Conversion of biarticular to monoarticular muscles as a component of multilevel surgery in spastic diplegia

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We treated 20 children (40 limbs) with diplegic cerebral palsy who could walk by multilevel soft tissue operative procedures including conversion of the biarticular semitendinosus and gastrocnemius to monoarticular muscles. The mean age at surgery was 11.5 years (5.6 to 17.0). All patients underwent clinical and radiological examination and three-dimensional instrumented gait analysis before and at a mean of 3.1 years (2.0 to 4.5) after surgery.

The passive range of movement at the ankle, knee and hip showed improvement at follow-up. Kinematic parameters indicated a reduced pelvic range of movement and improvement of extension of the knee in single stance after operation ($p < 0.0001$). However, post-operative back-kneeing was detected in five of the 40 limbs. The kinetic studies showed that the power of the hamstrings and plantar flexors of the ankle was maintained while the maximum knee extensor moment during stance was reduced. The elimination of knee flexor activity of semitendinosus and gastrocnemius combined with transfer of distal rectus femoris led to an improvement in gait as confirmed by gait analysis.

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Patients with cerebral palsy have more difficulty in controlling biarticular than monoarticular muscles because the former demand a high level of motor control.¹ The biarticular muscles of the lower limbs work under normal conditions as activatable slings.²⁻³ This reduces the overall energy consumption of walking^{4,5} by transferring energy from one

joint to the other. The co-ordinated linked movement of the joints which they span⁶ requires a high level of motor control as they change their contraction status which may be eccentric, concentric or isometric.^{7,8}

The function of the biarticular muscles in cerebral palsy is characterised by their decreased ability to work as energy transfer straps and to adapt with fine control changes to the demands of eccentric or concentric contraction in quick movements. Gage et al¹ stated that the abnormal function of biarticular muscles can be simplified or modified by surgery.

Operations on the biarticular muscles of patients with cerebral palsy who can walk may be divided into two groups. The first includes aponeurotic or z-plasty lengthenings and muscle transfers,^{9,10} which do not change the biarticular character of the muscle. In the second the biarticular muscles are converted to monoarticular muscles.¹¹⁻¹³ Operative elongation of a muscle can lead to structural changes in the muscle or tendon¹⁴ and to post-operative muscle weakness.¹⁵ This can be a disadvantage in the long term because the muscles are already weakened by the cerebral palsy.¹⁶

Silfverskiöld¹¹ converted the gastrocnemius, hamstrings and rectus femoris into monoarticular muscles and later Eggers¹² transplanted the medial and lateral hamstring tendons to the femoral condyles. Thom¹³ and Döderlein¹⁷ reported a modification of the methods of Eggers and Silfverskiöld. These methods, however, which involved both the medial and lateral hamstrings, led to insufficiency of the hamstrings and did not address the concomitant extensor spasticity of the knee.¹⁸ Our aim was to evaluate the effects of converting specific biarticular to monoarticular muscles in children with diplegic cerebral palsy. The changes in the children's gait were assessed by gait analysis.

Patients and Methods

Between March 1996 and July 2001 we carried out a prospective study on 20 patients (40 limbs) with cerebral palsy. Approval had been given by the local Ethics Committee. The inclusion criteria were a spastic diplegic pattern of cerebral palsy, walking with or without aids, the ability to perceive instructions and an age between five and 17 years. The exclusion criteria were an athetotic pattern of cerebral palsy

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Table I. Details of the patients including operations

Case	Age at op (yrs)	Gender	Previous lower limb surgery*	Walking aids		Surgery†
				Pre-op	Post-op	
1	7.2	M	No	No	No	B pRFrel, B dRFtrG, B STtrDF, B GAtPT, R SPOTT
2	14.5	M	B TAL at 4 yrs	No	No	B pRFrel, L AddL, B dRFtrG, B STtrDF, B SMimL, B GAtPT, R Bam, L Steind
3	11.0	F	No	No	No	B PsOTB, B AddL, B dRFtrG, B STtrDF, B SMimL, B BFimL, B GAtPT
4	16.5	F	No	No	Crutches	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B BFimL, B GAtPT
5	9.3	F	No	No	No	B dRFtrG, B STtrDF, B GAtPT, R Baum, B SPOTT
6	13.4	M	No	No	No	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B GAtPT, B FIDO
7	13.5	M	B Add ten at 3 yrs	No	No	B PsOTB, B dRFtrG, B STtrDF, B SMimL, B BFimL, B GAtPT, B FIDO
8	10.9	M	No	No	No	B pRFrel, B dRFtrG, B STtrDF, B GAtPT, R FIDO, R TSMDO, R SPOTT
9	14.6	M	B TAL at 9 yrs	Crutches	Crutches	BpRFrel, B dRFtrIT, B STtrDF, B SMzL, B GAtPT
10	8.6	M	No	No	No	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B GAtPT, B StrOp
11	10.0	F	No	No	No	B pRFrel, B dRFtrG, B STtrDF, B GAtPT, B Baum, B FIDO
12	11.0	M	B Add ten, B Vulpius op at 9 yrs	No	No	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B BfimL, B GAtPT
13	17.0	M	No	No	No	B PsOTB, B AddL, B dRFtrG, B STtrDF, B SMimL, B GAtPT, R FIDO, R TSMDO, L Evans
14	10.0	M	No	Posterior walker	No	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B GAtPT, B Baum
15	13.5	F	No	No	No	L pRFrel, B dRFtrG, B STtrDF, B GAtPT, L Baum, R StrOp, R FIDO, R TPOimL, R Steind, L EvansOp, L KramerOp, R FhIL
16	12.3	M	No	No	Crutches	B pRFrel, B dRFtrG, B STtrDF, B SMimL, B GAtPT, R Pemb.Op, B FIDO
17	11.0	M	No	No	No	B pRFrel, B PsOTB, R AddL, B dRFtrG, B STtrDF, B SMimL, B BFimL, B GAtPT, R Triple, R open hip reduction, R FIDO, L Evans, L dorsFlexL
18	7.4	F	No	Crutches	No	B pRFrel, B dRFtrG, B STtrDF, B GAtPT
19	15.7	M	B TAL at 6 years	No	No	L PsOTB, B dRFtrG, B STtrDF, B GAtPT
20	5.6	F	No	No	No	B dRFtrG, B STtrDF, B GAtPT, B Baum, L TPOimL, R Evans, L Grice

* B, bilaterally; TAL, tendo Achilles lengthening; Vulpius, Vulpius gastrocnemius lengthening; Add ten, adductor tenotomy

† AddL, adductor longus lengthening; BFimL, biceps femoris intramuscular lengthening; Baum, Baumann procedure; dorsFlexL, lengthening of the foot dorsiflexors; dRFtrG, distal rectus femoris transfer to gracilis; dRFtrIT, distal rectus femoris transfer to iliotibial band; Evans, Evans calcaneal lengthening osteotomy; FhIL, flexor hallucis longus lengthening; FIDO, femoral intertrochanteric derotational osteotomy; GAtPT, gastrocnemius transfer to proximal tibia; Grice, Grice subtalar fusion; KramerOp, Kramer procedure for Hallux valgus; Pemb. Op, Pemberton pelvic osteotomy; pRFrel, proximal femoris release; PsOTB, psoas lengthening over the brim; SMimL, semitendinosus intramuscular lengthening; SMzL, semimembranosus z-lengthening; SPOTT, split posterior tibial tendon transfer; Steind, Steindler procedure; STtrDF, semitendinosus transfer to distal femur; StrOp, Strayer procedure; TPOimL, tibialis posterior intramuscular lengthening; Triple, triple pelvic osteotomy; TSMDO, tibial supramalleolar derotational osteotomy

and orthopaedic surgery on a lower limb in the year before the study. There were 13 boys and seven girls. Their mean age at surgery was 11.5 years (5.6 to 17.0) Seventeen were independent walkers and three walked with an aid (Table I). **Pre-operative assessment.** Passive range of movement (ROM) and muscle strength (manual muscle testing, MRC scale 0 to 5) were assessed clinically by one of the authors (DM or LD). Clinical measurements, such as the Thomas test, the measurement of the popliteal angle and the Silfver-skiöld test were carried out pre- and post-operatively and additionally under anaesthesia just before surgery.

Radiological examination was used to detect any deformities of the hip and foot. Three-dimensional instrumented gait analysis included videotaping in the frontal and sagittal planes, kinematics with a six-camera (50Hz) video-based motion-capturing system (Vicon 370; Oxford Metrics, Oxford, UK) and kinetics with two floor-mounted force plates (Kistler, Winterthur, Switzerland). The patients were instructed to walk at a self-selected speed along a level 7m walkway for all tests. All the data were integrated into a custom-made database. A mean of eight consistent cycles was averaged per side and the mean stride analysed. Data collected from a group of ten normal subjects served as a reference base for the interpretation of the results.

Table II. Details of the surgical procedures performed on the 20 patients

Procedure	Total
Psoas lengthening over the brim	9
Adductor longus lengthening	6
Proximal rectus femoris release	27
Medial hamstring lengthening	26
Lateral hamstring lengthening	10
Distal semitendinosus transfer	40
Distal rectus femoris transfer	40
Proximal gastrocnemius transfer	40
Intramuscular gastrocnemius transfer	12
Foot soft-tissue surgery	9
Other soft-tissue surgery	2
Pelvic osteotomy	2
Proximal femur derotation osteotomy	10
Distal tibia derotation osteotomy	2
Foot bony surgery	6
Total soft-tissue procedures	221
Total bony procedures	20
Total surgical procedures	241
Mean procedures per patient	12.05

Surgery. The surgical procedures (Table II) were performed according to specific criteria based on clinical examination and gait analysis (Table III). All the patients had single-stage, multilevel surgery including soft-tissue and bony

Table III. Selection criteria for the surgical procedure

Operations	Clinical	Gait analysis
Intramuscular psoas lengthening	Fixed hip flexion deformity of 30°	Inadequate hip extension in stance
Proximal rectus femoris release	Duncan-Ely test positive	Pelvic 'double-bump' pattern*
Distal semitendinosus transfer	Popliteal angle 30°	Inadequate knee extension in stance
Semimembranosus lengthening	Popliteal angle >40°	Inadequate knee extension in stance
Biceps femoris lengthening	Severe crouch, intra-operative correction of popliteal angle after semimembranosus lengthening not possible	Inadequate knee extension in stance
Distal rectus femoris transfer to gracilis	Duncan-Ely test positive, foot dragging, shoe-wear pattern	Inadequate knee flexion in swing
Proximal gastrocnemius transfer to tibia	Silfverskiöld test positive	Increased plantar flexion in stance
Gastrocnemius/soleus lengthening	Intra-operative rest equinus in knee extension after proximal gastrocnemius transfer	Increased plantar flexion in stance
Pelvic osteotomy	Hip luxation/subluxation	Hip abductor insufficiency
Femoral intertrochanteric osteotomy	Internal rotation exceeds external rotation by more than 30° (prone)	Hip internal rotation deformity
Tibial supramalleolar osteotomy	Tibial external torsion >15°	Excessive external rotation of the tibia
Foot (bone/soft tissue)	Pes planovalgus, equinovarus	Increased/decreased foot progression angle

*the double-peak kinematic pattern of the pelvis in the sagittal plane during stance and swing, due to rapid change from anterior to posterior pelvic tilt, resulting from a poor dissociation between spastic hip flexors and extensors

operations. The mean length of surgery was 3.5 hours (1.6 to 6.0). There were no intra-operative complications.

Operative technique. With the patient prone, a midline longitudinal incision of approximately 6 to 8 cm was made in the popliteal fossa (Fig. 1a). The tendon of semitendinosus was dissected and released from its insertion. The medial tendinous origin of gastrocnemius was released from the femur leaving a stump of 2 cm proximally. The lateral head of gastrocnemius was also released from its femoral origin and both heads were sutured to the tibial condyles in order

to convert gastrocnemius into a monoarticular muscle. The distal tendon of semitendinosus was sutured to the proximal medial tendinous stump of gastrocnemius (Fig. 1b). The tendon of gracilis was released proximally and prepared for transfer to the distal rectus which was completed with the patient in the supine position (Fig. 1c).

Post-operative management. Epidural anaesthesia was used to manage post-operative pain for the first two to five days. All the patients wore below-knee, weight-bearing casts for four weeks and above-knee, night splints for six

Fig. 1a

Fig. 1b

Fig. 1c

Table IV. Clinical parameters (mean $\pm$ SD) evaluated before and after operation

Parameter	Pre-op	Post-op	p value
Thomas test ($^{\circ}$)	12.4 $\pm$ 9.1	3.4 $\pm$ 4.7	0.0000
Popliteal angle ($^{\circ}$)	53.6 $\pm$ 13.6	25.00 $\pm$ 12.6	0.0000
Knee flexion power (MRC scale)	4.0 $\pm$ 0.0	3.1 $\pm$ 0.3	0.0000
Ankle dorsiflexion passive (knee in 90 $^{\circ}$) ($^{\circ}$)	3.8 $\pm$ 8.9	12.3 $\pm$ 7.6	0.0000
Ankle dorsiflexion passive (knee in 0 $^{\circ}$) ($^{\circ}$)	-3.8 $\pm$ 9.7	6.5 $\pm$ 6.4	0.0000
Plantar flexion strength (MRC scale)	3.8 $\pm$ 0.6	3.6 $\pm$ 0.5	0.0385

Table V. Time-distance parameters (mean $\pm$ SD and normalised data) before and after operation.

Parameter	Pre-op	Post-op	p value
Cadence (steps/min)	118.26 $\pm$ 25.26	102.50 $\pm$ 23.54	0.0064
Velocity (1/sec)*	0.59 $\pm$ 0.19	0.58 $\pm$ 0.20	0.6542
Stride length*	0.60 $\pm$ 0.14	0.67 $\pm$ 0.13	0.0227
Stride time (sec/cm)*	0.007 $\pm$ 0.00	0.008 $\pm$ 0.00	0.0366

*normalised to body length

Table VI. Kinematic parameters (mean $\pm$ SD) before and after operation

Parameter	Pre-op	Post-op	p value
Pelvic ROM	8.42 $\pm$ 2.06	6.84 $\pm$ 1.83	0.0009
Max anterior pelvic tilt ($^{\circ}$)	20.18 $\pm$ 3.60	20.00 $\pm$ 6.66	0.9464
Min hip angle stance ($^{\circ}$)	10.11 $\pm$ 13.11	0.85 $\pm$ 8.49	0.0000
Knee angle ROM ($^{\circ}$)	31.86 $\pm$ 15.24	45.23 $\pm$ 13.88	0.0000
Knee ankle angle at initial contact ($^{\circ}$)	41.49 $\pm$ 15.43	19.10 $\pm$ 12.78	0.0000
Min knee angle in single stance ($^{\circ}$)	28.67 $\pm$ 23.38	6.23 $\pm$ 14.49	0.0000
Max knee angle in swing ($^{\circ}$)	59.29 $\pm$ 12.89	51.44 $\pm$ 8.09	0.0040
Timing of max knee angle in swing (% of gait cycle)	80.63 $\pm$ 6.81	80.65 $\pm$ 4.85	0.7178
Ankle angle ROM ($^{\circ}$)	27.96 $\pm$ 12.08	20.89 $\pm$ 6.06	0.0023
Max ankle angle at initial contact ($^{\circ}$)	-4.53 $\pm$ 20.55	-2.38 $\pm$ 8.87	0.8825
Max ankle angle in single stance ($^{\circ}$)	6.89 $\pm$ 21.91	12.81 $\pm$ 7.70	0.2883
Max ankle angle in swing ($^{\circ}$)	-2.03 $\pm$ 20.36	3.51 $\pm$ 6.20	0.1466

months to maintain extension of the knee. The patients were mobilised early and given a posterior control walker. After four weeks, floor reaction ankle foot orthoses were fitted to assist passive extension of the knee. This was discontinued when the power of gastrocnemius and the hamstrings was sufficient to stabilise the knee in stance. When additional bony surgery had been performed there was a non-weight-bearing period of four to six weeks after surgery. The stay in hospital ranged from six to ten weeks during which daily training in gait and posture was undertaken. After discharge, an outpatient programme of physiotherapy was followed and the patients were reviewed at intervals of six months. The only post-operative complication was a case of unilateral transient palsy of the common peroneal nerve in one patient which had recovered completely five months after operation.

Post-operative assessment. Post-operative clinical examination and three-dimensional gait analysis was performed at a mean follow-up of 3.1 years (2.0 to 4.5) after surgery.

Statistical analysis. We compared the pre-operative and follow-up data of clinical examination, kinematic/kinetic measurements and time-distance parameters using the non-parametric Wilcoxon rank test for matched pairs. The level of statistical significance was set at $p < 0.05$.

Results

Clinical examination. The clinical findings at follow-up (Table IV) showed an improvement of the flexion contracture of the hip from a pre-operative mean of 12.4 $^{\circ}$ to 3.4 $^{\circ}$ at follow-up ($p < 0.0001$). The popliteal angle improved from a mean of 53.6 $^{\circ}$ to 25.0 $^{\circ}$ ($p < 0.0001$). The power of the knee flexors and ankle plantar flexor muscles was decreased. The mean dorsiflexion of the ankle with the knee extended changed from -3.8 $^{\circ}$ to 6.5 $^{\circ}$ ($p < 0.0001$) and with the knee flexed to 90 $^{\circ}$ from 3.8 $^{\circ}$ to 12.3 $^{\circ}$ ($p < 0.0001$).

Time-distance parameters. After operation the patients walked with significantly decreased cadence ($p < 0.05$) and increased stride length and time ($p < 0.05$) (Table V).

Kinematics. Anterior pelvic tilt remained unchanged after operation, while the pelvic range of movement was significantly reduced ($p < 0.001$) and extension of the hip in stance phase was improved ($p < 0.0001$) (Table VI). The kinematics of the knee showed a decrease of maximum flexion in the swing phase ($p < 0.01$) with unchanged timing, an improvement of the knee angle at initial contact ($p < 0.0001$) and an increase in range of movement of the knee ($p < 0.0001$) (Fig. 2). Extension of the knee in single stance was improved ($p < 0.0001$) but in four patients (five

Fig. 2

Graph showing the kinematic changes of the knee (sagittal plane) for all patients before (thin line) and after surgery (thick line). The dotted line indicates the normal values. The vertical line separates the stance from the swing phase.

legs) aged between 7.2 and 11.0 years, an increased extension in single-limb stance (back-kneeing) of 11°, 14°, 11°, 22° and 23°, respectively, was noted. Although changes in the ankle angle at the initial contact and during the single-stance and swing phase were not significant, there was a tendency towards improvement.

Kinetics. Pre- and post-operative kinetic measurements were possible in only 11 patients, because of insufficient step length or the use of assistive devices. The hip extensors preserved their maximum hip moment and power in the first double-support phase and in the first half of the stance phase (Table VII). The maximum hip power during the second double-support phase showed a slight but not significant decrease. In the timing of the hip moment crossover (from extensor to flexor) there was a mean decrease of 3% which was not statistically significant. The maximum knee extensor moment during stance was significantly reduced ($p < 0.001$) and remained post-operatively within normal levels (Fig. 3). The maximum ankle plantar flexor moment during the first double-support phase was significantly decreased ($p < 0.05$) and the ankle power generation in the second double support (push-off) was slightly increased ($p < 0.05$).

Discussion

Our aim was to assess the post-operative results after conversion of the biarticular muscles of the lower limb to

monoarticular muscles in children with diplegic cerebral palsy who can walk. Previous operative methods of converting biarticular muscles (rectus femoris, hamstrings, gastrocnemius) have addressed mainly the hamstrings.^{12,13,17,19-28} These procedures can be grouped according to either the muscles converted (hamstrings (medial, lateral, or both), gastrocnemius, rectus femoris) or the site of the conversion (proximal or distal). Post-operative problems such as genu recurvatum, muscle weakness and extensor spasticity have been reported in previous clinical studies.^{17,19-28} The value of clinical examination in cerebral palsy has been questioned because of its static nature, and the lack of repeatability and reliability.²⁹ Except for some objections,^{30,31} the use of instrumented gait analysis has become widely accepted for the planning of treatment and assessment in patients with spastic cerebral palsy.³²⁻³⁴ To the authors' knowledge, there has been no previous study which has described the outcome of conversion of biarticular to monoarticular muscles using objective and dynamic methods.

Single-stage, multilevel surgery including bony and soft-tissue procedures in all planes and at all levels has become an established method for the surgical management of cerebral palsy.^{35,36} The conversion of biarticular muscles, such as semitendinosus and gastrocnemius to monoarticular, should be performed as part of an integrated surgical approach and not as an isolated procedure. Careful interpretation of the pre- and post-operative gait analysis is needed to extract the specific effects of this conversion. Aponeurotic lengthenings of semimembranosus (26/40) and in selected cases of biceps femoris (10/40) were added in order to achieve a popliteal angle of 20° intra-operatively. We excluded conversion of semimembranosus because of its important contribution to the posterior stability of the knee.³⁷ In some cases, lengthening of gastrocnemius and soleus fasciae (12/40), in addition to the proximal gastrocnemius transfers, was necessary in order to achieve adequate correction of equinus. Clinically, an improvement in the popliteal angle was noted probably as a result of lengthening of the hamstrings and the conversion of semitendinosus. The operations on gastrocnemius and soleus increased the passive range of dorsiflexion of the ankle.

Post-operative muscle weakness has been reported after conversion^{20,25} of biarticular muscles. The clinical results of our study demonstrate a decrease in muscle strength of

Table VII. Kinetic parameters (mean $\pm$ SD) in 11 patients only (see text).

Parameter	Pre-op	Post-op	p value
Max hip extensor moment in first half of stance (Nm/kg)	1.11 $\pm$ 0.37	1.12 $\pm$ 0.44	0.9612
Max hip extensor power in first half of stance (W/kg)	1.24 $\pm$ 0.46	1.10 $\pm$ 0.99	0.0824
Max hip extensor moment in first double support (Nm/kg)	1.10 $\pm$ 0.39	1.12 $\pm$ 0.44	0.9612
Max hip extensor power in first double support (W/kg)	0.98 $\pm$ 0.46	0.97 $\pm$ 0.70	0.4852
Max hip power in preswing (W/kg)	0.70 $\pm$ 0.59	0.55 $\pm$ 0.34	0.2491
Timing of hip crossover moment (% of gait cycle)	35.77 $\pm$ 5.38	32.9 $\pm$ 5.49	0.0646
Max knee extensor moment in stance (Nm/kg)	0.80 $\pm$ 0.34	0.39 $\pm$ 0.23	0.0003
Max ankle moment first double support (Nm/kg)	0.97 $\pm$ 0.54	0.65 $\pm$ 0.29	0.0061
Max angle power second double support (W/kg)	0.96 $\pm$ 0.71	1.19 $\pm$ 0.61	0.0455

Fig. 3a

Fig. 3b

Example of an 11-year-old patient a) before and b) 25 months after operation with corresponding knee kinematics (left column), moments (middle column) and power (right column). There is an improvement in kinematics and kinetics after surgery.

the hamstrings and ankle plantar flexors, which could not be identified in the kinetic results. Although moments and powers have been used in assessing the post-operative outcome in combination with clinical examination,³⁸ they do not always correlate with muscle strength.³⁹ It appears that the decrease in muscle strength seen in our patients did not have an adverse effect on parameters of gait.

DeLuca et al⁹ found that lengthening of the medial and lateral hamstrings led to increased anterior pelvic tilt in patients with a normal pre-operative tilt. Zwick et al³⁸ noticed a slight increase in anterior pelvic tilt after intramuscular lengthening of the medial and lateral hamstrings in 17% of their cases. We noticed no change in anterior pelvic tilt after surgery, although in ten of the 40 limbs, intramuscular lengthening of the lateral hamstrings was performed. The decrease in the pelvic range of movement in the sagittal plane indicated a post-operative reduction of the pelvic 'double-bump' pattern. Lengthening of psoas over the brim was performed in nine limbs with a flexion contracture of the hip and was aimed at preserving the power of psoas.^{40,41} The reduction of crouch corrected the positional lever-arm dysfunction⁴² of the medial hamstrings and contributed to the improvement of hip extension in stance.

Genu recurvatum after conversion of the hamstrings has been reported by several authors.^{17,24,27} In our study, although no recurvatum was demonstrated on clinical examination, increased knee extension (back-kneeing) during stance was detected by gait analysis in five knees (four patients). In three mild cases the reason was probably slight persistent equinus which exaggerated the plantar flexion-knee extension couple. In the more severe case, in a patient with a pre-operative recurvatum and post-operative bilateral back-kneeing (22° and 23°), no orthotic devices were considered to be necessary because there was sufficient stability of the knee and no problems with unlocking in the terminal stance. In the patient with bilateral involvement, although the hamstring-lengthenings were considered to be necessary intra-operatively, as there was no correction of the popliteal angle after conversion of semitendinosus and lengthening of semimembranosus, back-kneeing could have been avoided if biceps femoris had not been lengthened.

Sutherland et al¹⁸ reported an increase in peak flexion of the knee in swing after transfer of the distal rectus. Öunpuu et al⁴³ and Zwick et al³⁸ showed that maximum knee flexion during swing was maintained after transfer of rectus femoris. We noticed a significant reduction of the maximum knee

flexion in swing which was probably due to simultaneous proximal release in 27 limbs. In these cases rectus femoris was converted to a monoarticular muscle in order to reduce its contribution to the flexor spasticity of the hip and the post-operative risk of anterior pelvic tilt. Nevertheless, the post-operative pattern of the average knee kinematics indicates an improvement of the knee excursion towards normal (Fig. 2). The improvement of the angle at initial contact, extension in stance and range of movement of the knee indicate the reduction of crouch. Similar improvements in kinematics after lengthening of the hamstrings have been demonstrated by other authors.⁴⁴

The mean persistent post-operative equinus at initial contact was 2° which could be considered to be of limited clinical significance. The maximum dorsiflexion in single stance and swing showed improvement. Both findings correlated with previous studies^{45,46} and contributed to the improvement of stability in stance and foot clearance in swing.

The normalisation of the time distance parameters to height was considered to be necessary since the patients grew 5.6 cm on average during the mean follow-up time of 3.1 years. Although we did not include any measurements of oxygen consumption, the post-operative decrease in cadence could indicate a lower energy consumption as shown by Abel and Damiano.⁴⁷

Ounpuu et al⁴⁸ have pointed out that the interpretation of the kinetic results should emphasise their patterns and timing. Release of proximal rectus femoris in 27 limbs and intramuscular lengthening of psoas in nine did not seem to affect the ability of the hip flexors to generate power during the preswing. The importance of the propulsive function of the hamstring muscles has been already emphasised.⁴⁹ We found no signs of insufficiency of the hamstrings in the post-operative kinetic results. The extensor moment and the power generation of the hip during the first half of stance remained unchanged. The knee extension moment during stance was reduced due to the correction of crouch gait.

The ankle plantar flexor moment at loading response was reduced after operation indicating a reduction of the spastic reaction of the calf muscles during transfer of weight. A significant increase in positive work for push-off after intramuscular lengthening of triceps surae has been reported by Rose et al⁴⁵ and Saraph et al.⁴⁶ In our patients gastrocnemius, despite its exclusion from knee flexion, increased its maximum power which contributed to propulsion during push-off.

Winter⁵⁰ suggested that ankle power is transferred above the knee through rectus femoris, but Lieber⁵¹ postulated that semitendinosus works as an activatable sling and links the monoarticular knee extensors with the knee. Van Ingen Schenau² suggested that gastrocnemius facilitates the transfer of energy from the knee to the ankle. Our results indicate that excluding semitendinosus and gastrocnemius from crossing the knee did not affect their propulsive power during walking. According to Waters et al,⁴⁹ the hamstrings contribute approximately one-third of the extensor power of

the hip in a normal subject. A conventional way of expressing a muscle's force-generating capacity is in terms of its physiological cross-sectional area (PSCA).⁵² Friederich and Brand⁵³ found in a cadaver study that semitendinosus constitutes 22% of the total hamstring PCSA. From the kinematic and kinetic results, we could not estimate accurately the contribution made by conversion of semitendinosus and gastrocnemius. Our findings suggest, however, that the dynamic coupling between the knee and ankle is not interrupted by the conversion of semitendinosus and gastrocnemius to monoarticular muscles. Despite its limitation,⁵⁴ computer modelling may provide an additional insight into the function of the converted biarticular muscles.

Bell et al⁵⁵ and Johnson, Damiano and Abel⁵⁶ have documented a decline in gait function with growth in children with cerebral palsy using gait analysis. In our study the variation in follow-up time (2.0 to 4.5 years) makes it impossible to assess the effects of growth, but could indirectly provide information about the tendency to recurrence of dysfunction of gait. Therefore, both the unknown impact of growth and the risk of recurrence after multilevel surgery should be investigated in the long-term results of further prospective, controlled studies.

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