebral palsy in the lower extremities. **Contemp Orthop** **16**:79-111, 1988
13. Johnson DC, Damiano DL, Abel MF: The evolution of gait in childhood and adolescent cerebral palsy. **J Pediatr Orthop** **17**:392-396, 1997

14. Kuban KCK, Leviton A: Cerebral palsy. **N Engl J Med** **330**:188-195, 1994
15. Marty GR, Dias LS, Gaebler-Spira D: Selective posterior rhizotomy and soft-tissue procedures for the treatment of cerebral diplegia. **J Bone Joint Surg (Am)** **77**:713-718, 1995
16. McLaughlin JF, Bjornson KF, Astley SJ, et al: The role of selective dorsal rhizotomy in cerebral palsy: critical evaluation of a prospective clinical series. **Dev Med Child Neurol** **36**:755-769, 1994
17. McLaughlin JF, Bjornson KF, Astley SJ, et al: Selective dorsal rhizotomy: Efficacy and safety in an investigator masked randomized clinical trial. **Dev Med Child Neurol** (In press, 1998)
18. Molnar GE, Gordon SU: Cerebral palsy: predictive value of selected clinical signs for early prognostication of motor function. **Arch Phys Med Rehab** **57**:153-158, 1976
19. Nene AV, Evans GA, Patrick JH: Simultaneous multiple operations for spastic diplegia. Outcome and functional assessment of walking in 18 patients. **J Bone Joint Surg (Br)** **75**:488-494, 1993
20. Norlin R, Odenrick P: Development of gait in spastic children with cerebral palsy. **J Pediatr Orthop** **6**:674-680, 1986
21. Oberg T, Karsznia A, Oberg K: Basic gait parameters: reference data for subjects, 10-79 years of age. **J Rehab Res Dev** **30**:210-223, 1993
22. Palisano R, Rosenbaum P, Walter S, et al: Development and reliability of a system to classify gross motor function in children with cerebral palsy. **Devel Med Child Neurol** **39**:214-223, 1997
23. Park TS, Owen JH: Surgical management of spastic diplegia in cerebral palsy. **N Engl J Med** **326**:745-749, 1992
24. Peacock WJ, Staudt LA: Functional outcomes following selective posterior rhizotomy in children with cerebral palsy. **J Neurosurg** **74**:380-385, 1991
25. Penn RD, Corcos DM: The management of spasticity by central nervous system infusion techniques, in Youmans JR (ed): **Neurological Surgery**, ed 4. Philadelphia: WB Saunders, 1996, pp 3687-3700
26. Phelps WM: Long-term results of orthopaedic surgery in cerebral palsy. **J Bone Joint Surg (Am)** **39**:53-59, 1957
27. Rosen MG, Dickinson JC: The incidence of cerebral palsy. **Am J Obstet Gynecol** **167**:417-423, 1992
28. Russell D, Rosenbaum P, Gowland C, et al: **Gross Motor Function Measure Manual**, ed 2. Hamilton, Ontario, Canada: McMaster University, 1993
29. Steinbok P, Reiner AM, Beauchamp R, et al: A randomized clinical trial to compare selective posterior rhizotomy plus physiotherapy with physiotherapy alone in children with spastic diplegic cerebral palsy. **Dev Med Child Neurol** **39**:178-184, 1997
30. Sutherland DH: **The Development of Mature Walking**. Oxford: MacKeith, 1988
31. Thomas SS, Aiona MD, Pierce R, et al: Gait changes in children with spastic diplegia after selective dorsal rhizotomy. **J Pediatr Orthop** **16**:747-752, 1996

32. Thometz J, Simon S, Rosenthal R: The effect on gait of lengthening of the medial hamstrings in cerebral palsy. **J Bone Joint Surg (Am)** **71**:345-353, 1989

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