Correction of Severe Crouch Gait in Patients with Spastic Diplegia with Use of Multilevel Orthopaedic Surgery

By J.M. Rodda, PhD, H.K. Graham, MD, FRCS(Ed), FRACS, G.R. Nattrass, MD, FRCS(C), FRACS, M.P. Galea, PhD, R. Baker, PhD, CEng, and R. Wolfe, PhD

Investigation performed at The Royal Children's Hospital, Melbourne, Australia

Background: Severe crouch gait in patients with spastic diplegia causes excessive loading of the patellofemoral joint and may result in anterior knee pain, gait deterioration, and progressive loss of function. Multilevel orthopaedic surgery has been used to correct severe crouch gait, but no cohort studies or long-term results have been reported, to our knowledge.

Methods: In order to be eligible for the present retrospective cohort study, a patient had to have a severe crouch gait, as defined by sagittal plane kinematic data, that had been treated with multilevel orthopaedic surgery as well as a complete clinical, radiographic, and instrumented gait analysis assessment. The surgical intervention consisted of lengthening of contracted muscle-tendon units and correction of osseous deformities, followed by the use of ground-reaction ankle-foot orthoses until stable biomechanical realignment of the lower limbs during gait was achieved. Outcome at one and five years after surgery was determined with use of selected sagittal plane kinematic and kinetic parameters and valid and reliable scales of functional mobility. Knee pain was recorded with use of a Likert scale, and all patients had radiographic examination of the knees.

Results: Ten subjects with severe crouch gait and a mean age of 12.0 years at the time of surgery were studied. After surgery, the patients walked in a more extended posture, with increased extension at the hip and knee and reduced dorsiflexion at the ankle. Pelvic tilt increased, and normalized walking speed was unaltered. Knee pain was diminished, and patellar fractures and avulsion injuries healed. Improvements in functional mobility were found, and, at the time of the five-year follow-up, fewer patients required the use of wheelchairs or crutches in the community than had been the case prior to intervention.

Conclusions: Multilevel orthopaedic surgery for older children and adolescents with severe crouch gait is effective for relieving stress on the knee extensor mechanism, reducing knee pain, and improving function and independence.

Level of Evidence: Therapeutic Level IV. See Instructions to Authors for a complete description of levels of evidence.

Crouch gait is a term that is frequently used generically to describe a gait pattern characterized by increased knee flexion in the stance phase of the gait cycle, especially in individuals with spastic diplegic cerebral palsy[1-8]. Bipedal gait has evolved to be energy-efficient by keeping the foot reasonably close to plantigrade position during stance, while adopting a relatively extended posture at the hip and knee. The body is maintained in this upright, extension posture by the action of three main muscle groups: the hip extensors, the knee extensors, and the ankle plantar flexors[9]. The ground-reaction force is maintained close to the centers of the hip, knee, and ankle joints, reducing the demands on the antigravity support muscles. Failure of the total body extensor moment as a result of diminished ability of the hip, knee, or ankle plantar flexor moments may result in collapse of the extension posture into a flexion posture, described as crouch gait (Fig. 1). This often occurs as part of the natural history of gait in patients with cerebral palsy[10-12] but may be precipitated by any intervention that weakens the gastrocnemius-soleus muscle. Such interventions may include injection of Botulinum toxin A (Botox), selective dorsal rhizotomy[9,13], and surgical lengthening of the triceps surae as treatment for equinus deformity[7,14-16].

In patients with spastic diplegia, there is usually weakness in the three major groups of muscles responsible for resisting the tendency toward the development of a crouch gait, but the majority of younger individuals walk with a reasonably upright posture in early childhood[17]. Progressive crouch gait often develops rapidly around the time of the pubertal growth spurt[9]. Proposed explanations are the inherent lower limb weakness associated with spastic diplegic cerebral palsy, the development of an unfavorable body mass-to-strength ratio, and the development of musculoskeletal deformities, collectively referred to as lever arm deformities[9]. The antigravity support muscles must resist the external moments imposed by gravity by generating internal moments acting on the hip, knee, and ankle joint centers. If the femora or tibiae are malaligned and the hip joint or midfoot is unstable, the moment-generating capability of the muscle-tendon units may be diminished, contributing to the crouch position[18]. The deformities (termed lever arm deformities) that are frequently seen in adolescents with spastic diplegia are excessive femoral anteversion, hip subluxation, patella alta, excessive external tibial torsion, and pes valgus[9,19,20].

Once the crouch gait reaches a certain level of severity in the child, the degree of knee flexion and associated symptoms may progress rapidly because of high stresses at the knee and failure of the knee extensor mechanism[6]. Knee pain[16], patella alta, and fragmentation or fracture of the inferior pole of the patella all have been documented in this clinical setting[6,21,22]. Standing with >30° of knee flexion increases the forces acting on the quadriceps, patella, and proximal part of the tibia and requires the quadriceps muscle to work at >50% of its maximum moment-generating capacity in order to stabilize the knee joint[23]. Progressive failure of the knee extensor mechanism is associated with gait deterioration, increased dependence on walkers or crutches, and the need for wheelchair use in the community.

Given that the cause of crouch gait is usually multifactorial and difficult to characterize precisely, treatment is controversial[24]. Options include muscle-strengthening[16,25], external support with orthoses[9], and orthopaedic operations to correct fixed musculoskeletal deformities at single or multiple levels[9]. The choice of orthopaedic procedures may be based on clinical evaluation alone, but instrumented gait analysis is increasingly recommended to aid decision-making. There is also an increasing trend to correct as many musculoskeletal deformities as possible in one operative session, variously described as multilevel surgery, multiple lower extremity procedures, or single-event multilevel surgery[9,26-30]. The evidence base for the effectiveness of orthopaedic surgery to correct crouch gait in patients with spastic diplegia is poor. A number of single case reports[9] and small case series that include many different gait patterns[26-30] have been published, but no cohort studies with adequate follow-up and no clinical trials have been reported, to our knowledge. In addi-

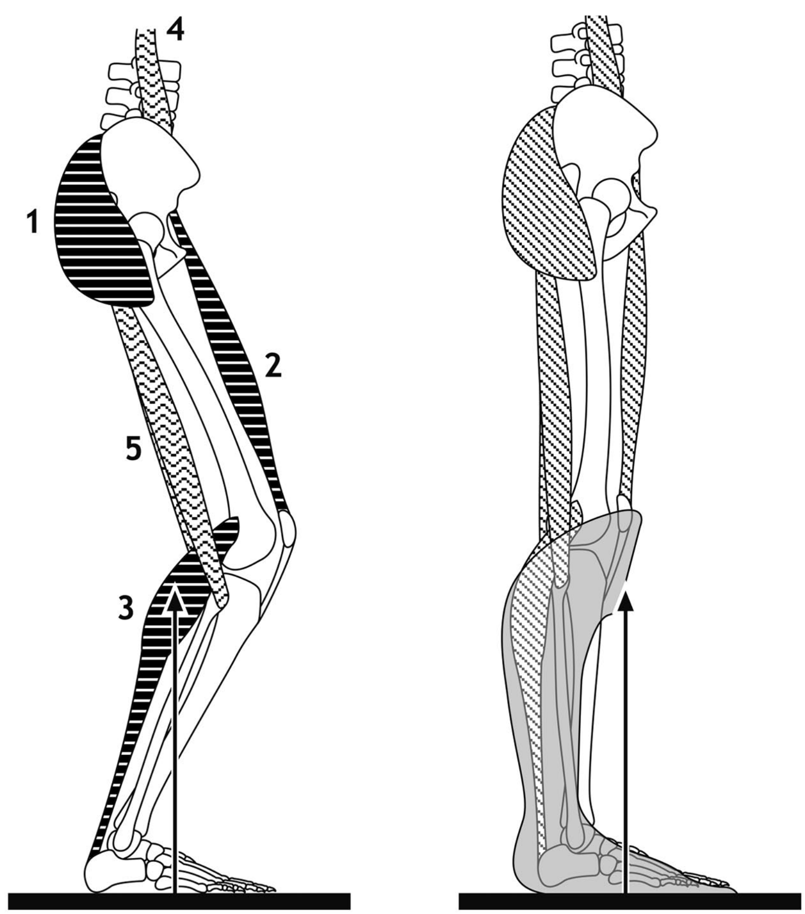

Fig. 1

Crouch gait is characterized by excessive ankle dorsiflexion, excessive knee flexion, increased hip flexion, and variable pelvic position (left). The ground-reaction force (shown as the vertical arrow) is directed posterior to the center of the knee joint and anterior to the hip joint. The three main muscle groups that contribute to the total body extensor moment are (1) the hip extensors, (2) the knee extensors, and (3) the ankle plantar flexors. In severe crouch gait, these muscles are weak and may be excessively long. Habitual standing and walking in flexion, combined with spasticity, may result in contractures of the iliopsoas (4) and the hamstrings (5). The principles for the correction of crouch gait may include lengthening of contracted muscle-tendon units (4 and 5) and support of long and weak muscle-tendon units (1, 2, and 3) in an extended position using a ground-reaction ankle-foot orthosis with the ground-reaction force (vertical arrow) now directed in front of the center of the knee joint (right).

tion, inconsistent definitions of the term crouch gait[1-6,8,17,25,31-36] and the failure to define gait patterns quantitatively further weakens the evidence base used to address this issue.

To our knowledge, this is the first study that documents the intermediate-term outcome of multilevel orthopaedic surgery combined with the use of orthoses and a rehabilitation program for the treatment of severe crouch gait in patients with spastic diplegic cerebral palsy. The key features of this cohort study were the utilization of a precise definition for severe crouch gait and the application of a balanced raft of objective outcome measures at one and five years after surgery. The purposes of the present study were to evaluate the functional and technical outcomes of single-event multilevel surgery on severe crouch gait at one year after surgery and to see if benefits observed at one year postoperatively were maintained at five years.

Materials and Methods

Subjects

This retrospective cohort study was conducted in a children's tertiary care hospital between 1995 and 2004. The granting of approval for clinical audit of these data complied with the ethical requirements of the Ethics in Human Research Committee at our institution. All data were gathered prospectively in accordance with established gait laboratory protocols, but the identification of the cohort and analysis of the data were retrospective.

The subjects were a consecutive sample of patients, ranging from four to eighteen years old, who had spastic diplegic cerebral palsy and walked with a severe crouch gait, either independently or with the use of assistive devices (walkers, crutches, or walking sticks). All subjects were classified as level II or III according to the Gross Motor Function Classification System with use of the nearest age-appropriate descriptor[37]. Severe crouch gait was defined according to sagittal plane kinematic data, collected during barefoot walking, as ankle dorsiflexion of >15°, knee flexion of >30°[38], and hip extension of <3° during late stance phase. These parameters were all outside the normal range for our laboratory and fulfilled the knee flexion definition for severe crouch gait proposed by Sutherland and Davids[38]. In this cohort, severe crouch gait was invariably symptomatic and in most patients was documented to be progressive on the basis of serial examination and gait laboratory assessment.

Exclusion criteria were previous selective dorsal rhizotomy, use of an intrathecal Baclofen pump, or Botulinum toxin A injections within the preceding twelve months.

Intervention: Multilevel Orthopaedic Surgery, Ground-Reaction Ankle-Foot-Orthoses, and Rehabilitation

All patients were offered a combined surgical, orthotic, and rehabilitation program for the treatment of severe crouch gait. The surgical recommendations were determined with use of a comprehensive gait laboratory assessment by the two treating orthopaedic surgeons (H.K.G. and G.R.N.) and a physiotherapist (J.M.R.). The soft-tissue surgical procedures were intramuscular lengthening of the psoas muscle at the pelvic brim[39], percutaneous lengthening of the adductor longus, fractional lengthening of the medial and/or lateral hamstrings[40], and transfer of the rectus femoris to the semitendinosus[41]. The osseous procedures for the correction of lever arm deformities were external rotation osteotomy of the femur[42-45], internal rotation osteotomy of the distal parts of the tibia and fibula[19,20,46], calcaneal lengthening[19,47], and subtalar fusion[19,48]. Stable internal fixation was used routinely to permit early weight-bearing. A first-generation cephalosporin was given at the time of induction of anesthesia and was continued for twenty-four hours postoperatively. In all patients, analgesia was administered by means of continuous epidural infusion of bupivacaine and fentanyl for three to five days after surgery.

After foot and ankle surgery, postoperative immobilization was achieved with use of padded, split, below-the-knee plaster casts, with knee immobilizers being used to maintain knee extension. Physical therapy began with the epidural infusion in place and consisted of passive and active joint movement. Plaster casts were removed to permit wound inspection and radiographs of the osteotomy sites at three weeks after surgery, followed by the application of fiberglass below-the-knee casts. If there was satisfactory healing at the wound and osteotomy sites, weight-bearing was encouraged at that time. The casts were removed six weeks after surgery and proximal rear-entry, ground-reaction, ankle-foot orthoses were fitted. Radiographs of all osteotomy sites were made, and full weight-bearing was encouraged when healing at the osteotomy sites was demonstrated. Knee immobilizers were used continuously for the first six weeks and at night only for another six months to reduce the risk of recurrent knee contractures. The knee immobilizers were removed for therapy and were replaced at the end of therapy sessions.

All patients were managed with an individually tailored, community-based rehabilitation program that initially incorporated three or four sessions of physical therapy and one or two sessions of hydrotherapy per week, starting six weeks after surgery (at the time of cast removal) and continuing for twelve weeks. The children gradually were advanced from a passive to an assisted range-of-motion protocol and finally to a resistance program. The frequency of physical therapy sessions was reduced to one per week after six months, and the subjects were encouraged to participate also in physical recreational activities such as bicycle riding, swimming, horseback riding, and/or a program at a local gymnasium. Formal physical therapy stopped after one to two years, although some subjects chose to continue with unstructured activities such as swimming, bicycle riding, or weight-training.

All patients were reviewed in the gait laboratory at three, six, and nine months after surgery with use of a combination of standardized clinical examination and two-dimensional video recording of gait. The purpose was to allow close monitoring of the rehabilitation process and to make appropriate changes to orthoses, assistive devices, and the physical therapy program to optimize each subject's rehabilitation process. The

TABLE I Demographic Characteristics, Previous Surgery, and Surgical Recommendations for Each Subject

Case	Gender	Gross Motor Function Classification System	Previous Surgery	Age at Single-Event Multilevel Surgery (*yr*)	Psoas Over Brim	Adductor Longus Lengthening
1	M	III	Baker calf lengthening	10.3		
2	M	III	Tendo-achilles lengthening × 2	12.8	Bilateral	Bilateral
3	M	III	None	13.3	Bilateral	
4	F	III	Baker calf lengthening	14.2	Bilateral	Bilateral
5	M	III	Tendo-achilles lengthening	10.9		
6	M	III	Tendo-achilles lengthening	10.7		
7	M	II	Tendo-achilles lengthening	12.4		
8	F	III	Tendo-achilles lengthening	11.4		
9	F	II	Botox injection, calves	7.9	Bilateral	
10	M	II	Tendo-achilles lengthening	16.2		
Mean (range)				12.0 (7.9 to 16.2)		
Total no. of procedures					8	4

ankle-foot orthoses were prescribed to be worn during all weight-bearing activities for the first twelve months after surgery, at which time the need for ongoing orthotic support was assessed with use of gait analysis. Only one subject continued to use the orthoses after twelve months. Between twelve and twenty-four months after surgery, eight patients had removal of implants and three had surgery for the treatment of ingrown toenails, but no additional surgery was performed for the treatment of contractures. All patients had a comprehensive evaluation in the gait laboratory at one and five years after surgery.

Outcome Measures: Physical Examination, Pain Scale, Knee Radiographs, Gait Analysis, and Functional Scales

A standardized physical examination was conducted as part of the preoperative gait analysis and at the twelve-month and five-year assessments. The findings were recorded on a gait laboratory data sheet and included measurements of joint contractures, muscle strength, spasticity, selective motor control, and osseous rotational abnormality. The parameters directly relevant to the present study included measurement of fixed flexion deformity at the hip and knee, measurement of hamstring contracture as demonstrated by the popliteal angle, and measurement of gastrocnemius and soleus length with use of the Silfverskiold test. The test protocol and reliability have been reported elsewhere[49].

Because of the high prevalence of knee pain in this population, all patients were evaluated on the basis of a pain score according to a 9-point Likert scale as well as anteroposterior and lateral radiographs of both knees before surgery and at the twelve-month and five-year assessments. The Insall-Salvati ratio[50-52] was measured on a lateral radiograph of the knee, made with the knee in 20° to 40° of flexion. The contrast and brightness were adjusted before printing to enhance the definition of the soft tissues, with particular reference to the patellar tendon and the cartilaginous portion of the tibial tuberosity. Patellar length was measured from the proximal pole to the distal pole, irrespective of patellar fractures or avulsions. Patellar tendon length was measured from the inferior pole of the patella to the maximum convexity of the tibial tuberosity. The Insall-Salvati ratio was calculated by dividing the length of the patellar tendon by the patellar length. Patella alta was considered to be present when the ratio was greater than the normal range for the subject's age according to previously published reference data[52]. In addition, the presence of avulsion injury to the inferior pole of the patella or the presence of patellar fractures was noted, including evidence of healing.

A Vicon 370 System (Oxford Metrics, Oxford, England) with five infrared cameras was used for the three-dimensional gait analyses. The walkway incorporated two force-plates (Advanced Mechanical Technology, Watertown, Massachusetts). Marker placement was performed as described in the Vicon Clinical Manager manual with the Knee Alignment Device used during the static trial[53]. The subject was asked to walk barefoot using the usual gait pattern, at a self-selected speed, along a 10-m walkway in the gait laboratory. If the subject usually used an assistive device in order to walk, then this device was used during the walking trials. All data were

TABLE I ***(continued)***

Single-Event Multilevel Surgery						
Medial Hamstrings Fractional Lengthening	Lateral Hamstrings Fractional Lengthening	Rectus Femoris Transfer to Semitendinosus	Femoral Derotation Osteotomy	Tibial Derotation Osteotomy	Foot Surgery	Number of Surgical Procedures
Bilateral		Bilateral		Unilateral		7
Bilateral			Unilateral distal			7
Bilateral					Bilateral os calcis lengthening	6
Bilateral			Unilateral distal			5
Bilateral	Bilateral		Unilateral distal	Unilateral	Unilateral subtalar joint fusion	7
Bilateral	Bilateral		Bilateral distal		Bilateral subtalar joint fusion	8
Bilateral	Bilateral	Bilateral	Bilateral distal			8
Bilateral	Bilateral			Bilateral		8
Bilateral	Bilateral	Bilateral				6
Bilateral	Bilateral	Bilateral	Bilateral proximal			8
						7 (5 to 8)
20	12	8	9	4	5	

processed with use of PIG (Plug-in Gait) software. Once processed, three to six trials were then scrutinized, from which a typical representative trial for the left and right sides was chosen for analysis. Selected temporospatial, kinematic, and kinetic parameters were analyzed for the purposes of this study, including normalized velocity[54-57], mean pelvic tilt, maximum hip extension in stance, knee extension at initial contact, maximum knee extension in stance, knee flexor moment in stance, dorsiflexion at initial contact, maximum dorsiflexion in stance, and maximum ankle power generation prior to toe-off. Gait data from the study cohort were compared with those for a subgroup of fourteen children without abnormality who were comparable to the study cohort in terms of demographic characteristics. A senior physiotherapist (J.M.R.) completed all data collection except for the radiographic data and pain scores, which were collected by a surgeon (H.K.G.).

We used three valid and reliable instruments to measure functional mobility: the Gross Motor Function Classification System[37], the Functional Mobility Scale[58], and the Functional Assessment Questionnaire[59]. The Gross Motor Function Classification System is best considered as a tool to stratify patients with cerebral palsy according to broad functional levels. It is considered to be stable over time[60], is not responsive to intervention, and is not usually used as an outcome measure. In contrast, the Functional Mobility Scale and the Functional Assessment Questionnaire are sensitive to change in the cerebral palsy population and are both used as outcome measures after orthopaedic surgery.

Statistical Analysis

To compare mean outcomes for the severe crouch group at baseline, one year, and five years, linear regression models with robust standard errors[61] to allow for the repeated measurements from individual patients over time were used[62]. Data from both limbs of each of the ten subjects were included in the statistical analysis as the robust standard errors are inflated to take into account any excess correlation in measurements from the two limbs from the same subject[62]. P values and 95% confidence intervals of the estimated difference in means were obtained. Parameters that were analyzed with use of this method were temporospatial parameters, physical examination findings, and kinematic and kinetic variables. Comparisons of mobility status over time were described by odds ratios calculated from ordered logistic regression with robust standard errors. Statistical analysis was performed with use of the Stata 7 software package[61] and was overseen by a senior biomedical statistician (R.W.). The level of significance was set at $p < 0.05$.

Results

Subjects

Ten subjects fulfilled eligibility criteria within the ten-year study period. Four additional patients with severe crouch gait were unable to attend the gait laboratory to complete all assessments within the follow-up period or had not been followed for at least five years postoperatively. The study group included seven male and three female patients with a mean age of 12.0 years (range, 7.9 to 16.2 years) at the time of surgery. Eight of the ten subjects had had previous surgery to lengthen the gastrocnemius-soleus, including six who had had bilateral lengthening of the Achilles tendon and two who had had a bilateral Baker procedure to lengthen the gastrocnemius aponeurosis and soleus fascia. One subject had received repeated injections of Botulinum toxin A (Table I).

The surgical procedures for each subject are documented in Table I. There were eighteen osseous procedures and fifty-two soft-tissue procedures. There were no delayed unions, malunions, or deep infections. Ten surgical complications occurred in four patients, including superficial wound infection at the sites of four incisions and partial separation at the sites of two hamstring incisions. All resolved with a combination of oral antibiotics and wound care. Two patients with knee flexion deformities of 22° and 28° had paresthesias in the distribution of the common peroneal nerve, without motor signs. Paresthetic pain was treated by removing the knee immobilizers, reducing the degree of knee extension, and gradually extending the affected knee over two to three weeks. One patient had persistent foot pain after calcaneal lengthening that had features of a type-II complex regional pain syndrome. This patient was managed with continuation of weight-bearing and administration of oral gabapentin for six weeks. These complications resolved without operative intervention but caused some delay in full weight-bearing and mobilization.

The mean increase in height was 7 cm at twelve months and 20 cm at five years. The mean increase in weight was 7 kg at twelve months and 15 kg at five years.

The fourteen subjects without abnormality who comprised a comparison group included five boys and nine girls with a mean age of 11.9 years (range, 7.5 to 14.9 years).

Clinical Examination

Hip flexion contracture as assessed with the Thomas test decreased from a mean of 21° preoperatively to a mean of 13° at twelve months postoperatively and 9° at five years postoperatively (Table II). Fixed flexion deformity at the knee improved from a mean of 17° preoperatively to a mean of 6° at one and five years postoperatively. There was a corresponding decrease in the popliteal angle. Passive ankle dorsiflexion with the knee flexed decreased from a mean of 23° preoperatively to a mean of 16° at five years postoperatively. Passive ankle dorsiflexion with the knee extended decreased from a mean of 3° at baseline to 1° at five years, but this change was not significant.

Temporal-Spatial Data

Normalized speed did not change and remained decreased compared with normal data (Table II).

Kinematic Data

Kinematic data were collected at baseline, twelve months, and five years for all subjects (Fig. 2). Mean pelvic tilt increased from 14° to 28° at twelve months and recovered slightly to 24° at five years after surgery (Table II). Two subjects had posterior pelvic tilt at baseline but had anterior pelvic tilt after surgery. Although there was a decrease in hip flexion contracture, there

TABLE II Selected Physical Examination, Temporal-Spatial, Kinematic, and Kinetic Data Before Surgery and One and Five Years After Surgery, Compared with Normal Values*

	Surgical Status			
Parameter	Preop.	1 Year Postop.	5 Years Postop.	Normal
Fixed flexion deformity, hip (*deg*)	21 ± 11	13 ± 8†	9 ± 5‡	0 ± 0
Fixed flexion deformity, knee (*deg*)	17 ± 8	6 ± 7†	6 ± 7‡	1 ± 2
Popliteal angle (*deg*)	70 ± 16	56 ± 15†	55 ± 13	39 ± 12
Ankle dorsiflexion (knee flexion) (*deg*)	23 ± 11	22 ± 11	16 ± 13	23 ± 7
Ankle dorsiflexion (knee extension) (*deg*)	3 ± 6	2 ± 8	1 ± 7	5 ± 4
Normalized velocity	0.02 ± 0.006	0.02 ± 0.008	0.02 ± 0.008	0.03 ± 0.004
Mean pelvic tilt (*deg*)	14 ± 12	28 ± 9†	24 ± 9‡	13 ± 4
Maximum hip extension, stance phase (*deg*)	17 ± 16	16 ± 12	14 ± 11	–8 ± 5
Knee extension, initial contact (*deg*)	52 ± 7	25 ± 9†	26 ± 10‡	7 ± 5
Maximum knee extension, stance phase (*deg*)	44 ± 9	13 ± 9†	17 ± 11‡	5 ± 4
Maximum knee flexor moment *(N m/kg)*	0.3 ± 0.2	–0.4 ± 0.3†	–0.2 ± 0.2‡	–0.2 ± 0.2
Ankle dorsiflexion, initial contact (*deg*)	12 ± 10	3 ± 9†	0 ± 6‡	–1 ± 3
Maximum ankle dorsiflexion, stance phase (*deg*)	29 ± 9	17 ± 8†	15 ± 6‡	15 ± 4
Maximum ankle power generation, late stance phase *(W/kg)*	1.2 ± 0.6	1.4 ± 0.6	1.8 ± 0.4‡	4.2 ± 0.8

*The values are given as the mean and the standard deviation. †The value at one year postoperatively was significantly different from the preoperative value ($p < 0.05$). ‡The value at five years postoperatively was significantly different from the preoperative value ($p < 0.05$).

was not a significant improvement in hip extension during stance phase. Knee extension at initial contact and maximum extension in stance phase improved significantly, with a slight deterioration at five years compared with twelve months (95% confidence interval, 0.3° to 7.4°) ($p = 0.03$) (Table II). At the ankle level, excessive dorsiflexion at initial contact and maximum dorsiflexion during stance phase decreased after surgery.

The mean baseline hip rotation during stance phase for the subjects with severe crouch gait was 10° ± 11° of internal rotation, which was significantly increased compared with the value for normally developing subjects, who had a mean of 2° ± 6° of internal rotation ($p < 0.003$). At one year postoperatively, the value for the subjects with severe crouch gait improved to 2° ± 10° of external rotation, indicating some overcorrection at the site of the femoral derotation osteotomies. At five years postoperatively, the value for these subjects was 6° ± 10° of internal rotation; this was still an improvement compared with the baseline value, but the difference was not significant.

Kinetic Data

Kinetic data could only be collected for seven subjects at baseline, for four subjects at one year, and for five subjects at five years. The excessive knee flexor moment decreased after surgery (Table II). There was a 50% increase in ankle power generation at toe-off at five years, but this was still only approximately 40% of the normal value (Table II).

Function

Improvements were seen in all three mobility scales, including the Gross Motor Function Classification System, which is not considered to be responsive to change (Fig. 3). There was no change in the Gross Motor Function Classification System at one year after surgery, but at five years two subjects had improved by one level, from level III to level II, meaning that they no longer required assistive devices to walk in the community. Improvements in the three subscales of the Functional Mobility Scale are detailed in Figure 3. Compared with the baseline value, the odds were four times greater (95% con-

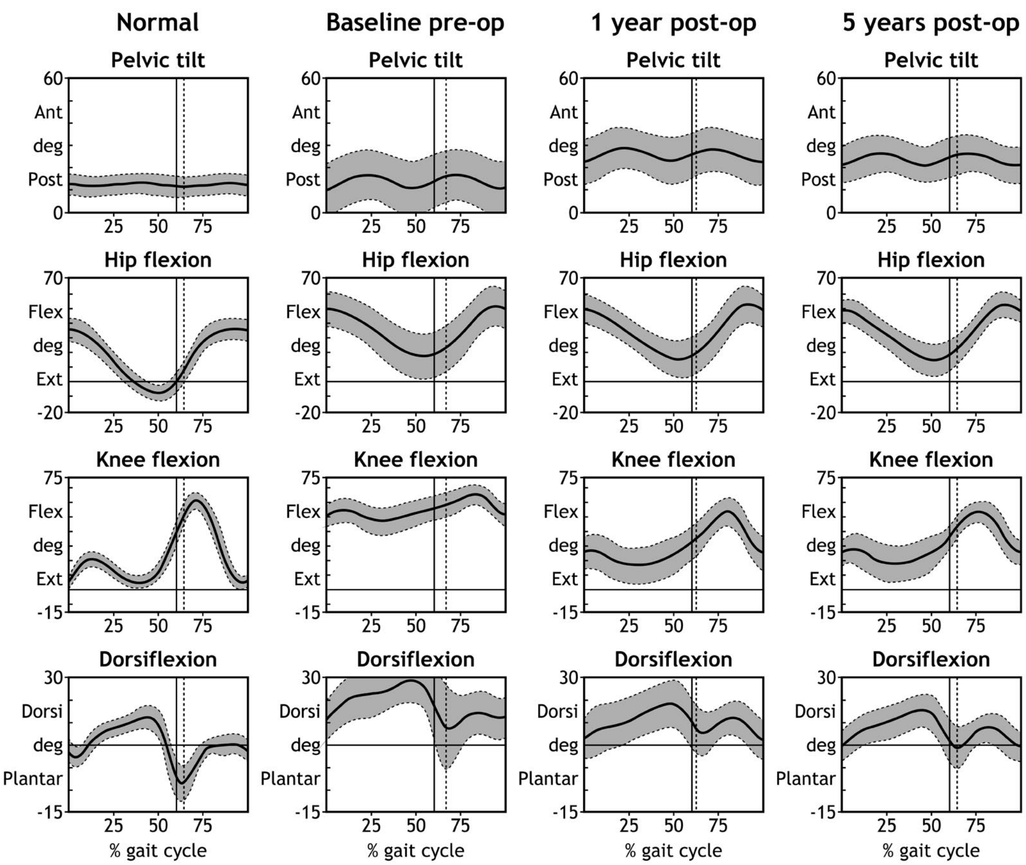

Fig. 2

Sagittal plane kinematic graphs for normal subjects and the subjects with severe crouch gait at baseline and at one and five years after surgery. The vertical axis of each graph is angular displacement in degrees, and the horizontal axis of each graph is the phase of the gait cycle, with the vertical lines indicating "toe-off." The thick black line indicates the mean kinematic value for the severe crouch cohort, with the dotted lines and shaded areas corresponding to one standard deviation about the mean. From top to bottom, the graphs show sagittal plane kinematics of pelvic tilt, hip flexion, knee flexion, and ankle dorsiflexion.

TABLE III Maximum Knee Extension in Stance Phase Prior to Single Event Multilevel Surgery, Knee Pain, Insall-Salvati Ratio, and Knee Radiographic Findings Before and After Surgery ➤

	Preop. Maximum Knee Extension *(deg)*		Knee Pain Score *(points)*		
Case	Right	Left	Preop.	1 Yr Postop.	5 Yr Postop.
1	56	34	2	0	1
2	41	49	8	0	2
3	41	37	6	0	1
4	54	49	3	2	3
5	43	44	4	0	0
6	58	60	6	0	1
7	35	43	4	0	0
8	41	46	5	1	—
9	46	46	2	0	0
10	31	31	4	0	1
Mean and standard deviation‡	45 ± 9	44 ± 8	4.4	0.3	1
P value§			NA	<0.001	<0.001
Estimated difference in means (and 95% confidence interval)				–4.1 (–5.7 to –2.5)	–3.4 (–4.8 to –2.0)

*Insall-Salvati ratio above the mean according to age. †Insall-Salvati ratio more than two standard deviations above the mean according to age. ‡Only the mean value is given for the knee pain score. §NA = not applicable.

fidence interval, 1.2 to 12.0 times greater) that a subject would have a rating of 5 or 6 (rather than 4 or less) at five years on the 500-m scale. At five years after surgery, more patients were walking independently, with reduced dependence on wheelchairs, for distances of >500m. Median Functional Assessment Questionnaire scores increased at twelve months and five years after surgery. One year postoperatively, the number of subjects decreased at levels 5, 6, and 7 and increased at level 8. Compared with baseline, this represented threefold greater odds (95% confidence interval, 1.0 to 7.9-fold greater odds) of a rating of 8 or higher rather than 7 or lower (Fig. 3).

Knee Pain and Radiology

All patellar avulsions and fractures were noted to have healed on follow-up radiographs (Figs. 4-A and 4-B), with the exception of two in one patient. One subject had stable, pain-free fibrous union of a bilateral patellar fracture. There was a large reduction in knee pain scores (95% confidence interval, –4.8 to –2.0) ($p < 0.001$) (Table III).

In nine patients the Insall-Salvati ratio was increased above the mean for age-matched subjects, and in seven patients it was more than two standard deviations above the mean for age-matched subjects. The prevalence of patella alta was very high before surgery but remained unchanged after surgery, with no change in the Insall-Salvati ratio (95% confidence interval, –0.018 to 0.026) ($p = 0.7$) (Table III).

Discussion

Crouch gait is often used to describe any gait pattern associated with spastic diplegia in which there is excessive knee flexion during stance phase[1-6,8,17,25,31-36]. However, there are at least three flexed-knee gait patterns in spastic diplegia that are associated with three different ankle alignments: calcaneus, plantigrade, and equinus[63]. These three flexed-knee subgroups are biomechanically and clinically distinct and may require different management strategies[63,64]. Sutherland and Davids[38] were the first to define crouch gait quantitatively (>30° of knee flexion throughout stance) and to specify excessive ankle dorsiflexion. In the present study, we used the qualitative description proposed by Frost[2] for crouch gait, which is calcaneus at the ankle with excessive flexion at the knee and hip (Fig. 1), and developed a quantitative definition for severe crouch gait on the basis of sagittal plane kinematic criteria. These are an extension of the criteria proposed by Sutherland and Davids[38]. This definition is proposed because crouch gait of this severity is invariably symptomatic, progressive, and may not be sustainable[17]. The majority of patients have knee pain and radiographic evidence of failure of the knee extensor mechanism (Table III, Figs. 4-A and 4-B).

TABLE III (continued)

Insall-Salvati Ratio						
Preop.		Postop.		Normal Values According to Age[52]	Radiographic Findings in Knee	
Right	Left	Right	Left		Preop.	Postop.
1.69*	1.63*	1.74†	1.66*	1.0 to 1.7	Patella alta	Patella alta
1.07	1.10	1.05	1.11	0.9 to 1.3	Fractures	Fibrous union
1.64†	1.56†	1.56†	1.57†	0.8 to 1.3	Patella alta, fractures	Patella alta, fractures healed
1.45†	1.40†	1.49†	1.41†	0.8 to 1.3	Patella alta	Patella alta
1.84†	2.00†	1.91†	2.00†	1.1 to 1.5	Patella alta, avulsions	Patella alta, avulsions healed
1.44*	1.53†	1.45*	1.48*	1.1 to 1.5	Patella alta, fractures	Patella alta, fractures healed
1.73*	1.98†	1.76†	2.00†	0.9 to 1.3	Patella alta, fractures	Patella alta, fractures healed
1.20*	1.24*	1.25*	1.23*	0.9 to 1.3	Patella alta	Patella alta
1.35*	1.54*	1.40*	1.49*	1.0 to 1.7	Patella alta	Patella alta
1.55†	1.57†	1.51†	1.52†	0.8 to 1.2	Patella alta, avulsions	Patella alta, avulsions healed
1.5 ± 0.3		1.5 ± 0.3				
NA		0.7				
		0.004 (–0.018 to 0.026)				

In the present study, lengthening of the psoas at the pelvic brim and lengthening of the hamstrings were only partially successful for the correction of hip and knee-flexion contracture. Some patients had a minor hip flexion contracture and on kinematic evaluation had a posterior pelvic tilt. Despite these findings, the pelvis became anteriorly tilted after hamstring lengthening. According to contemporary criteria[4,32,33], we performed too few psoas lengthenings and too many hamstring procedures. This resulted in good improvements at the knee level but much smaller improvements at the hip level and an increase in anterior pelvic tilt as the femur became more vertically aligned.

A substantial proportion of hip extensor torque comes from the proximal hamstrings[65]. Distal hamstring lengthening resulted in improvements at the knee but increased anterior pelvic tilt, a finding noted in previous studies[66-70]. Hamstring lengthening is not the only method available for the correction of a knee flexion deformity and may not be the most efficient method for correcting a knee flexion deformity in patients with a crouch gait associated with cerebral palsy. Alternatives include transfer of one or more of the hamstring tendons to the femur[71-76] or extension osteotomy of the distal part of the femur[9,77-80]. However, there have been few reports to support the use of these alternative procedures.

We relied on long-term use of ground-reaction ankle-foot orthoses to support an extension posture after surgery in the hope that the excessively long quadriceps and soleus would adaptively shorten as the femur and tibia continued to grow[9]. This may have happened to a useful degree in some patients. Excessive ankle dorsiflexion decreased, and calf power generation increased. A decrease in quadriceps lag was noted but was not quantified. However, there was kinematic evidence of much improved knee extension. We think that the shortening of the extensor mechanism may have occurred in the quadriceps muscle because the patellar tendon length, as determined with the Insall-Salvati ratio, was unchanged after surgery. Acute shortening of the extensor mechanism through patellar tendon-shortening surgery would be an alternative to slow, adaptive shortening, which is dependent on compliance with the use of ankle-foot orthoses. Patellar tendon shortening[9,81-87] combined with supracondylar extension osteotomy of the femur has been used more recently[9,79]. No long-term results of these procedures have been reported[79].

The most important gain from the treatment method used in our patients was increased function and independence in the community. The Gross Motor Function Classification System is considered to be stable over time, yet two patients improved from level III to level II, meaning that they no longer re-

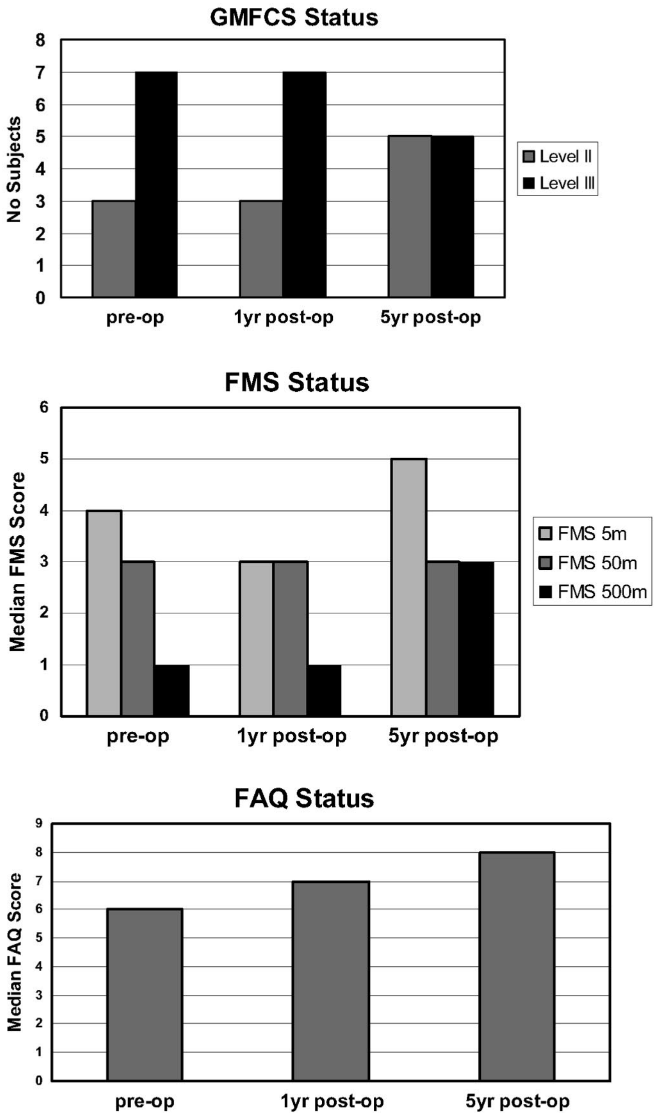

Fig. 3

Graphs illustrating changes in the mobility scales, including the Gross Motor Function Classification System (GMFCS), Functional Mobility Scale (FMS), and Functional Assessment Questionnaire (FAQ), from preoperatively to one year and five years postoperatively.

quired the use of assistive devices in the community. The Functional Mobility Scale over 500m confirmed similar improvements. Prior to surgery, the majority of the severe crouch subjects were rated as "limited community ambulators" on the Functional Assessment Questionnaire[59], but by five years the majority were rated as "community ambulators" (Fig. 3).

The present study had a number of limitations, including a small sample size, retrospective data analysis, lack of controls, and variable surgical prescription. Despite our precise definition of severe crouch gait, there was still considerable heterogeneity within the study cohort and variability in outcome. The natural history of gait in patients with cerebral palsy is deterioration of walking ability with time[10-12,88,89], particularly if there is a crouch gait. Five years after surgery, the majority of the patients in our study had gone through puberty and had reached or were close to skeletal maturity, with improved gait and function.

Issues for further investigation include increased efforts to prevent progressive crouch gait by the avoidance of interventions that weaken the gastrocnemius-soleus, attempts to delay progression with use of orthotic support, and a search for more efficient surgical management.

In conclusion, a combined program of multilevel orthopaedic surgery, orthotic support, and rehabilitation for children and adolescents with spastic diplegic cerebral palsy and severe crouch gait resulted in relief of knee pain, increased extension during gait, and improved ability to function in the community. Improvements in dynamic knee, ankle, and hip function were accompanied by increased anterior pelvic tilt. The improvements that were noted at one year were largely maintained at five years.

Fig. 4-A

Fig. 4-B

Figs. 4-A and 4-B Case 2. **Fig. 4-A** Lateral radiograph of the knee, showing fracture separation of the patella at the time of surgery for severe crouch gait, which included distal hamstring lengthening and distal femoral derotation osteotomy with plate fixation. **Fig. 4-B** Five years after surgery, the distal femoral osteotomy site has united, the patellar fracture has healed with fibrous union, and patella alta persists.

Appendix

eA Additional information and illustrations of the Gross Motor Function Classification System (GMFCS) and the Functional Mobility Scale (FMS) are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

J.M. Rodda, PhD
H.K. Graham, MD, FRCS(Ed), FRACS
G.R. Nattrass, MD, FRCS(C), FRACS
R. Baker, PhD, CEng
Hugh Williamson Gait Laboratory, University of Melbourne, Royal Children's Hospital, Flemington Road, Parkville 3052, Victoria, Australia. E-mail address for H.K. Graham: kerr.graham@rch.org.au

M.P. Galea, PhD
School of Physiotherapy, University of Melbourne, Parkville 3010, Victoria, Australia

R. Wolfe, PhD
Department of Epidemiology and Preventive Medicine, Monash University, Commercial Road, Melbourne 3004, Victoria, Australia

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