Gait before and 10 years after rhizotomy in children with cerebral palsy spasticity

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Selective dorsal rhizotomy is a neurosurgical procedure performed for the relief of spasticity in children with cerebral palsy, but its long-term functional efficacy is still unknown. The authors sought to address this issue by means of an objective, prospective study in which quantitative gait analysis was used. Eleven children with spastic diplegia (mean age at initial surgery 7.8 years) were evaluated preoperatively in 1985 and then at 1, 3, and at least 10 years after surgery. For comparison, 12 age-matched normal individuals were also studied. Retroreflective targets were placed over the hip, knee, and ankle joints, and each individual's gait was videotaped. The video data were subsequently entered into a computer for extraction and analysis of the gait parameters. An analysis of variance yielded a significant time effect ($p < 0.05$), and post hoc comparisons revealed differences before and after surgery and with respect to the normal control subjects. The knee and hip ranges of motion (59° and 44°, respectively, for controls) were significantly restricted prior to surgery (41° and 41°, respectively), but were within normal limits after 10 years (52° and 45°, respectively). The knee and hip midrange values (31° and 3°, respectively, for controls), indicative of posture, were significantly elevated preoperatively (42° and 15°) and increased sharply at 1 year (56° and 18°), but by 10 years they had decreased to within normal limits (36° and 9°). Step length and velocity improved postoperatively but were not within the normal range after 10 years. Ten years after surgery our patients not only had increased ranges of motion, they also used that movement about a normal midrange point. Selective dorsal rhizotomy is an effective method for alleviating spasticity; furthermore, the authors provide evidence to show that lasting functional benefits, as measured by improved gait, can also be obtained.

Key Words * cerebral palsy * spasticity * rhizotomy * gait analysis * children

Cerebral palsy is the most common motor disorder originating in childhood,[20] and spasticity is the most frequent manifestation.[9] Spastic diplegia is still an important type of cerebral palsy and, with the improved survival of low-birthweight infants,[28] accounts for more than 30% of the cerebral palsy cases in Cape Town, South Africa.[21] The child with spastic diplegia has a walking pattern that may include

scissoring of the legs, internal rotation of the thighs, an equinus ankle at foot contact, and frequently there is exaggerated knee flexion in stance.[4] Treatment strategies to ameliorate these gait abnormalities have included physiotherapy, orthoses, antispastic medications, orthopedic surgery, and neurosurgery.[23] Of these, the neurosurgical procedure selective dorsal rhizotomy (SDR) has gained widespread acceptance, despite some controversy as to its efficacy.[18,19]

As a method of treating spasticity, rhizotomy is not new, having first been performed almost a century ago;[13] however, it fell into disuse because there was extensive sensory loss resulting from indiscriminate sectioning of the dorsal roots. In the 1960s the procedure was revised by sectioning a fraction of the rootlets[15] and then further refined by electrically stimulating the rootlets and measuring the electromyographic response prior to cutting the rootlets.[11] These European studies provided the impetus for our own work here in Cape Town with further modifications to the procedure during the early 1980s.[24] In the past decade, there has been a sustained interest in dorsal rhizotomy to treat spastic diplegia in children with cerebral palsy, and there are now over 30 centers in North America offering the service.[22] With the dramatic increase in patients treated worldwide, and the skepticism among some clinicians,[18,19] it is imperative that the long-term effects of the surgery be evaluated.

The long-term results to date are based almost exclusively on subjective data. We have shown that 5 years after surgery, over 80% of 51 patients were still making progress,[1] whereas at 10 years, 97 of 110 patients had improved their patterns of ambulation, although a formal gait analysis was not conducted.[26] Fasano and Broggi[12] have provided anecdotal evidence of functional benefits 15 years after SDR for 80 patients. We report here the final objective results of a prospective study, initiated in 1985, in which gait data were gathered preoperatively, at 1 year after surgery,[33] and after 3 years.[32] All patients were evaluated at least 10 years after the original surgery.

CLINICAL MATERIAL AND METHODS

Patient Selection

All individuals evaluated had cerebral palsy of congenital origin, the main criterion for inclusion being the presence of spasticity. The selection for surgery was based on the following criteria: 1) exhibition of spasticity; 2) absence of athetosis; 3) absence of significant underlying muscle weakness; and 4) access to postoperative therapy.[3] The original study conducted by Vaughan, et al.,[33] involved 14 ambulatory patients who were part of a cohort of 29 children with spasticity who underwent SDR in 1985 (15 patients in the cohort were nonambulators). Eleven of the original 14 patients were again contacted in 1996 and provided informed consent to participate in a follow-up gait analysis study; the remaining three were not available for testing. The mean patient age at surgery was 7.8 years (range 2.5-13.2 years), and the average period between surgery and evaluation was 10.6 years (range 10.4-11 years). The mean age of the patients at the time of the gait study in 1996 was 18.4 years (range 12.9-24.1 years). For purposes of comparison, gait analysis was performed on a group of 12 age-matched normal control individuals with a mean age of 19 years.

Surgical Procedure

All surgery was performed by a single surgeon at the Red Cross War Memorial Children's Hospital in Cape Town.[24] All patients received endotracheal general anesthesia without the use of muscle relaxants. A narrow laminectomy from L-2 to S-1, exposing the cauda equina, was performed with preservation of the facet joints. The dorsal roots were identified at their respective levels by their

anatomical features and verified using electrical stimulation. The dorsal roots were separated from the anterior roots bilaterally from L-2 to S-1, and the rootlets comprising the dorsal roots were stimulated using two insulated microneurosurgical electrodes (Aesculap Surgical Instruments, Burlingham, CA). The threshold for a motor response was determined by using a nonsinusoidal stimulus; a tetanic stimulus (50 Hz) was then applied to the rootlet for 1 second, and the electromyographic responses were recorded. Rootlets that were associated with a low threshold for motor response, produced sustained responses beyond the 1-second stimulus, spread to the contralateral side, or led to activity in inappropriate muscle groups were sectioned.[32]

Gait Evaluation

The system used in the present study differed slightly from the digital camera system used for the previous studies.[32,33] The new system was developed because it was more transportable (some of the patients were living more than 1500 km from Cape Town) and it offered a greater data capture rate (25 vs. 12 Hz). It consisted of a video camera (National Panasonic Corp., Osaka, Japan) used to film the subjects, a video cassette recorder (VCR) connected to a personal computer that was equipped with a Frame Grabber card (Matrox Systems, Quebec, Canada), and customized software for data capture and analysis. Careful tests were conducted to ensure that this system produced results that were identical to the previous system.

Retroreflective markers were attached to the greater trochanter of the femur (representing the hip), the lateral femoral epicondyle (representing the knee), and the lateral malleolus of the fibula (representing the ankle). The subject was then required to walk at his or her normal pace in a plane perpendicular to the camera's optical axis. The videotapes were played back on a VCR and the Frame Grabber extracted the X and Y coordinates (in pixel units) of the target markers as a function of time (temporal resolution of 0.04 seconds). Through suitable scaling, the coordinates of the joints (X,Y) were obtained in real-life units in meters. From these data it was possible to calculate all relevant gait parameters, including the knee and hip ranges of motion and midrange values (Fig. 1), and the temporospatial parameters. These latter parameters included cadence (steps per second); step length (distance in meters between left and right heels at midstance); and the average velocity, which was calculated from the following equation:

velocity (m/s) = cadence (steps/second) X step length (m) (1).

Fig. 1. Illustrative definitions of the knee angle and the hip angle for a child with spastic cerebral palsy compared with a normal child. These diagrams not only show the extremes of the range of movement but also the midrange values for the knee and hip angles. Note that the angle at the knee joint was defined as the angle between the thigh and calf, whereas the hip angle was defined as the angle between the thigh and a vertical axis.

The joint ranges of motion indicate the total arc of motion used by the individual during the gait cycle, and the midrange values reflect the location of this movement arc within the child's available range (Fig. 1). The midrange values are particularly relevant parameters for spastic diplegia because they are a measure of the degree of crouch gait.[32]

Because joint angles are well established by age 3 years,[30] they do not have to be normalized for growth and can be compared across age span. This is not the case for the temporospatial parameters, however. We used the normalization method recommended by Hof,[16] in which leg length may be used to convert cadence and velocity into dimensionless units. The following equations enabled us to compare patients with themselves (over the 10 years of the study) and with the age-matched normal controls:

$$\text{dimensionless cadence} = \text{cadence} \div \sqrt{g \div (\text{leg length})} \quad (2)$$

$$\text{dimensionless step length} = \text{step length} \div \text{leg length} \quad (3)$$

$$\text{dimensionless velocity} = \text{velocity} \div \sqrt{g \div (\text{leg length})} \quad (4)$$

where g is the acceleration due to gravity (9.81 m/second^2), leg length is measured in meters, cadence in steps per second, step length in meters, and velocity in meters per second.

Statistical Analysis and Comparisons

A factorial repeated-measures analysis of variance (ANOVA) procedure was used to compare the data and the significance level was set at probability greater than 0.05 (Statistica; Statsoft Inc., Tulsa, OK). Post hoc analysis was accomplished using the Scheffé test with the following Comparisons: 1, Preoperative versus 1 year postoperative; 2, Preoperative versus 3 years postoperative; 3, Preoperative versus 10 years postoperative; 4, Preoperative versus normal controls; 5, 1 year postoperative versus 3 years postoperative; 6, 1 year postoperative versus 10 years postoperative; 7, 1 year postoperative versus normal controls; 8, 3 years postoperative versus 10 years postoperative; 9, 3 years postoperative versus normal controls; and 10, 10 years postoperative versus normal controls.

Because of the relatively low number of patients (11 patients and 12 controls), we had some concern whether there would be sufficient statistical power in the data to allow meaningful comparisons. Based on a preliminary analysis of the data, with a desired power of 0.8, the phi coefficient was greater than 1 for each of the seven parameters, indicating an adequate sample size.

RESULTS

A factorial repeated measures ANOVA was performed. Side (left, right) and time (preoperative, 1, 3, and 10 years postoperative, and normal controls) were the independent measures, whereas the dependent variables were ranges of motion (knee and hip), midrange values (knee and hip), and temporospatial parameters (cadence, step length, and velocity). There were no statistically significant differences between the left and right sides and thus these data were combined. There were statistically significant differences for time; see Table 1 for summary of results.

TABLE 1
MEAN VALUES OF BIOMECHANICAL PARAMETERS FOR THE WALKING PATTERNS OF 11 SPASTIC INDIVIDUALS BEFORE AND AFTER SDR COMPARED WITH 12 AGE-MATCHED NORMAL CONTROLS*

Parameter	Preop Values (SD)	Postop Values (SD)			Normal Control Values (SD)
		1 yr (SD)	3 yrs (SD)	10 yrs (SD)	
knee range of motion	41 [2 ^I 4] (17)	50 (21)	59 [2] (14)	52 (11)	59 [4] (3)
hip range of motion	41 [1 ^I 2] (10)	53 [1] (14)	51 [2] (7)	45 (8)	44 (4)
knee mid-range	42 [1 ^I 4] (13)	56 [1 ^I 5 ^I 6 ^I 7] (11)	44 [5 ^I 9] (12)	36 [6] (9)	31 [4 ^I 7 ^I 9] (7)
hip mid-range	15 [4] (9)	18 [6 ^I 7] (8)	14 [9] (9)	9 [6] (7)	3 [4 ^I 7 ^I 9] (2)
cadence	0.42 [4] (0.16)	0.42 [7] (0.12)	0.42 [9] (0.14)	0.44 [10] (0.12)	0.56 [4 ^I 7 ^I 9 ^I 10] (0.04)
step length	0.59 [2 ^I 4] (0.14)	0.66 (0.23)	0.78 [2 ^I 8] (0.13)	0.60 [8 ^I 10] (0.15)	0.78 [4 ^I 10] (0.07)
velocity	0.26 [4] (0.12)	0.30 [7] (0.15)	0.34 [9] (0.12)	0.27 [10] (0.12)	0.43 [4 ^I 7 ^I 9 ^I 10] (0.06)

* The measurements of cadence, step length, and velocity are dimensionless, in accordance with the normalization procedure of Hof. Significant differences have been indicated by superscripted numbers in square brackets; see text for definition of comparisons. Abbreviation: SD = standard deviation.

Ranges of Motion

Before surgery, the knee range of motion was significantly less than normal (41 vs. 59š; Comparison 4), a manifestation of spastic diplegia and tight hamstring muscles.[14] After surgery, this range of motion increased (Comparison 2), so that by 3 years the value was the same as normal (59š). Whereas this range had decreased slightly to 52š by 10 years, there was no statistical difference from normal (note absence of Comparison 10 in Table 1). Figure 2 left, based on the data in Table 1, illustrates the changes in the knee range of motion over time.

Fig. 2. Graphs showing the mean data for the knee range of motion (left) (with 1 standard deviation) and the hip midrange value (right) (with 1 standard deviation) for 11 patients preoperatively and then at 1, 3, and 10 years after SDR. The mean data for 12 age-matched controls are also included. This figure is based on the data in Table 1.

Preoperatively, the hip range of motion was no different from normal (41 vs. 43š, absence of Comparison 4). However, after surgery this value increased significantly (see Comparisons 1 and 2), a natural consequence of the release of spasticity.[32] This excessive range of motion at the hip decreased from 1 to 3 years, and further still between 3 and 10 years, so that at 10 years there was no difference from normal (45 vs. 43š; absence of Comparison 10 in Table 1).

Mid-Range Values

Before surgery, the knee midrange value was significantly greater than normal (42 vs. 31°; Comparison 4), a natural consequence of the crouch gait pattern of spastic diplegia.[14] One year after surgery, this parameter was significantly elevated to 56° (Comparison 1), which may be attributed to the dramatic reduction in spasticity as well as the underlying muscle weakness. Between 1 and 10 years the parameter steadily decreased, so that by 10 years the knee midrange value of 36° was not significantly different from normal (see Table 1, absence of Comparison 10).

Preoperatively, the hip midrange value was significantly greater than normal (15 vs. 3°; Comparison 4). As with the knee midrange value, this is a natural consequence of crouch gait in spastic diplegia.[14] By 1 year this value had deteriorated to 18° (Comparison 1), but over the next 9 years it decreased (Fig. 2 right). At 10 years postoperatively, the hip midrange value of 9° was not significantly different from normal (absence of Comparison 10 in Table 1).

Temporospatial Parameters

Before surgery, the dimensionless cadence was significantly lower than normal (0.42 vs. 0.56; Comparison 4). The rhizotomy surgery did not change this parameter, however, with the value remaining in the range 0.42 to 0.44 over the following 9 years (Comparisons 7, 9, and 10).

Preoperatively, the dimensionless step length was significantly lower than normal (0.59 vs. 0.78; Comparison 4). After surgery, with the reduction in spasticity and the increase in knee and hip ranges of motion, the stride length increased. By 3 years there was no difference from normal (absence of Comparison 9), although at 10 years the value was statistically less than normal (0.60 vs. 0.78; Comparison 10). The possible reason for this reduction is explored in the Discussion section.

As pointed out in Equation 1, velocity is the product of cadence and step length. Not surprisingly, before surgery the patient's velocity was significantly less than normal (0.26 vs. 0.43; Comparison 4). Despite the significant increase in step length at 3 years after surgery, the velocity (0.34) was still significantly less than normal (Comparison 9). By 10 years, with the reduction in step length, the velocity had decreased to 0.27, which was no different from the preoperative value.

DISCUSSION

The degree of spasticity can be quantified,[10] and the immediate consequence of SDR is a dramatic reduction in spasticity.[29] The significance of this alteration in the state of muscle tone is that children with cerebral palsy, whose spasticity is their predominant neurological problem, have the potential after surgery to improve their neuromuscular function. It can be inferred from the gait analysis data that in the short term (that is, from 1-3 years after surgery), patients do benefit by an improvement in their locomotor function.[5,31-33] The present study addresses the long-term efficacy.

The ranges of motion at the knee and hip increased as a result of surgery (Fig. 2 left), and by 10 years there is no difference from normal ranges (Table 1). This is an important finding because spastic diplegia restricts range of motion and can lead to joint contractures if the patient is not treated.[14,23,30] Concomitant with the increased range of motion, there was also the deleterious increase in midrange values immediately after surgery (Table 1). This was of some concern because the midrange values represent a measure of strength and control exhibited by a patient during locomotion. The greater the midrange value, the more flexed the posture of the individual, and this resulted in an exaggerated crouch

gait. Fortunately, the midrange values decreased over time (Fig. 2 right), so that by 10 years postoperatively there was no variance from normal values (Table 1). Thus, 10 years after surgery, patients not only had increased ranges of motion that were within normal limits, they also used that functional movement about a normal midrange point.

A noteworthy finding of this study was that SDR had no effect on cadence (Table 1). Although the neural mechanisms underlying spasticity in cerebral palsy are poorly understood, it is presumed that brain damage leads to a loss of supraspinal inhibition of the activity in the spinal stretch reflex.[23] Rhizotomy attacks the problem at the level of the spinal cord by reducing the afferent reflex activity but does not address the primary lesion in the brain. Because cadence would appear to be centrally mediated,[14] it is perhaps not surprising that rhizotomy had no effect on this parameter.

With the increased range of motion postoperatively, the step length naturally increased so that by 3 years postoperatively there was no difference from normal range (Table 1). Of concern, however, is the reduction from 3 to 10 years after surgery. To explain this apparent diminution in motor function, we reviewed the individual data on a post hoc basis. Not all patients were studied in the same environment. Six of the 11 were evaluated in Cape Town where the laboratory was spacious and the walkway was 8 m long. The other five lived elsewhere in South Africa, and we were obliged to gather our gait data in rooms that were 4 to 5 m wide, yielding an effective walkway of only 2 to 3 m. This length is insufficient to attain a normal walking speed,[30] and it is therefore not surprising that all five patients who were studied outside Cape Town exhibited large reductions (an average of 31%) in their step lengths between 3 and 10 years. In contrast, the six patients from Cape Town, on average, showed no such reduction. We speculate, therefore, that the decrease in step length and velocity at 10 years has more to do with our experimental protocol than an actual deterioration in function.

Five of the 11 patients underwent some form of orthopedic surgery after the rhizotomy. Three of these surgeries were for foot and toe deformities (tarsal osteotomy and flexor tendon releases), one patient received hamstring lengthening, and another received hamstring and Achilles tendon lengthenings. Although these latter two procedures are widely applied by orthopedic surgeons to improve locomotor function,[14,30] we do not believe that the data for these two patients skewed our results. Equal levels of improvement were noted in individuals who did not undergo orthopedic surgery. Each patient has to be treated on an individual basis and it has recently been reported that rhizotomy reduces the need for some orthopedic procedures.[6]

The importance of physiotherapy and occupational therapy in the early years following rhizotomy has been emphasized by a number of authors.[2,17,25] In the present study, eight of the 11 patients were not receiving physiotherapy on a regular basis at the time of evaluation. We have speculated that the positive changes seen between 1 and 3 years after surgery, particularly the reduction in the midrange values, were a direct result of the active physiotherapy being received by most of the patients. One of the problems with rhizotomy is that it can unmask underlying muscle weakness.[17] Traditionally, physiotherapists have tended to avoid muscle strengthening exercises in children with neurological disorders, believing that such exercises would do more harm than good.[8] However, it has been clearly demonstrated that children with spastic diplegia can not only significantly increase the strength in the quadriceps muscles, but this gain in knee extensor function also leads to an improvement in the swing phase of gait.[7,8] It is therefore conceivable that patients scheduled for SDR should undergo appropriate muscle-strengthening exercise before surgery so that once the spasticity is removed, they are well placed to derive the maximum benefit during postoperative rehabilitation.

One of the criticisms leveled against rhizotomy--that improvement could be the result of natural maturation in the first decade of life[18]--has been answered in our previous study of rhizotomy in teenagers and young adults when maturation is already complete.[27] Another criticism of long-term surgical studies, including this one, is the lack of a patient control.[19] Although this argument is based on sound scientific principles, it would mean that a cohort of children with spastic diplegia would need to be identified and then surgical treatment withheld for a period of 10 years. Unfortunately, few clinicians, or indeed families, would be prepared to follow such a protocol. Selective dorsal rhizotomy is not a panacea for children with spastic cerebral palsy. However, we believe that we have provided some objective evidence demonstrating its efficacy in improving gait function over a long-term period.

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