Flexed-knee gait in children with cerebral palsy: a 10-year follow-up study

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Abstract

Background While several studies have evaluated the short-term effectiveness of conservative and surgical treatment of flexed-knee gait in children with cerebral palsy (CP), few have explored the long-term outcomes using gait analysis. The purpose of this study was to examine, through gait analysis, the 10-year outcomes of flexed-knee gait in children with CP.

Methods Ninety-seven children with spastic CP who walked with a flexed-knee gait underwent two gait evaluations [age 6.1 ± 2.1 and 16.2 ± 2.3 years, Gross Motor Function Classification System (GMFCS) I (12), II (45), III (37), IV (3)]. Limbs with knee flexion at initial contact $>15^\circ$ were considered walking with a flexed-knee gait and were included in the study ($n = 185$). Kinematic data were collected using an eight-camera motion analysis system (Motion Analysis, Santa Rosa, CA). Surgical and therapeutic interventions were not controlled.

Results A comparison between the two gait studies showed an overall improvement in gait at 10 years follow-up. Significant improvements were seen in knee flexion at initial contact, Gait Deviation Index (GDI), Gross Motor Function Measure (GMFM), and gait speed ($P < 0.01$ for all). Outcome was also evaluated based on the severity of flexed-knee gait at the initial visit, with functional skills and overall gait (GDI) improving in all groups ($P < 0.01$ for all). The group with a severe flexed-knee gait exhibited the most improvement, while subjects with a mild flexed-knee improved the least.

Conclusions Children at a specialty hospital whose orthopedic care included gait analysis and multi-level surgery showed improvement of flexed-knee gait and gross motor function over a 10-year course, regardless of the initial severity.

Keywords Cerebral palsy · Flexed-knee gait · Gait analysis · Motion analysis

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Introduction

Cerebral palsy (CP) is the most common movement disorder in children [1, 2], and flexed-knee gait, which is defined by abnormally high knee flexion, is the most common pattern of gait deformity in the CP population [1, 3–8]. The etiology of flexed-knee gait is multi-factorial and evolves over the child's growth and maturation. The factors include abnormal motor control, muscle weakness and imbalance, progressive muscle contractures, spasticity, torsional malalignments, and foot deformities [1, 6, 9, 10]. The natural history of flexed-knee gait has not been well defined, but it has been subjectively reported in the literature to increase over time with the collapsing of the

midfoot and hindfoot, increasing stance phase ankle dorsiflexion, and increasing knee and hip flexion as children grow [4, 11–13]. The evolution of flexed-knee gait often includes knee pain (resulting from apophysitis of the distal pole of the patella and tibial tubercle), increasing torsional malalignment of the lower extremity, increasing foot pain, posterior knee capsule contracture, and progressive loss of gait function during adolescent growth [1, 3, 4, 14]. This evolution is a probable cause of loss of ambulation in severe cases [14].

The current standard of care for the treatment of flexed-knee gait is single-event multi-level surgery (SEMLS), which works to correct primary factors as well as secondary deformities. The term birthday syndrome surgery was coined by Mercer Rang to define the (now obsolete) practice of performing isolated surgical procedures each year [14–16]. SEMLS minimizes the number of surgical events by combining procedures at multiple joints, resulting in reduced overall recovery and rehabilitation time, as well as reduced total financial cost during childhood and adolescence [15, 17, 18]. By carefully monitoring the child during growth, treatments can be performed either after motor function and gait have plateaued or just when the child begins to lose function, before significant functional loss and development of secondary deformities occurs. Often, procedures are required at both times during the child's growth and development. Previous studies [10, 19–25] looked at the short-term effectiveness of conservative and surgical treatment of flexed-knee gait. Few, however, have explored the long-term outcomes of a treatment program using full diagnostic gait analysis to identify the etiology and guide the correction of the multi-level deformities of a group [13–15, 17].

The purpose of this study is to report the 10-year follow-up of children initially identified with flexed-knee gait during childhood whose orthopedic care included three-dimensional motion analysis and SEMLS with follow-up into adolescence. A secondary aim is to examine outcomes according to kinematic patterns and motor severity subgroupings thought to be clinically relevant.

Materials and methods

This is a retrospective review of children with diplegic pattern CP who: had an initial gait analysis between 1993 and 1999, had an element of flexed-knee gait, and had a follow-up gait analysis at least 8 years later. All evaluations included a kinematic assessment performed with a motion analysis system (Motion Analysis, Santa Rosa, CA), data reduction using OrthoTrak (Motion Analysis), and a complete physical examination including measures of passive range of motion. Gait interpretation was

performed by a team of orthopedists and physical therapists. Flexed-knee gait [7] was defined as $>15^\circ$ of knee flexion at initial contact, which corresponds to one standard deviation (SD) above the mean knee flexion at initial contact of a typically developing 6-year-old child. Children with a wide range of maximal knee extension during stance were included to examine differences in outcome in children with crouch (excessive knee flexion through the gait cycle) and children with mid-stance extension. Children with CP in this facility routinely have follow-up gait analyses for clinical diagnostic purposes to ascertain the need for further treatment, so those children who were determined to have flexed-knee gait at the initial evaluation were expected to have follow-up gait analyses.

Limbs were classified by the severity of crouch based on knee flexion at foot contact (KFFC) as follows: mild, 15° – 30° (1–3 SD above the mean); moderate, 31° – 45° (3–5 SD above the mean); and severe, greater than 45° (>5 SD above the mean). Limbs were also grouped according to motor severity, maximum knee extension in stance (MKE), and maximum ankle dorsiflexion in stance (MAD). Motor severity was established by retrospectively using the Gross Motor Function Classification System (GMFCS) levels of function: I, 12 children; II, 45 children, III, 37 children; and IV, three children.

Surgical treatment occurred prior to having an initial gait analysis in 45 children. These children had a total of 45 surgical events and 216 procedures (Table 1); most were soft-tissue lengthenings to treat spastic hip disease (Table 2). For the 97 children in the study, there were 158 surgical events, with a total of 815 procedures performed between the initial and final gait analysis (Table 1). There were 1.6 surgical events per child and 5 procedures per surgical event for these children between the initial and

Table 1 Surgical events in the 97 study children with cerebral palsy (CP)

	Before initial gait analysis	Between initial and final gait analysis	Lifetime
% of children with no surgical events	55	6	4
% of children with one surgical event	40	35	24
% of children with two surgical events	5	46	41
% of children with three or more surgical events	0	12	31
Average surgical events per patient	0.5 (44/97)	1.6 (158/97)	2.1 (202/97)
Average procedures per surgical event	4.9 (216/44)	5.1 (815/158)	

Table 2 Breakdown of surgical procedures in the 97 study children with CP

Procedure	Before initial gait analysis		Between initial and final gait analyses		Total procedures
	Unilateral	Bilateral	Unilateral	Bilateral	
Hamstring lengthening	6	50	14	180	250
Gastrocnemius lengthening	3	16	23	132	174
Rectus transfer	1	8	14	102	125
Tendo-Achilles lengthening	3	34	13	24	74
Tibia osteotomy	3	4	26	48	81
Femur osteotomy	1	2	15	44	62
Varus foot correction	1	2	3	6	12
Psoas lengthening	2	30	2	26	60
Subtalar fusion	0	2	4	32	38
Hip adductor lengthening	1	44	9	40	94
Lateral calcaneus lengthening	0	2	11	34	47
Knee capsule release	0	0	3	0	3
Distal femoral extension osteotomy	0	0	0	6	6
Total procedures	22	194	141	674	1,031

Selective dorsal rhizotomy was performed in one child before the initial gait analysis and in four children between the initial and final gait analyses

final gait analysis. The number of surgical events that children underwent before the study was initiated, during the study period, and the total number of events is presented in Table 1. Up to the final gait analysis, 4 % of children had undergone no surgical events, 24 % of children underwent one surgical event, 41 % underwent two surgical events, and 31 % had undergone three or more surgical events. Surgical events included many variations to address gait problems during the treatment period between the initial and final gait evaluations. Treatment was considered complete if the final gait analysis was completed after skeletal maturity and no further treatment was recommended (31 children); it was incomplete if these criteria were not met (66 children).

Statistical methods

Statistical analysis was completed with the Gait Deviation Index (GDI) as the primary outcome variable. The GDI, as described by Rozumalski et al. [26–28], assigns a score that represents the relative deviation from normal in the overall gait pattern. A score of 100 represents normal gait, and lower scores demonstrate deviation from normal, with each ten points representing one standard deviation. Additionally, KFFC, MKE, and MAD were used to classify limbs into subgroups. A change in motor function was reported using the Gross Motor Function Measure (GMFM) dimension-D. The GMFM is a standardized observational instrument designed and validated to measure change in gross motor function over time in children with CP [29–31]. This change was reported as a percentage. These outcomes were compared across several subgroups based on KFFC, MKE, MAD, and GMFCS.

For the three gait variables (KFFC, MKE, and MAD), the limbs were divided into three subgroups. Limbs with KFFC with a value one to three SDs above the normal mean were in the mild group; those between three and five SDs above the normal mean were in the moderate group; and those above five SDs above the normal mean were in the severe group. Limbs with MKE with a value one SD below the normal mean were placed in the hyperextended group; those with a value above one SD of the mean were considered flexed; and those within a standard deviation of the mean were placed in the normal group. Limbs with MAD with a value one SD below the normal mean were in the equinus or jump knee group; those with a value one SD above the mean were in the hyperdorsiflexed or crouched gait group; and those within a standard deviation of the mean were in the normal or apparent equinus group [7].

Finally, two groups were created based on the GMFCS level (I and II vs. III and IV). Paired *t*-tests were used to assess statistical significance between initial and final visits, with $P < 0.01$. The data were normally distributed based on a histogram analysis, and all variables had equal variance between groups, except for GDI. To account for the unequal variance, the Wilcoxon non-parametric *t*-test equivalent was used to analyze GDI.

Results

Initially, approximately 928 charts (based on the average number of visits yearly) were identified and reviewed from children with spastic diplegia who underwent a full clinical gait analysis between 1993 and 1999 (see Fig. 1). There were 549 unique children with spastic CP meeting our

criteria for flexed-knee gait. From those children, 248 were found to have their initial evaluation when they were 12.5 years old or less and, therefore, would have sufficient

Fig. 1 Subject inclusion criteria

time to have at least an 8 years follow-up visit prior to their 21st birthday. From that group, 97 children were found to have had a gait analysis 8 years or more following their initial testing. In the 97 children (194 limbs) involved in the study, nine limbs were found to have normal knee extension at initial contact and were excluded from the study. This left us with 185 limbs. The mean age of the 97 children was 6.1 years (± 2.1) at the first evaluation, with the age range being 2.6–12.5 years, and was 16.2 years (± 2.3) at the final evaluation, with the age range being 11.7–20.9 years.

From the initial evaluation until the final evaluation, the whole group improved in nearly all outcome measures (Table 3). GDI improved from 54.5 to 67.8 ($P < 0.01$), GMFM-D improved from 60 to 69 % ($P < 0.01$), KFFC improved from 39.2° to 26.6° ($P < 0.01$), and gait speed improved from 67.2 to 82.3 cm/s ($P < 0.01$). There was also a change in foot progression angle (FPA), from 0.4° to 6.1° external ($P < 0.01$). Knee flexion contracture increased from -1.4° to -4.2° maximum passive extension ($P < 0.01$), and the popliteal angle increased from 43.4° to 62.2° ($P < 0.01$). There was no significant change in the maximum anterior pelvic tilt, which remained at 24° between visits.

The severely and moderately flexed-knee groups showed an improvement in KFFC at the final visit. The severe group improved the most, from 54.7° to 31.4° of KFFC ($P < 0.01$), and the moderate group improved from 37.2° to 25.4° of KFFC ($P < 0.01$); the mild group was unchanged. All groups significantly improved ($P < 0.01$) in GMFM and GDI. The severe group improved from 52 to 63 % for GMFM and 47.6 to 65.0 for GDI; the moderate group improved from 64 to 72 % for GMFM and 56.7 to 69.7 for

Table 3 Change in flexed-knee gait over 10 years in 185 limbs

Variables	Group totals ($n = 185$)			Normals	
	Initial	Follow-up	Change	Initial	Follow-up
Age	6.1 $\pm$ 2.1	16.2 $\pm$ 2.3	+10.1*	6	16
GMFM dimension-D (%)	60 $\pm$ 23 %	69 $\pm$ 22 %	+9 %*	100	100
Gait index	54.5 $\pm$ 15.0	67.8 $\pm$ 10.4	+13.3*	100	100
Knee flexion at initial contact	39.2 $\pm$ 13.4	26.6 $\pm$ 12.6	-12.6*	-1.4–13.9	-2.6–9.1
Knee extension max in stance	15.6 $\pm$ 16.0	12.5 $\pm$ 14.8	-3.1	-5.0–10.65	-3.7–7.7
Dorsiflexion max in stance	8.1 $\pm$ 12.2	19.0 $\pm$ 19.4	+10.9*	5.7–16.6	9.5–14.5
Gait speed (cm/s)	67.2 $\pm$ 32.4	82.3 $\pm$ 27.2	+15.1*	142.5–158.5	107–138.6
Knee extension PROM	-1.4 $\pm$ 6	-4.1 $\pm$ 10	+2.7*	0.2–7.6	0.2–7.6
Pop angle	43.4 $\pm$ 15	62.3 $\pm$ 16.4	+18.9*	17.9–45.1	25.2–48.8
Foot progression angle	-0.4 $\pm$ 27.5	-6.1 $\pm$ 16.6	-5.7*	-18.4 to -4.7	-19.2 to -2.8
Pelvic tilt	24.3 $\pm$ 10.2	24.3 $\pm$ 9.7	0	9.3–21.5	4.8–14.0
Stride length (cm/s)	62.4 $\pm$ 23.3	89.1 $\pm$ 27.8	+16.8*	83.4–106.4	116.7–145.4

GMFM Gross Motor Function Measure, PROM passive range of motion, Pop popliteal

* $P < 0.01$

Table 4 Change in flexed-knee gait grouped by KFFC over 10 years

Outcome variables	Mild (15–30), <i>n</i> = 53			Moderate (30.1–45), <i>n</i> = 72			Severe (>45), <i>n</i> = 60		
	Initial	Follow-up	Change	Initial	Follow-up	Change	Initial	Follow-up	Change
GMFM dimension- <i>D</i> (%)	65 ± 0.24	71 ± 16	+6*	64 ± 22	72 ± 21	+8*	52 ± 21	63 ± 23	+11*
Gait index	57.6 ± 13.5	68.0 ± 9.6	+10.4*	56.7 ± 14.0	69.7 ± 10.5	+13*	47.6 ± 15.8	65.0 ± 10.7	+17.4*
Knee flexion at initial contact	24.4 ± 4.2	22.7 ± 11.2	−1.7	37.2 ± 3.8	25.4 ± 11.6	−11.8*	54.7 ± 9.3	31.4 ± 13.1	−23.3*
Knee extension max in stance	4.2 ± 13.3	6.3 ± 11.7	2.1	14.0 ± 11.7	12.5 ± 13.2	−1.5	27.9 ± 14.5	18.1 ± 17.2	−9.8*
Dorsiflexion max in stance	7.2 ± 10.0	17.1 ± 19.7	+9.9*	9.2 ± 11.8	20.0 ± 20.5	+10.8*	7.6 ± 14.4	19.4 ± 17.9	+11.8*
Gait velocity (cm/s)	76.8 ± 29.9	83.9 ± 25.9	7.1	70.3 ± 32.2	86.9 ± 26.3	+16.6*	55.6 ± 31.7	75.2 ± 28.3	+19.6*

Knee flexion is positive

KFFC knee flexion at foot contact, GMFM Gross Motor Function Measure

* *P* < 0.01**Table 5** Change in flexed-knee gait grouped by MKE over 10 years

Outcome variables	Hyperextension (−36.1 to −5.2), <i>n</i> = 13			Normal (−5–10.5), <i>n</i> = 67			Flexion (12–55.8), <i>n</i> = 105		
	Initial	Follow-up	Change	Initial	Follow-up	Change	Initial	Follow-up	Change
GMFM dimension- <i>D</i> (%)	66 ± 11	69 ± 9	3	61 ± 25	69 ± 21	+8*	59 ± 22	68 ± 23	+9*
Gait index	58.8 ± 12.1	69.0 ± 10.0	10.2	55.9 ± 14	68.8 ± 10.3	12.9*	53.0 ± 15.8	67.1 ± 10.6	+14.1*
Knee flexion at initial contact	26.4 ± 6.8	19.6 ± 16.7	−6.8	33.2 ± 12.0	25.7 ± 12.4	−7.5*	44.4 ± 12.4	28.1 ± 11.9	−16.3*
Knee extension max in stance	−13.2 ± 7.6	−1.4 ± 9.4	+11.8*	4.2 ± 4.7	9.4 ± 14.2	+5.2*	26.6 ± 11.2	16.2 ± 14.4	−10.4*
Dorsiflexion max in stance	4.5 ± 8.9	21.6 ± 25.4	+17.1**	8.6 ± 9.2	21.7 ± 26.1	+13.1*	8.0 ± 14.1	17.0 ± 12.4	+9*

MKE maximum knee extension (negative values indicate hyperextension), GMFM Gross Motor Function Measure

* *P* < 0.01, ** *P* < 0.05

GDI; and the mild group improved from 65 to 71 % for GMFM and 57.6 to 68.0 for GDI (all *P* < 0.01). In the severe group, MKE improved significantly (*P* < 0.01) from 27.9° of flexion to 18.1° of flexion. All groups had significant increases in MAD (*P* < 0.01) (Table 4).

The normal and flexion MKE groups improved in GMFM, GDI, and KFFC (*P* < 0.01). Limbs in these groups also had an increase in MAD (*P* < 0.01). Limbs in the MKE flexion group improved significantly in MKE (*P* < 0.01), from −26.6° to −16.2°, whereas subjects in the normal MKE group had a reduced MKE (*P* < 0.01), from −4.2° to −9.4°. The mean MKE for subjects in the normal group, however, did not increase outside of the normal limits. The hyperextension MKE group had an increase in MAD (*P* < 0.05), from 4.5° to 21.6°, and a reduction in hyperextension (*P* < 0.01), from 13.2° to 1.4°. Although the hyperextension group showed a trend for improvement in GMFM, GDI, and KFFC, none of the differences were

significant at *P* < 0.01. It is important to note that the relatively small sample size for the hyperextension group is likely the cause for a negligible statistical significance. This negligible change is due to combined small sample size and small effect size (Table 5).

Subgrouping limbs based on MAD found that GMFM significantly improved (*P* < 0.01) in the equinus group, from 58 to 72 %. All groups showed significant improvement (*P* < 0.01) in GDI and KFFC. The equinus group showed improvement in GDI from 49.4 to 68.3 and in KFFC from 38.6° to 27.3°; the hyperdorsiflexion group improved in GDI from 55.0 to 70.0 and in KFFC from 42.3° to 27.3°; and the MAD group within normal limits improved in GDI from 58.2 to 66.3 and in KFFC from 37.7° to 25.5°. A significant increase (*P* < 0.01) in MAD was seen in the equinus and normal groups. Lastly, the hyperdorsiflexion group showed a significant improvement in MKE (*P* < 0.01), from 18.8° to 12.5° (Table 6).

Table 6 Change in flexed-knee gait grouped by MAD over 10 years

Outcome variables	Equinus (−37–5.9), <i>n</i> = 62			Normal (6–15.9), <i>n</i> = 76			Hyperdorsiflexion (16–37), <i>n</i> = 47		
	Initial	Follow-up	Change	Initial	Follow-up	Change	Initial	Follow-up	Change
GMFM dimension- <i>D</i> (%)	58 ± 21	72 ± 17	+14*	60 ± 25	65 ± 24	5.00	62 ± 22	69 ± 24	7
Gait index	49.4 ± 15.5	68.3 ± 11.5	+18.9*	58.2 ± 13.5	66.3 ± 10.6	+8.1*	55.0 ± 15.0	70.0 ± 8.5	+15*
Knee flexion at initial contact	38.6 ± 13.3	27.3 ± 13.7	−11.3*	37.7 ± 12.5	25.5 ± 12.1	−12.2*	42.3 ± 15.0	27.3 ± 12.0	−15*
Knee extension max in stance	15.5 ± 18.4	13.8 ± 15.4	−1.7	13.4 ± 14.3	11.4 ± 15.3	−2	18.8 ± 14.6	12.5 ± 13.7	−6.3*
Dorsiflexion max in stance	−4.9 ± 10.2	18.7 ± 19.7	+23.6*	10.4 ± 2.5	18.8 ± 22.6	+8.4*	21.6 ± 4.5	19.6 ± 13.0	−2

MAD maximum ankle dorsiflexion in stance, GMFM Gross Motor Function Measure

* $P < 0.01$

Table 7 Change in flexed-knee gait grouped by GMFCS level over 10 years

Outcome variables	GMFCS I and II, <i>n</i> = 110			GMFCS III and IV, <i>n</i> = 75		
	Initial	Follow-up	Change	Initial	Follow-up	Change
GMFM dimension- <i>D</i> (%)	73 ± 16	80 ± 12	+7*	43 ± 18	53 ± 21	+10*
Gait index	55.0 ± 15.5	70.4 ± 9.7	+15.4*	53.3 ± 14.3	64.0 ± 10.2	+10.7*
Knee flexion at initial contact	38.5 ± 12.4	23.9 ± 11.4	−14.6*	40.6 ± 14.8	30.6 ± 13.2	−10*
Knee extension max in stance	15.4 ± 14.5	11.5 ± 13.0	−3.9	15.9 ± 18.3	14.1 ± 17.1	−1.8
Dorsiflexion max in stance	6.8 ± 13.0	19.4 ± 18.5	+12.6*	9.8 ± 11.0	18.5 ± 21.0	+8.7*

GMFCS Gross Motor Function Classification System, GMFM Gross Motor Function Measure

* $P < 0.01$

Limbs of children with GMFCS III and IV were compared with limbs of children with GMFCS I and II. The GMFCS I and II group improved significantly ($P < 0.01$) in GMFM from 73 to 80 %, GDI from 55.0 to 70.4, and KFFC from 38.5° to 23.9° ($P < 0.01$). The GMFCS III and IV group improved significantly ($P < 0.01$) in GMFM from 43 to 53 %, GDI from 53.3 to 64.0, and KFFC from 40.6° to 30.6° ($P < 0.01$). Both groups also showed significant increases in MAD ($P < 0.01$) and showed no significant differences for MKE (Table 7).

Discussion

The etiology of flexed-knee gait in CP has many contributory factors and requires a treatment algorithm customized to the individual child. The standard method for diagnosis includes a combination of (1) serial history and physical examinations to define the progression of the deformity and (2) three-dimensional gait analysis for quantitative measurement and definition of the biomechanics of the pathologic gait pattern. The GDI and GMFM provide quantitative measurements of overall gait severity

and motor function. Specific kinematic and kinetic measures, such as KFFC and ankle moments, help to assess the pathomechanical etiologies of flexed-knee gait. This study aimed to describe gait outcome over a 10-year period in a diverse group of children with flexed-knee gait. Most experts agree that the natural history of flexed-knee gait is one of gradual decline and loss of walking function [13, 32], although objective data defining the untreated natural history is lacking in the literature. This study documents that, with a treatment approach of serial clinic visits and surgery guided by comprehensive gait analysis, a child's gait function is maintained or improves from age 6 through 16 years. This was true for both mild and severe flexed-knee gait and for higher- and lower-functioning children.

Indications for specific operative procedures to treat flexed-knee gait continue to be debated and were not the focus of this study. With regard to hamstring lengthening, there are concerns that this procedure decreases hip extension and increases pelvic tilt [10]. In this cohort of mixed surgical procedures, there was no significant increase in anterior pelvic tilt at 10 years follow-up. The impact of hamstring lengthening on knee flexion during stance is also much debated [10, 19, 20]. Our finding was

that its impact was primarily on KFFC as a swing phase extension controller of the knee. With regard to distal femoral extension osteotomy in our retrospective group of patients, its use was limited to severe fixed knee flexion contractures. At our institution, children at risk for progressive crouch are monitored every 6 months during their rapid growth. When fixed knee flexion contractures and flexed-knee gait were increasing, we proceeded to hamstring lengthening and correction of the other flexed-knee gait factors. If there were more than 10° of fixed knee flexion contractures, a posterior knee capsulotomy was added. There is a recent trend for some centers to perform more frequent knee extension osteotomies; our outcomes are similar to the outcomes reported in these studies [23, 24, 33].

Instituting the use of clinical gait analysis in this population allowed for a decrease in recurrent minor birthday syndrome surgery procedures. There are, however, no published data on the frequency or total number of surgical procedures for children receiving orthopedic care guided by gait analysis over this length of time. Our sample of 97 children underwent 158 surgical events, with 815 total procedures, in a 10-year period. The concept of SEMLS does not imply that the child has surgery once in their lifetime, but conveys a philosophy intended to reduce surgical events as much as possible. The goal at our institution is to limit a child to two surgical events through growth to skeletal maturity in order to decrease the impact and cost on the child and their family. Looking at the total number of surgical procedures up until the time of the final gait analysis, 69 % of children in the study had two or fewer surgical events, while 31 % had three or more. These numbers need to be evaluated carefully though, as 68 % of the children included were considered to have “incomplete” treatment, as they were either skeletally immature or considered as candidates for additional surgical intervention at the time of final gait analysis. It is not clear if other protocols would be able to get the same or improved motor function with fewer surgical events, since there are no similar publications for comparison. Because the majority of children in this study were still in active treatment, further study is necessary to describe outcomes at maturity.

In this study, we elected a methodology to study the outcome of a group of patients with a single commonly treated and objectively defined kinematic gait deviation. Rather than study the effect of a single treatment intervention, we chose to examine all patients with excessive knee flexion at initial contact as a means to look at the long-term outcomes of a defined group whose orthopedic care was objectively guided by gait analysis. Our future goal is to evaluate the effectiveness of treatments for specific flexed-knee gait etiologies, such as torsional

malalignment and planovalgus foot deformity, as these are often the primary causes of flexed-knee gait. These etiologies need to be addressed when flexed-knee gait is progressing with growth. We hope to participate in future studies with multi-center data collection from sites with different protocols and philosophies. This would contribute to the development of a gait-treatment protocol for children and youths with CP, which yields the best functional outcome for young adults as their care is transitioned away from pediatric centers.

We elected not to utilize the flexed-knee gait classifications described by Rang et al. [16] and more recently by Rodda et al. [7]. Although these classifications provide a nice framework for conceptualizing the pathology of crouch gait based on pelvic, hip, knee, and ankle position, because of overlap in categorization, it is difficult to apply objective quantifiable borders between the groups, making statistical analysis of group changes very difficult. We have classified children according to single kinematic gait parameters (KFFC, MKE, and MAD) and into functional motor severity groups (GMFCS). If we were to combine this relatively simplified kinematic approach with a five-level crouch gait classification system similar to Rodda et al., we would have 324 unique groups, which is clearly not practical. In addition, we found that changes over time do not follow consistent patterns; a child classified as group 2 by Rodda et al. at initial presentation may progress to almost any other group by maturity. Alternatively, we chose not to categorize patients with global measures such as the GDI, as it gives no information regarding the specific deformity. For these reasons, we chose to use specific quantifiable measures of knee and ankle position to define deformity, to use the GDI to describe global gait deviation, to use the GMFM to describe motor capability and the GMFCS to describe overall motor severity.

Given that the current study is retrospective, there are several limitations. We could not control for the number or presentation of children who completed follow-up testing. Of the children who initially qualified for inclusion based on age and knee flexion criteria, only 39 % had the required 8 years or greater follow-up completed. The practice at our institution is to obtain a gait analysis at the conclusion of growth or when clinical history or physical examination suggests the possible need for further deformity correction. Insurance companies often rejected coverage for patients who did not have specific deformity concerns being considered for correction, and this likely represents the largest group for which follow-up was not available. There were also patients who left our practice before skeletal maturity, which is likely the second most common cause of limited follow-up. There might be a concern that some children were unable to walk and, therefore, did not receive the follow-up gait analysis,

implying that we only studied the best-performing children. Because we follow the vast majority of these patients in our clinic every 6 months, we can report that very few children fall into this group. Another limitation of this retrospective study is the lack of an untreated control group. Although such a group is difficult to find given the current evidence demonstrating short-term benefits of a variety of interventions, without an untreated control group, we are unable to conclusively determine that our treatment caused the observed improvements. Finally, the limitation of uncontrolled confounding variables such as age at initial evaluation, the effects of growth, the diversity of flexed-gait etiology, and the variations in rehabilitation programs and other treatment intervention is acknowledged. Many children included in this study had surgical intervention prior to their initial study evaluation, and we acknowledge that the surgeries likely affected their gait. Our attempt was to be inclusive due to the complex flexed-knee gait etiology, as it is often difficult to identify the source of the flexed-knee gait, and hope that future research can provide further clarification as to the comparative effectiveness of treatments in different flexed-knee gait etiologies.

Contrary to the general assumption of slow deterioration and loss of gait function, this report demonstrates that a treatment program of careful orthopedic follow-up by history and physical examination, combined with the use of diagnostic gait analysis, leads to improved gait through childhood and adolescent growth in a large group of children with CP followed at a pediatric specialty center.

Conflict of interest None.

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