Sagittal gait patterns in spastic diplegia

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Classifications of gait patterns in spastic diplegia have been either qualitative, based on clinical recognition, or quantitative, based on cluster analysis of kinematic data. Qualitative classifications have been much more widely used but concerns have been raised about the validity of classifications, which are not based on quantitative data.

We have carried out a cross-sectional study of 187 children with spastic diplegia who attended our gait laboratory and devised a simple classification of sagittal gait patterns based on a combination of pattern recognition and kinematic data. We then studied the evolution of gait patterns in a longitudinal study of 34 children who were followed for more than one year and demonstrated the reliability of our classification.

Children with spastic diplegia usually walk independently but most have an easily recognised disorder of gait which may include deviations in the sagittal plane such as toe-walking, flexed-stiff knees, flexed hips and an anteriorly tilted pelvis with lumbar lordosis.[1] When compared with their peers many also walk at a reduced speed, with increased energy expenditure and impaired functional capability.[2-4] Instrumented gait analysis gives detailed information and quantitative measurements. By a process of clinical interpretation this may help the clinician to understand the gait pattern and perhaps to plan appropriate intervention.[5,6] However, experienced clinicians often describe gait patterns using a combination of clinical examination and clinical observation. In 1986, Rang, Silver and De La Garza[7] described a number of gait patterns in spastic diplegia and classified them on a purely observational basis, related to spasticity or contracture of muscles which work in the sagittal plane. They observed associations between contractures of the psoas and lumbar lordosis, of the adductors and scissoring, of the hamstrings and knee flexion, of rectus femoris and stiff knee gait and of gastrocsoleus and tip-toe gait. By linking these observed patterns to specific shortening of the muscles, the association with management was implied.[7]

In 1993, Sutherland and Davids[8] described four typical abnormalities of gait affecting the knee in children with spastic diplegia, namely jump knee, crouch knee, stiff knee and recurvatum knee. Although these patterns were illustrated by sagittal plane kinematic data, no information was given regarding the quantitative assessment of the individual patients in the study and there was no discussion of any deviation of gait at other anatomical levels. Since these two landmark studies, Miller et al[1] have further elaborated on the sagittal gait patterns originally described by Rang et al.[7] The five patterns were described as jump, crouch, equinus, jump plus equinus, and recurvatum plus equinus. A number of authors[9-11] have taken a different approach and have used cluster analysis techniques to classify gait patterns in cerebral palsy on a purely quantitative basis. While the patterns identified by cluster analysis appear to have statistical validity, none has become widely accepted or is regularly used by clinicians.

Our aim was to combine pattern recognition and quantitative kinematic data in order to devise a clinically useful classification of sagittal gait patterns in spastic diplegia. We planned to develop a template for describing sagittal gait patterns to evaluate muscle-tendon surgery and orthoses in the management of spastic diplegia. Our study was made in three inter-related parts. The first was a cross-sectional study of gait patterns in children with spastic diplegia. We then carried out a longitudinal study of a subset of patients who had had more than one instrumented gait analysis. Finally, we investigated the intra- and inter-observer reliability of the classification.

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Table I. The definition of the sagittal plane posture at each level in late stance. The total number of patients is 174; 13 patients of the original cohort of 187 had sagittal kinematics which fell within our laboratory normal range and are therefore not included in this table

	Sagittal kinematics				
Gait pattern	**Number**	**Pelvic tilt**	**Hip Fx/Ext**	**Knee Fx/Ext**	**Ankle Df/Pf**
Group I, true equinus	47	Normal Anterior	Normal	Normal Recurvatum	Equinus
Group II, jump gait	38	Normal Anterior	Normal Flexed	Flexed	Equinus
Group III, apparent equinus	31	Normal Anterior	Flexed	Flexed	Normal
Group IV, crouch gait	28	Anterior Normal Posterior	Flexed	Flexed	Calcaneus
Group V, asymmetrical gait	30	Combination of any two of the above patterns			
Total	174				

Patients and Methods

The classification of gait patterns was based on the position of the ankle, followed by that of the knee, hip and pelvis (Table I, Fig. 1).

Group I, true equinus. The ankle is in equinus. The knee extends fully or goes into mild recurvatum. The hip extends fully and the pelvis is within the normal range or tilted anteriorly.

Group II, jump gait. The ankle is in equinus, particularly in late stance. The knee and hip are excessively flexed in early stance and then extend to a variable degree in late stance, but never reach full extension. The pelvis is either within the normal range or tilted anteriorly.

Group III, apparent equinus. The ankle has a normal range but the knee and hip are excessively flexed throughout stance. The pelvis is normal or tilted anteriorly.

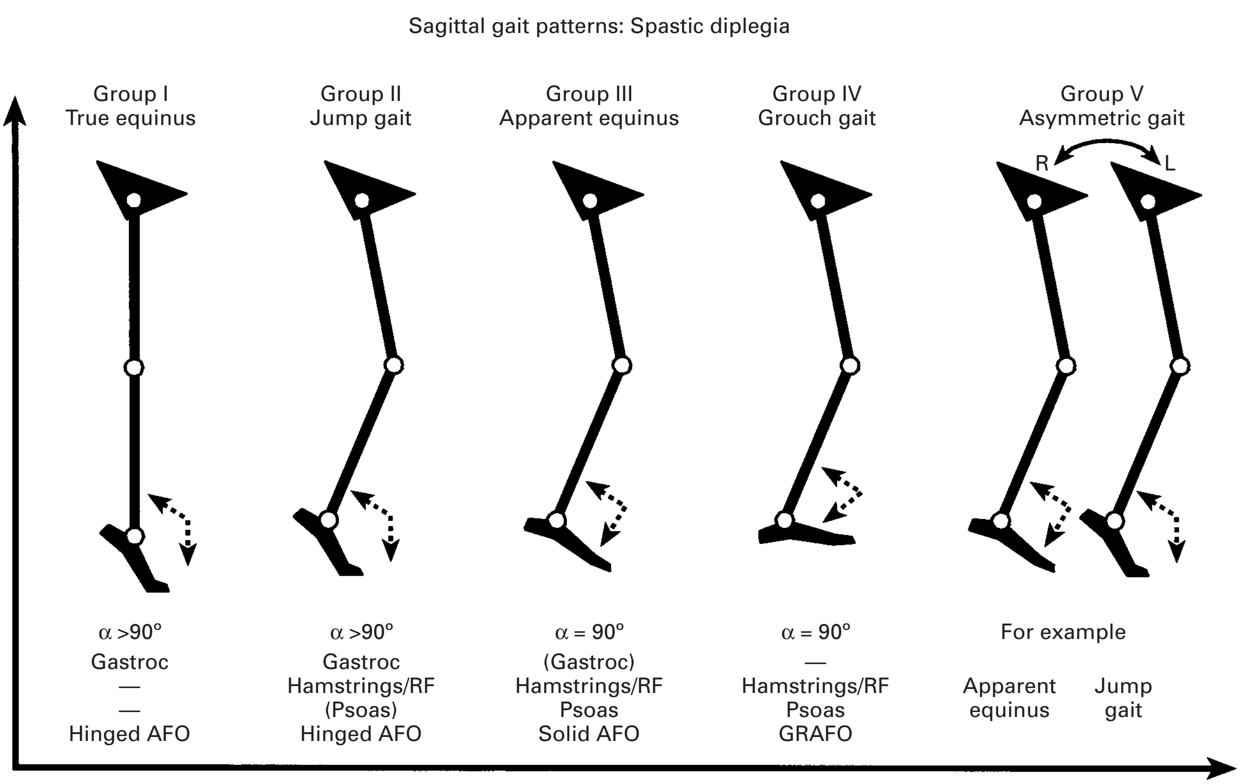

Fig. 1

Diagrams showing each gait pattern, with the dominant muscle groups identified for the management of spasticity and/or contracture and appropriate orthotic prescription. Group V is a combination of groups I to IV, with a different group in the right lower limb compared with the left lower limb. In this example, the right lower limb is group III, apparent equinus, and the left lower limb is group II, jump gait.

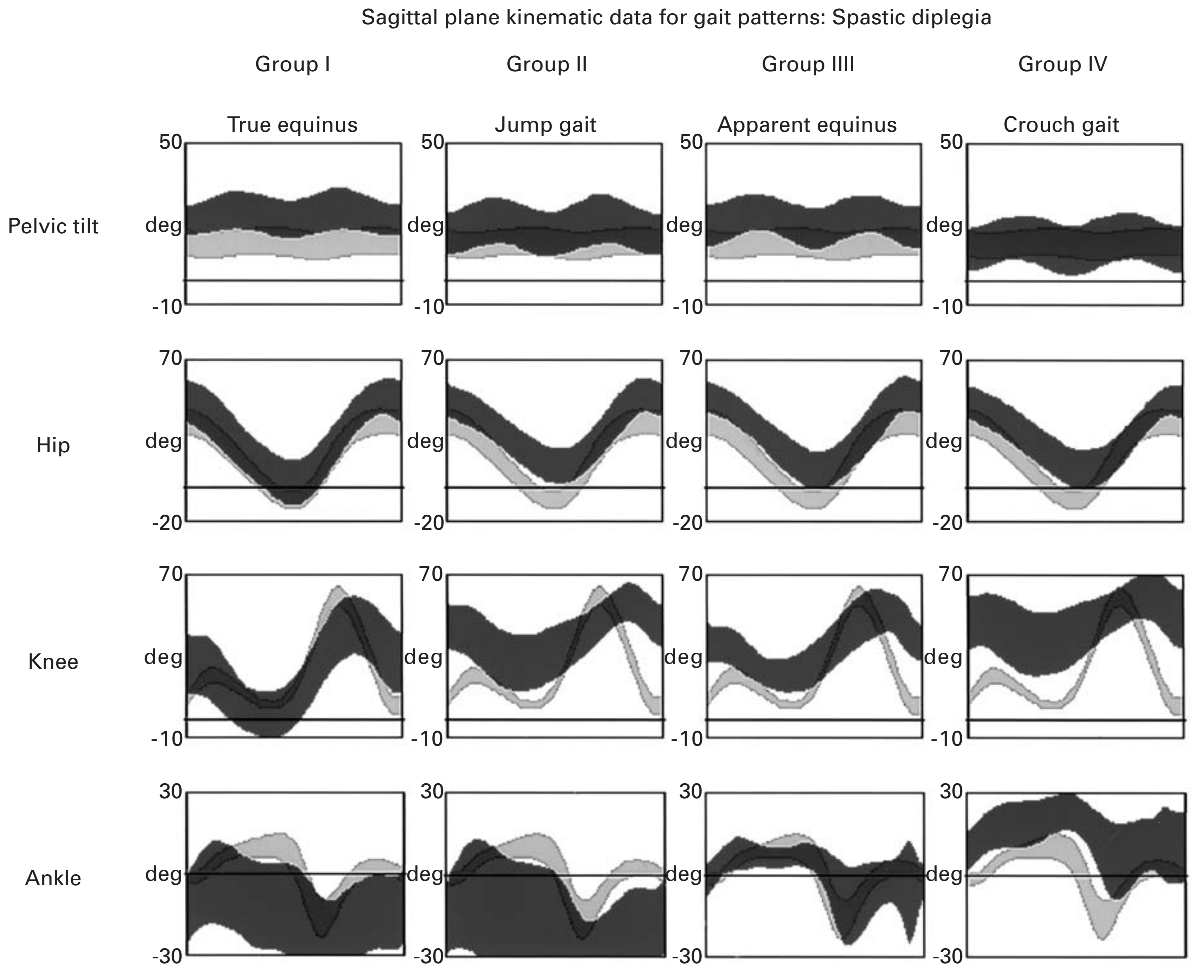

Fig. 2

The summarised sagittal plane kinematic data for each gait pattern for the study population. The light grey band represented the mean ± 1 SD for the laboratory's normal database, and the black band the mean ± 1 SD for each gait pattern. The vertical axis represents joint angular displacement and the horizontal axis, 100% of the gait cycle.

Group IV, crouch gait. The ankle is excessively dorsiflexed throughout stance and the knee and hip are excessively flexed. The pelvis is in the normal range or tilted posteriorly.

Group V, asymmetric gait. The gait pattern is asymmetrical to the degree that the subject's two lower limbs are classified as belonging to different groups; e.g. right lower limb group III, apparent equinus and left lower limb group II, jump gait (Fig. 1).

Cross-sectional study. This comprised 187 patients who fulfilled the study criteria. In addition to the five basic groups we found it necessary to add an additional group, which we have described as 'mild gait'. We considered that true equinus, jump gait, apparent equinus, and crouch gait were the four basic patterns and, because terminology has varied in different reports, we have defined them as groups I to IV. The asymmetrical gait, group V, was defined as a combination of any two of the four basic gait patterns. In the mild gait pattern the sagittal plane kinematics of the pelvis, hip, knee and ankle were within the 1 SD band of the laboratory normal range.[12] These subjects had been referred to the gait laboratory with transverse plane deviations, usually in-toeing. We have chosen to present the groups in a sequence of decreasing equinus (Table I, Figs 1 and 2). The mild and asymmetrical gait patterns were not analysed further since mild gait did not show a significant deviation in the sagittal plane, and asymmetrical gait was simply a combination of two of the four basic gait patterns.

Longitudinal study. There were 34 subjects (68 limbs) who fulfilled the criteria with a mean time between first and second analyses of 30.2 months (13 to 65). Given that a number of subjects had an asymmetrical gait pattern, we have reported limbs rather than subjects.

Repeatability study. The repeatability study was undertaken after two weeks. The sagittal plane kinematic data and video clips from ten subjects, randomly chosen from each gait pattern in the cross-sectional study, were presented to the raters who comprised three paediatric orthopaedic surgeons (HKG, GN, PS) and three physiotherapists (JR, RB, AH) experienced in three-dimensional gait analysis. On each occasion, the raters were provided with written definitions and illustrations of the posture of the ankle, knee, hip and pelvis for each gait pattern. They were shown the kinematic traces and video clips for each of the ten subjects and asked to identify and to record the gait pattern which best described each subject's gait.

For the cross-sectional study the inclusion criteria were the diagnosis of spastic diplegia, in patients aged between four and 18 years, the ability to walk independently, with or without mobility aids and a three-dimensional gait analysis conducted before any surgical intervention except for calf surgery. Previous calf surgery was not an exclusion factor since such surgery had already been used widely in our patients.[13] The exclusion criteria were other disorders of movement such as hereditary spastic paraplegia, dystonia or ataxia, previous orthopaedic surgery other than calf surgery, previous selective dorsal rhizotomy or the administration of intrathecal baclofen, severe asymmetrical fixed deformity or scoliosis (Cobb angle >20°), limb-length discrepancy >2.5 cm, or dislocation of the hip.

For the longitudinal study, patients were required to have had two gait analyses, at least 12 months apart with no treatment of spasticity or orthopaedic surgery in the interim.

Each subject's gait was recorded on videotape, using the sagittal, coronal and split screen views. A six-camera 50hz Vicon 370 machine (Oxford Metrics, Oxford, UK) was used for the collection of the kinematic data and the processing was done through Vicon Clinical Manager. The standard marker system was used.[14,15] The subjects walked barefoot down a ten-metre walkway at their normal self-selected speed. Data were collected from five trials and the most representative trial for each side was reported. Gait patterns were classified by comparing the stance phase of the ankle, knee, hip and pelvic kinematics with the normal range for our laboratory. The following sagittal plane kinematic permutations were recorded. Ankle, equinus, normal range, or calcaneus; knee, flexed, or normal range (modified as stiff, not stiff); hip, flexed, or normal range; pelvis, anterior tilt, normal range, or posterior tilt.

Knees were classified as stiff if the excursion throughout the gait cycle (stance and swing phases) was less than 30°, which is 55% of our laboratory normal range.

Statistical analysis. The mean age between subjects grouped by the two combinations of gait patterns, true equinus and jump gait, and apparent equinus and crouch gait, was compared using a two-sample *t*-test. Velocity was compared between the four gait patterns, true equinus, jump gait, apparent equinus and crouch gait, using analysis of variance (ANOVA). The binary characteristics of stiff knee and calf surgery were compared between the five gait patterns using logistic regression. Weighted kappa statistics were used to summarise 'intra-rater' and 'inter-rater' repeatability with quadratic weights for the four ordered patterns, true equinus, jump gait, apparent equinus and crouch gait. Group V (asymmetrical gait) was considered to be a category discordant from the four basic patterns, groups I to IV.

Table II. Kappa statistics with 95% CI for intrarater repeatability

Rate number	Kappa statistic (95% CI)	
1	1.00*	
2	0.77	*(0.37, 1)*
3	0.90	*(0.67, 1)*
4	0.92	*(0.81, 1)*
5	0.88	*(0.70, 1)*
6	0.66	*(0.26, 0.92)*

* a confidence interval could not be calculated because observed agreement was perfect

Table III. Kappa statistics with 95% CI for inter-rater repeatability

Inter-rater repeatability	Time 1	Time 2
Group I, true equinus	0.90	0.56
Group II, jump gait	0.76	0.31
Group III, apparent equinus	0.46	0.45
Group IV, crouch gait	0.67	1.00
Group V, asymmetrical gait	0.90	0.76
Overall (95% CI)	0.74 *(0.58, 0.95)*	0.60 *(0.36, 0.83)*

Results

Repeatability study. Intra-rater repeatability varied between 1.00 and 0.66 (median 0.89) according to kappa statistics. The overall inter-rater repeatability across the five groups for both the paediatric orthopaedic surgeons and the physiotherapists was 0.74 (95% confidence interval (CI): 0.58, 0.95) on the first test and 0.60 (95% CI: 0.36, 0.83) on the second (Tables II and III).

Cross-sectional study. The summarised sagittal plane kinematic data for the study population is shown in Figure 2. Across the gait patterns, from true equinus to crouch gait, there were changes between the anatomical levels. At the ankle, there was a change from equinus, through a neutral plantargrade position, to calcaneus. At the knee and hip, there was extension, which was followed by increasing flexion. At the pelvis, anterior pelvic tilt gradually became posterior pelvic tilt.

The mean age of children with apparent equinus and crouch gait was 2.9 years older than those with true equinus and jump gait (95% CI: 2.1, 3.8 – Table IV) providing at least a two-year difference in mean age between these two combinations of patterns. Surgery to the calf had most commonly been performed on children showing crouch gait followed by those with apparent equinus and those with true equinus and jump gait. The proportion of subjects who had had previous calf surgery was not significantly different between true equinus and jump gait (p = 0.08) but there was a higher incidence of calf surgery in those with

Table IV. The mean (SD) age, walking speed, incidence of knee stiffness and previous calf surgery according to gait pattern

Gait pattern	Number	Age (yrs)	Velocity (m/s)	Stiff knee (%)	Calf surgery (%)
Group I, true equinus	47	8 (2.4)	1.0 (0.3)	*0*	*7*
Group II, jump gait	38	7 (2.1)	0.8 (0.3)	*50*	*5*
Group III, apparent equinus	31	10 (2.6)	0.9 (0.4)	*39*	*29*
Group IV, crouch gait	28	12 (2.7)	0.8 (0.3)	*71*	*50*
Group V, asymmetrical gait	30	10 (3.1)	0.9 (0.3)	*23*	*27*

Table V. Longitudinal study (34 subjects; 68 limbs). Because we have analysed gait patterns according to involved limbs, not by individual patients, we have not included the group V asymmetrical gait. This shows the pattern of each limb at the first and second gait analyses. No change in pattern between analyses is shown in the shaded boxes. A change in pattern to the left is shown in italics and to the right in normal type

		2nd analysis				
Gait pattern	1st analysis	Mild gait	Group I, true equinus	Group II, jump gait	Group III, apparent equinus	Group IV, crouch gait
Mild gait	5		2	3		
Group I, true equinus	26	*2*	15	6	3	
Group II, jump gait	17	*2*	*5*	7	3	
Group III, apparent equinus	12		*3*	*3*	6	
Group IV, crouch gait	8				*2*	6

apparent equinus when compared with those with true equinus ($p = 0.01$), and those with crouch gait and true equinus ($p < 0.001$). The percentage of subjects with stiff knees was greatest in children with crouch gait, followed by those with jump gait and apparent equinus, with zero incidence in those with true equinus. The mean walking velocity was slower in those with jump gait than those with true equinus (95% CI for difference in mean velocities: 0.1, 0.4; $p = 0.001$). It was slower in those with apparent equinus than in those with true equinus (95% CI: 0.0, 0.3) although this could have been a chance finding ($p = 0.18$), and slower in those with crouch gait than in those with true equinus (95% CI: 0.1, 0.4; $p = 0.003$) (Table IV).

Longitudinal study. Table V shows the pattern of the limbs at the first gait analysis and then at the second. There was no alteration in gait pattern between gait analyses in 34 limbs; 17 limbs showed a shift to the left (towards true equinus) and 17 to the right (towards crouch gait).

Discussion

We have described five basic patterns of sagittal plane gait in spastic diplegia, and an additional 'mild' pattern. The groups are broad in definition and are aimed at practical clinical management. Previous authors[1,7,8] have identified some of the patterns, but a number of differing terms and definitions have been used. Our descriptions are based on clinical insight and biomechanical principles.

From left to right across the patterns, there is decreasing equinus, increasing proximal contracture and a change in the direction of the ground reaction force, from being in front of the knee, to behind it (Fig. 3). The flexors of the hip and the knee and plantar flexors of the ankle are the key muscle groups, showing spasticity and contracture, affecting the pattern of gait. We recognise that sagittal plane deformities (muscle-tendon contractures) may interact with transverse plane deformities (torsional deformities of the femur and tibia) in addition to weakness and poor selective motor control, to influence gait patterns.

True equinus is both real and apparent. The ankle is in equinus and the knee is fully extended in late stance. Recurvatum of the knee was not found in our cross-sectional study. It would require elongation of the hamstrings, which was *a priori* an exclusion criterion. Previous hamstring surgery was not excluded in the study carried out by Sutherland (personal communication), who found it necessary to include a specific genu recurvatum group.[8]

Jump gait is so called because it involves a decrease in flexion at the hip and knee from initial contact to late stance, coupled with equinus in late stance, giving the appearance that the subject is jumping up and down. In apparent equinus, the heel is not in contact with the ground because of flexion contractures at the knee and hip, but the ankle is not in equinus. The sagittal kinematic examination of the ankle showed a normal range in stance, and therefore calf-lengthening surgery was usually contraindicated.[13] In our classification, a flexed knee gait encompasses jump gait, apparent equinus and crouch gait, depending on the position of the ankle. We do not classify flexed knee gait as crouch gait, unless the ankle kinematics are in the calcaneus range. This is relevant to research into crouch gait, when both knee and ankle sagittal plane kinematics must be specified.

The mean age of the patients who walked with true equinus and jump gait was younger than in those with apparent equinus and crouch gait. True equinus and jump gait may be the most common pattern in younger children at the beginning of independent walking. The age gradient from true equinus and jump gait to apparent equinus and crouch

Fig. 3a

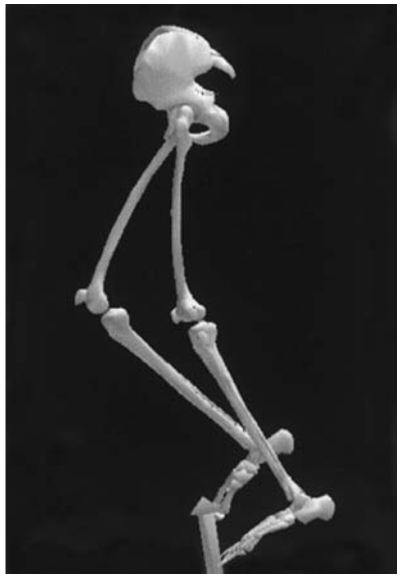

Fig. 3b

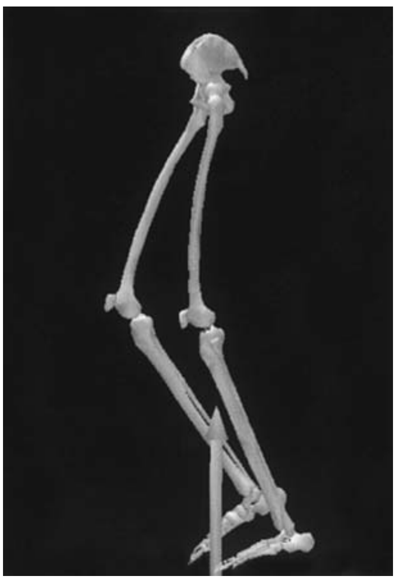

Fig. 3c

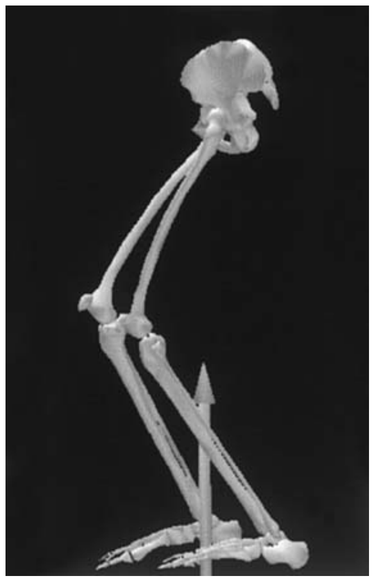

Fig. 3d

From left to right, an example of a subject in true equinus, jump gait, apparent equinus, and crouch gait (groups I to IV). The change in the direction of the ground reaction vector from anterior to the knee in true equinus (group I) progressing to posterior to the knee in crouch gait (group IV) is seen. The group V asymmetrical gait pattern has been excluded because the ground reaction vector is the same as for the four basic groups illustrated here.

gait suggests that these patterns may reflect the natural history in spastic diplegia, as was suggested by Rab.[16] The prevalence of previous calf surgery in the apparent equinus and crouch gait groups in our study, suggests that isolated calf surgery may be a major predisposing cause. However, apparent equinus and crouch gait are also part of the natural history of spastic diplegia, for some children. Stiff knees and a reduced speed of gait, were most common in jump gait and crouch gait.

By ordering the gait patterns in the way described (Figs 1 and 2), it appears that a change occurred in muscle involvement from distal to proximal. The gait pattern is the result of muscle imbalance in the sagittal plane, not at a single joint but between anatomical levels.[17]

In true equinus, the calf is spastic or contracted and is dominant. In crouch gait, the calf is long and weak and the hamstrings and iliopsoas are spastic or contracted, but dominant. Muscle weakness is also very important in determining the final gait pattern.[18] Children may demonstrate crouch gait because of weakness as well as being pulled into crouch gait because of contracted hamstrings and hip flexors. In most children, weakness and contracture contribute to the overall gait pattern.[18]

There is also a change in the integrity of the plantar flexion knee extension couple, from being overactive in true equinus, to being incompetent in crouch gait. The direction of the ground reaction force moves from being anterior to the knee in true equinus, to posterior to the knee in crouch gait (Fig. 3). These changes across the gait patterns can be linked with strategies for the management of spasticity and contractures and the prescription of orthoses (Fig. 1). We recognise that the management of abnormalities of gait in spastic diplegia is complex and cannot be reduced to a simple recipe. The following should be considered as broad guidelines, which may serve as a starting point to plan patient-specific management.

In group 1 (true equinus) calf spasticity and/or contracture is dominant over that of the hamstrings and psoas. This gait pattern is seen in the younger child, when injections of botulinum toxin A to the calf muscle may be appropriate.[19,20] Older children, walking in true equinus may have occult contractures at the level of the hip and knee. Although lengthening of the contracted gastrocsoleus may be the most obvious prescription, careful evaluation is required and all involved levels should be addressed.[21]

In group II (jump gait) all three levels are clearly involved. In the younger child showing spasticity in whom minimal or no contracture is present, selective dorsal rhizotomy (SDR) may be considered if the child fulfils appropriate prerequisites for this procedure.[22] Multilevel injections of botulinum toxin A, to the calf, hamstrings and psoas, have been suggested and remain under evaluation.[23-25] During the stage of fixed contracture in jump gait, simultaneous bilateral lengthening of the calf, hamstrings and psoas may be considered, i.e. single event, multilevel surgery.[21,23]

Orthotic requirements in true equinus and jump gait are similar since the spasticity or contracture of the calf restricts or curtails second rocker at the ankle. The ground reaction force is directed anteriorly to the knee, leading to an overactive plantar flexion knee extension couple. A posterior leaf spring or hinged ankle foot orthosis restricts excessive plantar flexion and aids movement into dorsiflexion during the second rocker, thereby realigning the ground reaction force and normalising the plantar flexion knee-extension couple.[26]

The hamstrings and psoas are the dominant influences in groups III and IV, apparent equinus and crouch gait. Lengthening of the hamstrings and psoas may be required. In apparent equinus, a solid ankle-foot orthosis can assist the plantargrade alignment of the tibia with the foot during the second rocker and correct the direction of the ground reaction force.[26] About half of the children in the crouch gait group had a history of isolated lengthening of the gastrocsoleus, but for the remainder, it was part of the natural history of their gait disorder. The second rocker is excessive into the dorsiflexion range with the ground reaction force directed posterior to the knee. The plantar flexion knee-extension couple is incompetent. A ground reaction foot orthosis restricts excessive dorsiflexion during the second rocker. The orthosis directs the ground reaction force in front of the knee throughout stance so that knee extension is gained and the plantar flexion knee extension couple is restored.[27] The presence of stiff knees in three of the four gait patterns demonstrated that this is not a separate gait pattern but is a specific knee pattern. Management of a stiff knee gait may require transfer of rectus femoris.[28-32] However, caution is advised if the quadriceps muscles are weak and the gait pattern is characterised by excessive knee flexion.

In our longitudinal study, the sagittal gait pattern was stable in 50% of patients, but for the others there was a change in gait pattern, some to the left (towards true equinus) and others to the right (towards crouch gait). Yokochi[33] demonstrated similar findings in a longitudinal study documenting changes in gait patterns in 20 young children with spastic diplegia, who were all managed non-operatively. The direction of change from one gait pattern to another, is probably influenced by which muscle group develops contracture and becomes dominant with time.[33] Movement to the left (towards true equinus) is possibly associated with progressive contracture of the gastrocsoleus and equinus deformity.[34] A shift to the right (increased flexion/crouch gait) may be due to the development of foot deformities such breaching of the mid-foot, combined with the deleterious effects of the adolescent growth spurt. Two recent studies have confirmed that deterioration in normalised walking speed, increased flexion and increased stiffness may be the natural history for children with spastic diplegia.[34,35]

The validity of this classification of gait patterns has been established by reliance on the technique of choice, sagittal kinematics. Repeatability of the gait classification has been established by the weighted kappa statistic for both intra-rater and inter-rater repeatability, which showed substantial agreement. The limitations of our study are both theoretical and practical. There were no sharp demarcations between the various patterns. For example, the ankle kinematic traces varied continuously from equinus, through the normal range, to calcaneus. Given that management of the equinus ankle differs from the normal and calcaneus ankle, we considered it to be useful from a management perspective to separate the patterns accordingly.[36] Although repeatability was good, it was not perfect. We have considered the effects of weakness and deviations of gait in other planes but have not yet devised a suitable method to incorporate these issues into our current classification. However, we think that our classification may be useful to clinicians in its present form and we expect both modifications and improvements, in the future. We agree with Feinstein[37] who identified the need for clinicians to combine qualitative and quantitative data in an appropriate manner.

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