Published in final edited form as:
J Neurosurg. 2006 July ; 105(1 Suppl): 8–15.

Effect of selective dorsal rhizotomy in the treatment of children with cerebral palsy

Jack R. Engsberg, Ph.D., **Sandy A. Ross, P.T., M.H.S., D.P.T.**, **David R. Collins, Ph.D.**, and **Tae Sung Park, M.D.**
Department of Neurological Surgery, Human Performance Laboratory, and the Center for Cerebral Palsy Spasticity, St. Louis Children's Hospital; and Department of Neurological Surgery, Washington University School of Medicine, St. Louis, Missouri

Abstract

Object—In this investigation the authors compared impairment and functional outcomes between two groups of children with cerebral palsy (CP): one group underwent selective dorsal rhizotomy (SDR) followed by intensive physical therapy (PT), and the other group underwent the latter only (PT group). Data from an age-matched group of children without disability (nondisabled [ND] group) were also collected.

Methods—Data pertaining to the 68 children with CP were collected before any intervention and again 8 and 20 months afterwards. Data regarding the 40 children in the ND group were collected in a single session.

Conclusions—Although patients in both groups with CP were weaker than those in the ND group, they did have strength gains. Gait speed in the SDR-PT group was slower than that in the ND group preoperatively but not at 20 months postoperatively. Gait speed in the PT group remained slower than that in the ND group. The pre- to postoperative change in the Gross Motor Abilities Estimate score was significantly greater in the SDR-PT group than in the PT-only group. An effective treatment for children with CP, SDR offers gains in strength, gait speed, and overall gross motor function.

Keywords

cerebral palsy; rhizotomy; spasticity; strength; gait; Gross Motor Function Measure; pediatric neurosurgery

Selective dorsal rhizotomy is a surgical procedure used in patients with CP that involves partial sensory deafferentation at the levels of the L-1 through S-2 nerve rootlets.[29] The selection of rootlets for cutting is based on the lower-extremity muscular response to electrical stimulation of the rootlets. The operation is performed in children with CP to reduce spasticity and thereby improve motor function. In several of the most recent investigations in which the effectiveness of SDR was evaluated, three groups of researchers used the GMFM as the primary means of assessing outcome.[24,35,38] The results of two of these three recent randomized trials indicated that SDR followed by intensive PT was more effective than intensive PT alone in bringing about an increase in gross motor function.[35,38] According to the results of the third trial, SDR followed by intensive PT was not any more effective in improving gross motor function than intensive PT alone.[24] A metaanalysis of the combined results of the three investigations indicated that SDR followed by intensive PT was more effective in improving gross motor function than intensive PT only.[23]

Address reprint requests to: Jack R. Engsberg, Ph.D., Department of Physical Therapy, Saint Louis University, 3437 Caroline Street, St. Louis, Missouri 63104. email: jengsber@slu.edu.

In the metaanalysis of these randomized clinical trials based on relatively large sample sizes (~ 45 individuals per group), only the GMFM scores were used for analysis. Single investigations in which multidomain measures were examined for their usefulness in the assessment of SDR have not featured large samples. For example, in the studies by Graubert and McLaughlin and their colleagues[18,24] GMFM scores, gait measures, and an objective measure of spasticity (using an electromechanical torque measurement device) were studied in 21 participants in an SDR-PT group, and 17 in an intensive PT-only group. In two papers, Thomas and colleagues[36,37] reported on 26 and 23 participants, respectively, before and after they underwent SDR, but these authors did not include a PT-only group. The purpose of our investigation was to compare multidimensional outcomes in a group of children with CP undergoing SDR followed by intensive PT (the SDR-PT group) with those in a group of children undergoing intensive PT only (the PT group). Our hypothesis was that the outcomes in the SDR-PT group would be better than those in the PT group.

Clinical Material and Methods

Patient Population

Participants were recruited for the investigation in two ways. For the SDR-PT group, patients were enrolled through the SDR clinic at Washington University in St. Louis. The physical therapist coordinator within the clinic identified a consecutive series of potential participants and informed their parents about the research project. If the parents approved, the physical therapist for the study contacted them, verified their interest in proceeding, and obtained a patient history, which included a screening for study inclusion/exclusion criteria. The neurosurgeon then evaluated the patient on the basis of these criteria and determined if he or she was an acceptable candidate for SDR. If so, then the patient was enrolled in the SDR-PT group.

For the PT-only group, local and national advertisements were used to attract potential candidates. Parents of prospective volunteers called the study's physical therapist, and she went through the same history and screening procedure that was used in the SDR-PT group. If the volunteers were likely candidates, then a visit to the Human Performance Laboratory at the Washington University Medical School in St. Louis was arranged. During the visit, the candidate was screened by either the neurosurgeon or a neurologist to determine suitability for SDR. Willing candidates who met the study requirements participated in an intensive PT program. Unlike the randomized clinical trials mentioned earlier, in which volunteers and parents were informed about both interventions and then made a choice,[24,35,38] the participants recruited through advertisements were meant to participate in a nonsurgical group only. Thus, potential candidates for the PT group were informed about all aspects of the project, including the choice of interventions. If they preferred to have the SDR procedure first, then they could not participate in the PT group. They were also informed that they had the option of considering the SDR after participation in the PT group, but that it was not part of the ongoing investigation. Parents considering the nonsurgical option were eager for their children to have the intensive PT and recognized that they were delaying the opportunity to have an SDR, not eliminating it. At the end of the study periods, the participants and their parents were asked if there was interest in undergoing an SDR. In almost every case, they wanted to wait for the results of the study. No follow up was performed to determine if any of the participants eventually had the SDR.

Seventy-seven ambulatory children with spastic diplegic CP were recruited for this investigation. The SDR-PT group initially included 37 children (mean ± SD, 9 ± 5.3 years of age) and the PT group included 40 (9.7 ± 4.5 years). During the course of the investigation, nine children dropped out for the following reasons: 1) no SDR after initial testing (three children in the SDR-PT group); 2) lack of cooperation (one child in the PT group and one in

the SDR-PT group); 3) shunt malfunction (one child in the PT group); 4) no contact after the initial visit (one child in the SDR-PT group); 5) severe change in scoliosis after the initial visit (one child in the PT group); and 6) the distance between the research site and the participant's home (one child in the SDR-PT group). A final cohort of 68 participants (31 in the SDR-PT group and 37 in the PT-only group) was tested preoperatively and 8 and 20 months postoperatively (Table 1). Most participants in both groups were not from the St. Louis area, but six children from the SDR-PT group and four from the PT group were.

Data from the 40 participants in the ND group (mean ± SD 9.4 ± 3.4 years) were collected specifically for comparison with the CP groups (Table 1). These participants, who were tested once, were recruited by contacting parents within the hospital community and were age matched to the CP groups. Study participants older than 17 years of age signed an informed consent form approved by the Washington University Human Studies Committee. If they were younger, their parents signed the form.

Criteria for participation in the CP groups included the following: a diagnosis of spastic diplegic CP; classification in Levels I to III in the GMFCS; the ability to walk (with or without orthoses, including crutches and canes); a minimum level of cognitive skills for active participation; no surgical intervention within the preceding year; hypertonicity of the lower extremity measured with the modified Ashworth scale; ankle clonus; exaggerated deep tendon reflex in the legs; Babinski sign; and abnormal postures while sitting, standing, and walking. Participants had to be able to perform six to eight repetitions of barefoot walking for approximately 8 minutes. They were not permitted in the study until 6 months after any casting procedures or injections of botulinum toxin serotype A (Botox; Allergan, Inc., Irvine, CA). We established a minimum participant age of 4 years to facilitate cooperation with the collection of gait, spasticity, and strength data. This age requirement excluded approximately 40% of the patients who were being screened for and ultimately underwent an SDR.

Specifically excluded from the investigation were children who had motor deficits resulting from neurological injury or illness that began after the 1st month of life and children with malformations of the central nervous system. Other exclusionary criteria included moderate to severe dystonia, athetosis, ataxia, and severe cognitive delay. Children were excluded if their parents reported that they were unable to follow simple commands and understand concepts such as "push as hard as you can" and "relax your muscles."

Selective Dorsal Rhizotomy

In preparation for intraoperative EMG examinations, which took place with the patient prone and after induction of general anesthesia, needle electrodes were placed bilaterally in six major muscles of the lower extremity. A single-level laminectomy was performed at the L-1 vertebra, and ultrasonography was used to determine the location of the conus medullaris in relation to the laminectomy. The L-1 spinal nerve roots were identified at the foraminal exit, and the dorsal root was separated from the ventral root. Next, individual dorsal roots were identified at the level of the cauda equina. Each root was then subdivided into four to seven smaller rootlets, and these rootlets were individually suspended over rhizotomy probes. Electrical stimulation was used to grade a reflex response from the lower-extremity muscles. Rootlets were then cut according to the response. This procedure was repeated on the remaining L-2 through S-2 dorsal roots, and the entire procedure was repeated on the contralateral side. The number of rootlets that were cut varied depending on the EMG response. Approximately 65% of the rootlets were cut.

Intensive Physical Therapy

After discharge, the members of the SDR-PT group received PT from therapists in their hometowns four times per week for 8 months. Subsequently, treatments were reduced to three times per week for an additional 12 months. Members of the PT-only group received the same number of PT sessions. The physical therapists for both groups focused their treatment on the trunk and lower extremities, on strengthening, and on functional activities. The therapy for the PT group was paid for with the grant money received for this study. Participants in the SDR-PT group agreed to the amount of intensive PT and confirmed that they had financial support before undergoing SDR. Billing data were used to confirm that the PT group received the same amount of therapy as the SDR-PT group. The same guidelines provided by the SDR clinic to the SDR participants were used with the PT participants. Although these guidelines lacked specific therapy instructions, they mirrored current clinical practice.

Data Collection

Spasticity and Strength—Spasticity, characterized as a velocity-dependent resistance to passive stretch,[5,19,21] was measured with an isokinetic dynamometer (KinCom; Chattecx Corporation, Chattanooga, TN) for the ankle plantar flexors, knee flexors, and hip adductors.[11-16] For the sake of simplicity, the following description of the test for the ankle plantar flexors only is provided.[15] The participants sat on the dynamometer, and their ankle joint axis was aligned with the center of the lever arm. The therapist established the range-of-motion limits of ankle dorsiflexion and plantar flexion. The individual was instructed to remain as relaxed as possible as the joint was passively rotated by the dynamometer from a full plantar flexed to a full dorsiflexed position. Tests were conducted bilaterally at speeds of 10, 30, 60, 90, and 120° per second (a speed of 120° per second was not used for the knee and hip). The order of data collection at different speeds was not randomized because fast speeds were alarming to the patient if implemented first in the test sequence. Tests were repeated until the changes were minimal between successive tests. This observation was relatively simple because after each test, the dynamometer automatically overlaid the data from that test with the data from the previous test on the monitor. Commercially available software (Matlab; The MathWorks, Inc., Natick, MA) was used to eliminate the effects of inertia and fit a second-order polynomial to the torque-angle curves. Areas within the torque-angle curves were calculated using the trapezoid rule for each speed and joint, and this calculation yielded work values (for example, $\Sigma T \times \Delta$, where T is torque and Δ is a small angular displacement measured in radians). For each joint, a linear regression was performed to determine the line of best fit for the five work values as a function of speed. The slope of the linear regression line was considered to measure the magnitude of the spasticity. A slope close to zero represented no spasticity, whereas slopes greater than zero represented increasing amounts of spasticity (that is, increased velocity-dependent resistance to a passive stretch).

Intra- and intertest reliability for these and similar tests has been shown to be acceptable in patients with CP and other mild learning disabilities.[12,20,25] Strength tests were designed to measure the maximum active resultant torque-generating capacity that the child could produce.[10,12-16] As with the spasticity description, only the test for ankle plantar flexors is described. Tests at the knee flexors/extensors and hip abductors/adductors were similar. All participants actively moved their ankles from end-range ankle dorsiflexion to end-range plantar flexion and vice versa to obtain maximum concentric contractions of the ankle plantar flexors and dorsiflexors. Movement speed was 10° per second. Three to five repetitions of each movement were performed to permit the participants to achieve their best performance; however, the only test results used in the analysis were those indicating the greatest amount of torque produced. The maximum torque values for both dorsiflexion and plantar flexion were recorded. The trapezoid rule was used to determine the area bounded by the curve, the zero torque line, and the beginning and ending ROM for each dorsiflexion/plantar flexion torque-angle curve. The

values were subtracted when areas existed both above and below the zero torque line. We normalized all values by dividing the children's weights to permit comparisons between them.[10,12-16,20,22]

Gross Motor Function Measure—At each visit, GMFM scores were assessed for all participants with CP. The GMFM is a standard criterion-referenced test designed to be used in the assessment of change in gross motor function in children with CP.[34] The 88 items of the test are used to assess activities in five dimensions: 1) lying down and rolling; 2) sitting; 3) crawling and kneeling; 4) standing; and 5) walking, running, and jumping. Each item was scored using a 4-point Likert scale (0 = does not initiate; 1 = initiates; 2 = partially completes; and 3 = completes). Totals from each category for each child were divided by the total possible points to produce a category percentage score. These percentages were averaged to yield an overall score. Recently, a 66-question GMFM has been developed that includes a Rasch analysis to improve the sensitivity and interpretability of the test.[33] We used the GMFM-66 to produce a mean score, or GMAE.

Gait Analysis—The general methods used for the gait analysis in this investigation have been reported elsewhere, so we will describe them only briefly.[2,3,6-9,17] Three spherical reflective surface markers 2.5 cm in diameter were placed on the trunk, thighs, legs, and feet of each participant. While he or she walked barefoot at a self-selected pace along a 9-m walkway, video data were collected during the middle 3 m (six-camera HiRes Motion Analysis Corporation System; Motion Analysis Corp., Santa Rosa, CA). Data from at least six trials were collected from each participant.

Temporal gait variables were determined, including speed, stride length, and cadence. The location and time data of the surface markers were tracked, digitized, and converted to three-dimensional coordinates as a function of time before being uploaded into a software program (KinTrak; Motion Analysis Corp.) for further processing. The software produced data in which the averaged joint angle was described as a function of the complete gait cycle for each of the three principal planes of the body. The following nine variables were calculated: 1) ankle dorsiflexion at initial contact; 2) ankle dorsiflexion/plantar flexion ROM; 3) knee flexion at initial contact; 4) knee flexion/extension ROM; 5) hip flexion/extension ROM; 6) pelvic tilt ROM; 7) pelvic rotation ROM; 8) trunk rotation ROM; and 9) external foot progression angle at initial contact.

Statistical Analysis

Pairwise comparisons (by visit or group) and contrasts (the comparison of changes across groups) were analyzed using commercially available software (SAS Institute, Inc., Cary, NC) and a mixed linear model to perform analysis of variance.[26] Data from three visits (preoperative and 8 and 20 months postoperative) pertaining to the two CP groups were included. Participants in the ND group had no GMAE or GMFM scores, and their data were collected at a single session. Values for right and left sides were averaged. The mixed-model approach was selected over a traditional analysis of variance to accommodate optimally the unequal variances between groups and correlations between visits. Mixed models were estimated using separate group variances, autoregressive first-order covariance structures across visits, and Satterthwaite degrees of freedom. The Tukey–Kramer method was used to control the Type I error rate for multiple pairwise comparisons between visits or groups. This method does not apply to contrasts between group changes (for example, comparing the change from the preoperative visit to the 20-month postoperative visit for the SDR-PT group with the change in the PT group). Instead, the Scheffé method was implemented through a custom program (SAS Institute, Inc.). For each variable, data were included if they were available for the preoperative visit and for at least one of the two postoperative visits. Each mixed model

included two covariates, the patient's GMFCS level and age at the preoperative visit, so that the initial differences between the groups were accommodated. The mixed-model procedure was unable to fit the raw data for spasticity variables because of nonnormality, so these data were converted to normal scores on the basis of ranks. All other variables were sufficiently close to a normal distribution.

Means and SDs for each group at each visit are reported in Tables 2 through 6. Significant pairwise comparisons by group and visit and contrasts between group changes are noted. To simplify the results, we did not calculate comparisons involving 8-month visit data; however, means and SDs are included in the tables for completeness.

Results

Differences Among Groups

Differences among the three groups for age, sex, or weight were not significant; nor were they significant between the SDR and PT groups for GMFCS level and gait status.

Reduction in Spasticity

Ankle plantar flexor, knee flexor, and hip adductor spasticity was reduced in the SDR-PT group following the operation (Table 2). Knee and hip spasticity in the SDR-PT group was significantly different from that in the ND group pre- but not postoperatively. Ankle spasticity in the SDR-PT group was not different from that in the ND group at any visit. Although no changes were recorded for knee and hip spasticity in the PT group from initial to final testing, a decrease in ankle spasticity did occur. Hip spasticity values in the PT group were significantly greater than those in the ND group, but this was not the case for knee and ankle spasticity. The decrease in hip spasticity in the SDR-PT group from the preoperative test session to the final postoperative one was significantly different from the decrease in hip spasticity in the PT group.

Strength Results

The strength results (Table 3) indicated that the children in the CP groups were weaker than those in the ND group, regardless of the testing session. The one exception was maximum hip adduction for the final session in the PT group. Strength gains were observed in the SDR-PT group in the ankle plantar flexors (maximum and work values) and in the knee extensors (maximum and work values). The change in strength in the plantar flexors was significantly greater in the SDR-PT group than the change in the PT-only group. The PT group had strength gains in the knee flexors (maximum value), ankle dorsiflexors (work value), and hip adductors (maximum and work values).

Gait Kinematics

The gait kinematics measures indicated three key findings (Table 4). The first was that most of the variables in the CP groups were significantly different from those in the ND group, both pre- and postoperatively. The second was that the postoperative kinematics in the SDR-PT group indicated improvements, despite remaining significantly different from those of the ND group. Range of motion improvements were quantified for knee flexion/extension, pelvic tilt, pelvic rotation, and trunk rotation. Most of these changes were significantly greater than the changes in the PT group. The third finding was that the changes in lower extremity gait patterns were not significant in the PT group.

Gait Speed

The results for gait speed indicated that before the operation participants in the SDR-PT group walked at a slower speed than those in the ND group. The pre- to postoperative increase in

speed in the SDR-PT group was significant enough that the group's speed was not different from that in the ND group at 20 months postoperatively (Table 5). The pre- to postoperative increase in speed in the SDR-PT group was significantly greater than that in the PT-only group. The increase in gait speed was due to a significant increase in stride length and not to an increase in cadence. The speed in the PT group was slower than that in the ND group for all test sessions. The PT group experienced no change in stride length or cadence.

Gross Motor Function Measure

The GMFM and GMAE scores indicated improvement in both the SDR and PT groups (Table 6). The GMAE score increased seven points in the SDR-PT group and three points in the PT group. The increase in the GMAE score in the SDR-PT group was significantly greater than the increase in the PT group.

Discussion

The purpose of this investigation was to compare multidimensional outcomes in a group of patients with CP undergoing SDR followed by intensive PT with outcomes in a group of similar participants undergoing intensive PT only. The major limitation of the investigation was that it was not randomized. Our strategy was to use the same inclusion and exclusion criteria for both groups to ensure a larger number of participants relative to the number in the three previously reported investigations. Those studies had 12, 14, and 21 participants in their SDR-PT groups and 12, 14, and 17 in their PT-only groups; the studies took place in Vancouver,[35] Toronto,[38] and Seattle,[24] respectively. The current investigation had 31 participants in the SDR-PT group and 37 in the PT group. The study design also permitted a 2-year follow-up period, which was matched only by the Seattle study.[24] The Vancouver and Toronto investigations had 9-month and 1-year follow-up periods, respectively. Researchers in the previous investigations reported significant decreases in spasticity after SDR, which they measured using both the Ashworth Scale[23,24,35,37,38] and dynamometric data.[12-16,23] Our results match those of these previous studies, and we report a decrease in spasticity in the SDR-PT group. In patients in the PT-only group, we also report decreases in spasticity in the ankle plantar flexors as well as values for the ankle plantar and knee flexors that were not significantly different from those measured in patients in the ND group at any test session.

The large variability between participants explains some of these results. For example, participants whose ankles were assigned large spasticity values may have demonstrated little or no spasticity at the knees and vice versa. Nevertheless, we also recognize the limitations of our data-collection methods. When we began developing the measure (circa 1994), we were less concerned than at present with the variability from trial to trial during a single data-collection session.[11] We would generally reject the first two or three trials to eliminate any startle response and continued to repeat tests until successive trials overlaid one another on the KinCom monitor. We then accepted and used those data in the analysis. The data presented in the current study represent a conservative measure of spasticity (defined as a velocity-dependent resistance to passive stretch), one in which an unknown amount of spastic response has been eliminated as a result of repetition. A possible solution to the startle-response problem has at least two components: the first is to save each trial of data that we collect in a session. The analysis of each trial should provide us with a resistance-time history through which we can determine a point at which any startle response is eliminated but any spastic response remains. The second component is to collect EMG data simultaneously with the resistance data. We can then investigate the muscle-activity characteristics of both the muscle of interest (for example, ankle plantar flexors) and its antagonist (for example, dorsiflexors). Although these analyses may result in sacrificing the simplicity of the current measure (that is, one single

number representing the velocity, resistance, and stretch), they should increase the understanding of spasticity. These analyses are ongoing.

We have previously reported that children with CP undergoing SDR were weaker before the operation than children in the ND group, and remained weaker afterwards.[12,15,16,32] The results of the current investigation support those findings because of our additional data from the SDR and PT groups. Despite the overall weakness—and contrary to prior reports about weakness after SDR[1,27,30,31]—we have previously reported significant increases in knee flexor/extensor and hip adductor strength after SDR, with no significant change in the strength of the ankle plantar flexors.[12,15,16,32] Results from the current investigation support some of this work, but they also show increases in strength for the ankle plantar flexors. The results of our investigation also support those of other investigations indicating that strength can be increased in children who have CP.[4,22]

Researchers in previous investigations have reported improvements in gait kinematics after SDR.[18,36,37] Results from our investigation support those results. Despite general agreement for the improvement in gait kinematics, the improved variables have not always been the same. For example, both Thomas and colleagues[36,37] and Graubert and colleagues[18] reported no improvements in pelvic tilt ROM, whereas we did. Thomas and colleagues[36] reported improvements in ankle ROM, whereas we did not. On the other hand, our results and those of Thomas and colleagues[36] documented improvements in knee flexion/extension ROM. Our results and those of Graubert and colleagues documented improvements in foot progression angle; Graubert, et al., also reported no significant changes in gait kinematics in their PT group, and we found similar results.

Reports regarding changes in gait speed as a consequence of SDR have been inconclusive. Thomas and colleagues[37] found significant increases in speed for 13 children who walked independently at 1 year postoperatively, whereas Graubert and colleagues[18] and Wright and colleagues[38] reported no significant increases in the speed of ambulating children (18 and 12 individuals, respectively) at 1 year postoperatively. Not only did our results document increases in gait speed from the preoperative to the 20-month postoperative visit (31 participants), but the improvement was large enough that the postoperative gait speed was no longer significantly different from that in the ND group. The increase in gait speed of 25 cm/second in the SDR-PT group was significantly greater than the increase of 3 cm/second in the PT-only group. It is difficult to explain the differences between our study results and those of Graubert, et al., and Wright, et al. One potential explanation is related to the magnitudes of the speeds. Both groups of authors reported much slower walking speeds than we did. In the study by Graubert, et al., the walking speed was between approximately 53 and 61 cm/second, and in the Wright, et al., study it was between 38 and 58 cm/second. The gait speeds measured in children in the CP groups at the preoperative visit in our investigation (81 and 91 cm/second) were greater than those in the two previously mentioned investigations. Thomas and colleagues,[37] who also reported significant gains in speed, reported gait speeds between 78 and 98 cm/ second for their independent ambulators. Another potential explanation pertains to the number of rootlets cut during the operation. For example, approximately 25 and 45% of the rootlets were cut in the course of the investigations conducted by Graubert, et al., and Wright, et al., respectively, whereas approximately 65% of the rootlets were cut during our investigation. Thomas and colleagues[37] did not specifically report the percentage of rootlets cut, but they referred to a report by Peacock and colleagues,[30] in which it was stated that 25 to 50% of the rootlets were cut. According to the metaanalysis by McLaughlin and coworkers,[24] the greater the percentage of rootlets cut, the greater the gains in gross motor function.

As discussed in the introduction to this paper, results of two randomized clinical trials indicated that SDR followed by intensive PT was more effective than intensive PT alone in the increase

of GMFM scores.[35,38] Results of a third trial indicated that SDR followed by intensive PT was not any more effective in improving GMFM scores than intensive PT alone.[24] Furthermore, a metaanalysis of the combined results of the three investigations indicated that SDR followed by intensive PT was more effective in the improvement of GMAE scores than intensive PT alone.[23] The results from the current investigation support the results from the two randomized clinical trials and from the metaanalysis, which indicate significantly greater improvement in the SDR-PT group than in the PT group.[23,35,38] The work by Palisano and colleagues[28] seems relevant in the evaluation of whether the seven-point increase in our SDR-PT group's average GMAE score was clinically significant. Using figures and prediction equations, they presented typical improvement in GMFM scores as a consequence of increasing age for all GMFCS levels. Ninety-five percent confidence intervals were also part of the prediction equations. The mean GMFCS value was 4 for Levels I, II, and III for the 95% confidence bounds for GMFM scores for 9-year-old children. Thus, the seven-point GMAE increase and the 5% GMFM increase in our study indicate that the improvement would not be expected as a result of increasing age.

The results of the current investigation add to the body of knowledge in at least two areas, the first of which is related to strength. We demonstrated objectively the lower-extremity weakness characteristic of children who have CP. This weakness existed regardless of the level of intervention (that is, SDR and intensive PT or intensive PT only). Despite this weakness, strength in both CP groups improved after treatment.

The second area concerns the gait results. The results for gait kinematics further support results in previous studies that demonstrate improved gait characteristics. The results indicate that the postoperative gait pattern in the SDR-PT group was closer to that in the ND group than to its own preoperative pattern. The fact that no changes in gait kinematics were observed in the PT group means that despite the intensive PT, which resulted in some significant gains in strength, gait patterns in these patients did not change. The answers to the following three questions may explain the lack of pattern changes and would also be extremely interesting to investigate: 1) Would gait reeducation based on a gait analysis improve gait kinematics? 2) Are there specific muscles that need to be strengthened (for example, plantar flexors) to improve gait? The SDR-PT group was the only group to achieve considerable gains in plantar flexor strength. 3) Would a specific rather than a generalized PT protocol (currently used in the SDR clinic) result in greater gains in gait?

The results for the increased gait speed in the SDR-PT group are noteworthy for at least four reasons. First, the increase reached a point at which it was not significantly different from that in the ND group. Second, the increase was significantly greater than that in the PT-only group. Third, the results were taken from a relatively large cohort of participants (31 compared with 18 or fewer used in the other investigations). Fourth, the increase raises the issue of the relationship between the number of rootlets cut and concomitant increases in gait speed. This fourth issue is worthy of continued investigation.

Conclusions

The results of this investigation indicated that in the groups with CP, the patients were weaker than individuals in the ND group, regardless of data-collection time point or intervention. Despite this weakness, patients in both groups had strength gains. Preoperative gait speed in the SDR-PT group was slower than that in the ND group, but not at 20 months postoperatively. Gait speed in the PT group remained slower than that in the ND group at all data-collection time points. Patients in the SDR-PT group displayed improvements in gait kinematics, but those in the PT-only group showed none. Finally, the increase in the GMAE score from the preoperative to the 20-month postoperative visit was significantly greater in the SDR-PT group

than in the PT group. The current results support previous GMFM results from randomized clinical trials, which indicate the effectiveness of SDR but also provide additional information relating to improved gait speed. We conclude that SDR is an effective treatment for children with spastic diplegic CP, providing expected gains in strength, gait speed, and kinematics as well as in overall gross motor function.

Acknowledgements

This research was supported by Grant No. R01 NS35830 from the National Institute for Neurological Disorders and Stroke at the National Institutes of Health

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Abbreviations used in this paper

CP
cerebral palsy

EMG
electromyography

GMAE
Gross Motor Ability Estimate

GMFCS
Gross Motor Function Classification System

GMFM
Gross Motor Function Measure

ND
nondisabled

PT
physical therapy

ROM
range of motion

SD
standard deviation

SDR
selective dorsal rhizotomy

TABLE 1

Participant demographics, GMFCS level, and gait status by study group*

Group	No. of Participants	Age (yrs)†	Sex		Weight (kg)†	GMFCS Level			Gait Status	
			M	F		1	2	3	Independent	Needs Device
SDR-PT	31	9.0 ± 5.3	15	16	30.1 ± 17.8	12	11	8	25	6
PT-only	37	9.7 ± 4.5	19	18	34.5 ± 19.8	12	20	5	35	2
ND	40	9.4 ± 3.4	21	19	36.4 ± 15.7	NA	NA	NA	40	0

*NA = not applicable.

†Values are presented as the means ± SDs.

TABLE 2

Ankle plantar flexor, knee flexor, and hip adductor/abductor spasticity measured in SDR-PT, PT-only, and ND groups

	SDR-PT Group			PT-Only Group			
Spasticity Variable	**Preop**	**Postop (8 mos)**	**Postop (20 mos)**	**Pre-PT**	**Post-PT (8 mos)**	**Post-PT (20 mos)**	**ND Group**
ankle	0.009 ± 0.007	0.006 ± 0.005	0.005 ± 0.005*	0.012 ± 0.011	0.009 ± 0.006	0.007 ± 0.006*	0.006 ± 0.004
knee	0.008 ± 0.009†	0.004 ± 0.004	0.002 ± 0.004*	0.010 ± 0.011	0.005 ± 0.009	0.006 ± 0.011	0.003 ± 0.01
hip‡	0.023 ± 0.027†	0.013 ± 0.013	0.010 ± 0.01*§	0.026 ± 0.021†	0.030 ± 0.026	0.035 ± 0.029†	0.004 ± 0.014

*Significantly different from pretreatment or initial visit ($p < 0.05$).

†Significantly different from the ND group ($p < 0.05$).

‡The pre- to posttreatment change in the values for the SDR-PT group was significantly different from the change in the values for the PT group ($p < 0.05$).

§Significantly different from the PT group ($p < 0.05$).

TABLE 3

Maximum strength (torque) scores measured in the SDR-PT, PT-only, and ND groups*

	SDR-PT Group (29 children)			PT-Only Group (36 children)			
Max Strength (nm/kg)	**Preop†**	**Postop (8 mos)**	**Postop (20 mos)†**	**Pre-PT†**	**Post-PT (8 mos)**	**Post-PT (20 mos)**	**ND Group (39 children)**
ankle PF‡	0.37 ± 0.24	0.51 ± 0.27	0.51 ± 0.30§	0.41 ± 0.29	0.38 ± 0.27	0.37 ± 0.28†	1.10 ± 0.40
ankle DF	0.20 ± 0.10	0.20 ± 0.10	0.24 ± 0.10	0.20 ± 0.10	0.23 ± 0.09	0.22 ± 0.09†	0.41 ± 0.11
knee flex	0.52 ± 0.31	0.56 ± 0.29	0.64 ± 0.28	0.54 ± 0.25	0.57 ± 0.27	0.66 ± 0.31†§	0.92 ± 0.34
knee ext	0.86 ± 0.45	1.03 ± 0.44	1.14 ± 0.42§	0.92 ± 0.43	1.07 ± 0.44	1.06 ± 0.48†	1.66 ± 0.78
hip abd	0.48 ± 0.26	0.53 ± 0.25	0.59 ± 0.25	0.54 ± 0.22	0.58 ± 0.23	0.61 ± 0.30†	1.05 ± 0.31
hip add	0.68 ± 0.27	0.70 ± 0.30	0.76 ± 0.29	0.76 ± 0.25	0.87 ± 0.26	0.93 ± 0.35§	1.14 ± 0.42

* Data unavailable in four children. Abbreviations: abd = abductor; add = adductor; DF = dorsiflexor; ext = extensor; flex = flexor; max = maximum; PF = plantar flexor.

† Significantly different from the ND group ($p < 0.05$).

‡ Significantly different pre- to postoperative change compared with the change in the PT-only group ($p < 0.05$).

§ Significantly different from pretreament or initial visit ($p < 0.05$).

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TABLE 4

Gait kinematics scores measured in SDR-PT, PT-only, and ND groups*

Gait Kinematics Variable (°)	SDR-PT Group (29 children)			PT-Only Group (36 children)			ND Group (39 children)
	Preop	Postop (8 mos)	Postop (20 mos)	Pre-PT	Post-PT (8 mos)	Post-PT (20 mos)	
ankle DF at IC	−5 ± 7	−4 ± 6	−4 ± 6	−3 ± 7	−3 ± 7	−2 ± 6	−2 ± 3
ankle DF/PF ROM	15 ± 8†	16 ± 6	16 ± 4†	17 ± 7†	17 ± 6	19 ± 7†	20 ± 5
knee flex at IC‡	32 ± 12†	28 ± 11	28 ± 12†	29 ± 8†	28 ± 9	30 ± 8†	3 ± 3
knee flex/ext ROM‡	44 ± 13†	49 ± 12	52 ± 13†§	45 ± 12†	46 ± 13	47 ± 13†	61 ± 4
hip flex/ext ROM‡	43 ± 7	46 ± 7	46 ± 8	43 ± 7	43 ± 7	43 ± 7	40 ± 4
pelvic tilt ROM‡	8 ± 3†	7 ± 3	6 ± 3‡§	7 ± 3†	8 ± 3	7 ± 3†	3 ± 1
pelvis rot ROM	19 ± 7†	17 ± 6	18 ± 4†§	17 ± 7†	18 ± 7	18 ± 7†	11 ± 6
trunk rot ROM	15 ± 9†	11 ± 5	12 ± 7†	12 ± 6†	12 ± 6	12 ± 6†	5 ± 2
ext foot prog angle‡	−3 ± 18	−7 ± 15	−9 ± 15	−7 ± 13	−8 ± 12	−5 ± 11	−9 ± 5

* Data unavailable in four children. Abbreviations: IC = initial contact; prog = progression; rot = rotation.

† Significantly different from the ND group ($p < 0.05$).

‡ Significantly different pre- to posttreatment change compared with that found for the PT group ($p < 0.05$).

§ Significantly different from pretreatment or initial visit ($p < 0.05$).

J Neurosurg. Author manuscript; available in PMC 2008 June 10.

TABLE 5

Linear data scores measured in SDR-PT, PT-only, and ND groups*

	SDR-PT Group (29 children)			PT-Only Group (36 children)			
Linear Data Variable	**Preop**	**Postop (8 mos)**	**Postop (20 mos)**	**Pre-PT**	**Post-PT (8 mos)**	**Post-PT (20 mos)**	**ND Group (39 children)**
gait speed (cm/sec)†	81 ± 22‡	91 ± 25	101 ± 24§	91 ± 26‡	90 ± 22	93 ± 22‡	113 ± 18
stride length (cm)	79 ± 21‡	90 ± 22	96 ± 17§	85 ± 21‡	88 ± 18	90 ± 19‡	110 ± 21
cadence (steps/min)	122 ± 26	122 ± 28	126 ± 27	129 ± 25	124 ± 24	124 ± 21	124 ± 14

*Data unavailable in four children.

†Significantly different pre- to posttreatment change compared with the change in the PT-only group ($p < 0.05$).

‡Significantly different from the ND group ($p < 0.05$).

§Significantly different from pretreatment or initial visit ($p < 0.05$).

TABLE 6

GMAE and GMFM scores measured in the SDR-PT and PT-only groups*

	SDR-PT Group (29 children)			PT-Only Group (36 children)		
Measure	**Preop**	**Postop (8 mos)**	**Postop (20 mos)**	**Initial**	**Post-PT (8 mos)**	**Post-PT (20 mos)**
GMAE†	70 ± 12	72 ± 12	77 ± 13‡	71 ± 8	73 ± 10	74 ± 9‡
GMFM (%)	87 ± 10	88 ± 9	92 ± 8‡	89 ± 7	90 ± 7	91 ± 7‡

*Data unavailable in three children.

†Significantly different pre- to posttreatment change compared with change in PT-only group ($p < 0.05$).

‡Significantly different from pretreatment or initial visit ($p < 0.05$).