Original Article

Quantitative Analysis and Classification of Gait Patterns in Cerebral Palsy Using a Three-Dimensional Motion Analyzer

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ABSTRACT

Gait disorders in cerebral palsy can be accurately analyzed using the CODA-3 system presenting quantitative data representing movement of the hip, knee, and ankle in the sagittal plane. We describe a technique that classifies abnormal gait automatically on the basis of sagittal kinematic data. Fifty-five hemiplegic and 91 diplegic patients were analyzed using an opto-electronic scanner (CODA-3). The sagittal kinematics of the affected limb in hemiplegics correlated with those of both affected limbs in diplegics. We introduce the concept of the "plegic limb." Sagittal kinematics of 237 affected limbs were studied using cluster statistical analysis. Eight clear groups emerged. The predominant clinical features, typical of each group, were identified and described (eg, stiff leg gait, genu recurvatum, or crouch gait). We propose this classification system as a new technique to use gait analysis data to automatically classify abnormal movements of the lower limb in cerebral palsy. (*J Child Neurol* 1998;13:101–108).

Cerebral palsy is usually caused by an insult to the immature brain with the motor cortex commonly the most affected area. However, all areas of the brain may be affected, leading to very diverse patterns of neurologic abnormality. This range of clinical manifestations of cerebral palsy partly explains the difficulty in devising a satisfactory classification system to divide patients into the most homogeneous groups. Intra-observer agreement, even in trained personnel using the current classification system, which was developed by the American Academy of Cerebral Palsy,[1] has been shown to be only 55%.[2] Over the last 40 years, great advances have been made with the development of sophisticated gait laboratories and techniques to assess gait abnormalities. There has also been an increase in the range of interventional modalities and a realization that their success depends on accurate pretreatment assessment and diagnosis for patients with cerebral palsy.[3] Despite the vast amounts of quantitative data recorded during gait analysis, no attempt has been made to develop a classification system from this data. Furthermore, no attempt has been made to establish a system that will collect and analyze this quantitative data and classify it automatically. We set out to identify if data collected by a gait analysis system could be grouped automatically into a number of clinically recognizable groups using cluster statistical methods. A classification system that utilizes quantitative data measured in a gait laboratory should allow the clinician to automatically place the abnormal gait pattern into a particular group. The purpose of this classification system is primarily diagnostic.

PATIENTS AND METHODS

Over a 2-year period, 312 patients with cerebral palsy underwent gait analysis in the Gait Laboratory at the Central Remedial Clinic. Patients with neurologic abnormalities following trauma or cerebrovascular accident were not included. All patients underwent motion analysis using the CODA-3 system.[4-6] Six markers were placed on the limb being examined. These markers were placed on (1) the iliac crest, (2) the thigh, just below the great trochanter, (3) the lateral joint line of the knee, (4) the lateral malleolus, (5) the heel, and (6) the head of the fifth metatarsal. Each patient was then asked to walk at a self-selected pace and when a pattern had been established after about 100 steps, the recording was commenced. Five walks along the walkway were recorded. The motion analysis

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involved measurement of the basic gait parameters, determination of the stance and swing phases, and measurement of kinematics. The kinematics of the hip, knee, and ankle were measured in the sagittal plane. Abnormalities were studied in this plane because it reflects the plane of walking, kinematic abnormalities of flexion or extension occur in this plane, and most therapeutic interventions address sagittal abnormalities.

The study included 146 patients (88 male and 58 female) who had not undergone surgery and were not ataxic or choreoathetoid. Fifty-five were hemiplegic and 91 were diplegic. The quantitative sagittal kinematic measurements of range of movement and maximum flexion and extension at the hip, knee, and ankle were studied for the affected lower limbs in the hemiplegic and both lower limbs in the diplegic patients. The sagittal measurements from the lower limb in the diplegic subjects were found to be statistically similar to the measurements from the affected limb in the hemiplegic patients. From that finding evolved the idea of analyzing all of the affected limbs as a single group and using the term the "plegic" limb. Therefore the total number of "plegic" limbs analyzed was 237. The quantitative sagittal kinematic measurement data was then submitted to cluster statistical analysis. That attempted to identify relatively homogeneous groups based on multiple variables. K-means clustering was used. This splits a set of objects into a preselected number of groups by maximizing between relative to within cluster variation.[7,8] Cluster statistical analysis allows one to choose the number of groups that will exist in the classification system. There can be a large number of groups or very few. A range of numbers of groups was selected and the groups that emerged were studied for clinical characteristics. If the number of groups chosen was too small, limbs that were obviously clinically discrete were grouped together and if the number of groups chosen was too large, different clinical entities were effectively separated but, as a classification system, it was too cumbersome.

RESULTS

Clustering the patients into groups of ten or more identified different groups with different clinical patterns. However, as a classification it was cumbersome. Clustering the patients into groups of six or less created groups that did not distinguish different clinical entities.

The patients were clustered into eight groups. Each group was then studied and the most consistent identifying or discriminating clinical features were identified.

Table 1. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 1

n = 43	Minimum	Mean	Maximum	Standard Deviation
Hip range	24.14	39.12	55.26	7.13
Max hip flexion	47.35	63.63	77.99	7.28
Knee range	47.24	64.64	82.03	7.27
Max knee flexion	68.80	81.54	103.00	6.03
Ankle range	2.32	36.87	49.71	7.28
Max ankle dorsiflexion	–7.72	12.52	25.41	7.59

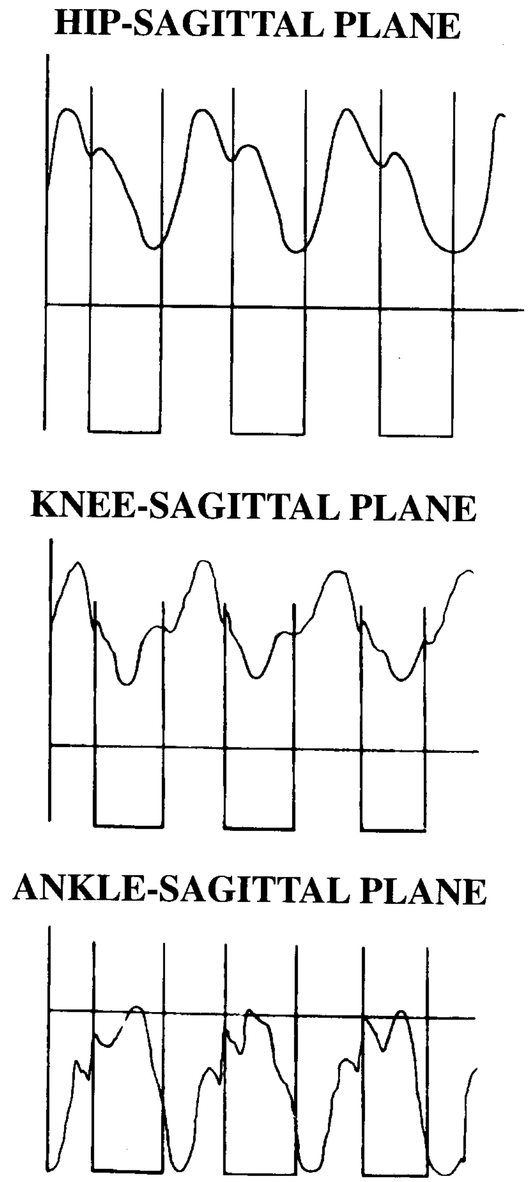

Figure 1. This sagittal kinematic graph represents the limb that is typical in Group 1.

Group 1 (Mobile Crouch)

That group included 43 limbs. Thirty-three were from diplegic and ten were from hemiplegic patients (Table 1). Those patients walk with flexed hips (Figure 1) that never extend near neutral, although with a reasonable range of movement (mean = 39 degrees). The knees are also in flexion throughout most of the cycle (17 degrees–81 degrees flexion) but have a good range (Figure 1). The ankle kinematics indicate a good range, however, that was predominantly in the plantar flexed position. At mid stance the ankle achieved minimal dorsiflexion, the knee is also flexed as is the hip maintaining the body-center over the foot. Both the first and second rocker were absent at the ankle (Figure 1). The limb that is most typical of this group demonstrates a gait with flexed hips, flexed knees, and an ankle that does attempt to dorsiflex during swing when the knee is maximally flexed. Initial contact is in plantarflexion with minimal passive dorsiflexion only as the weight of the body passes over the foot.

Group 2 (Stiff Crouch With Toe Walking)

That group contained ten limbs (Table 2). Two were from hemiplegic patients and eight were from diplegics. The pattern resembled the "stiff-leg gait" (Figure 2). Those limbs demonstrated a low range of movement of a flexed hip (mean range of 29 degrees flexion; flexing from 26 degrees to 55 degrees). They also exhibited flexed knees with a mean range of 400 degrees, flexing from 20 degrees to 64 degrees. The movement at the ankle was consistently in plantarflexion with a mean range of 27 degrees, which all occurred in plantarflexion from a mean of 15 degrees plantarflexion to 42 degrees plantarflexion. Those limbs were stiffer (narrow range) and straighter (less maximum flexion angle) than those in Group 1. The ankle movement in those patients is continuously in plantarflexion even during stance phase.

Group 3 (Drop Foot Pattern)

That group included 62 limbs. Fourteen were from hemiplegic patients and 48 were from diplegic patients (Table 3). Those patients also walk with flexed hips (mean 22–53 degrees) and knees (18–73 degrees). The range of movement at the ankle was from 12 degrees plantarflexion to 17 degrees dorsiflexion. However, in the typical patient in this group we found that the hip and knees are flexed throughout the cycle (Figure 3). At the ankle there is a "drop foot" pattern with the ankle falling into plantarflexion during swing and going into a passive during stance phase as the tibia rolls over the ankle. The ankle then plantarflexes to commence toe-off but very weakly pulls up towards dorsiflexion following toe-off. However, even though there was some attempt to dorsiflex during swing phase, the ankle does not even reach the neutral position.

Group 4 (Ankle Double Bump Pattern)

Thirty-two limbs were included in that group. Twenty-two were from diplegic patients and ten were from hemiplegic patients (Table 4). Those patients have a good range of movement at the hip and were only a mean of 18 degrees short of extension (Figure 4). At the knees they had a reduced range of movement but were only a mean of 12 degrees short of full extension at the knee (Figure 4). At the ankle the movement was from 16 degrees plantarflexion to 13 degrees dorsiflexion. However, those patients strike the ground with the

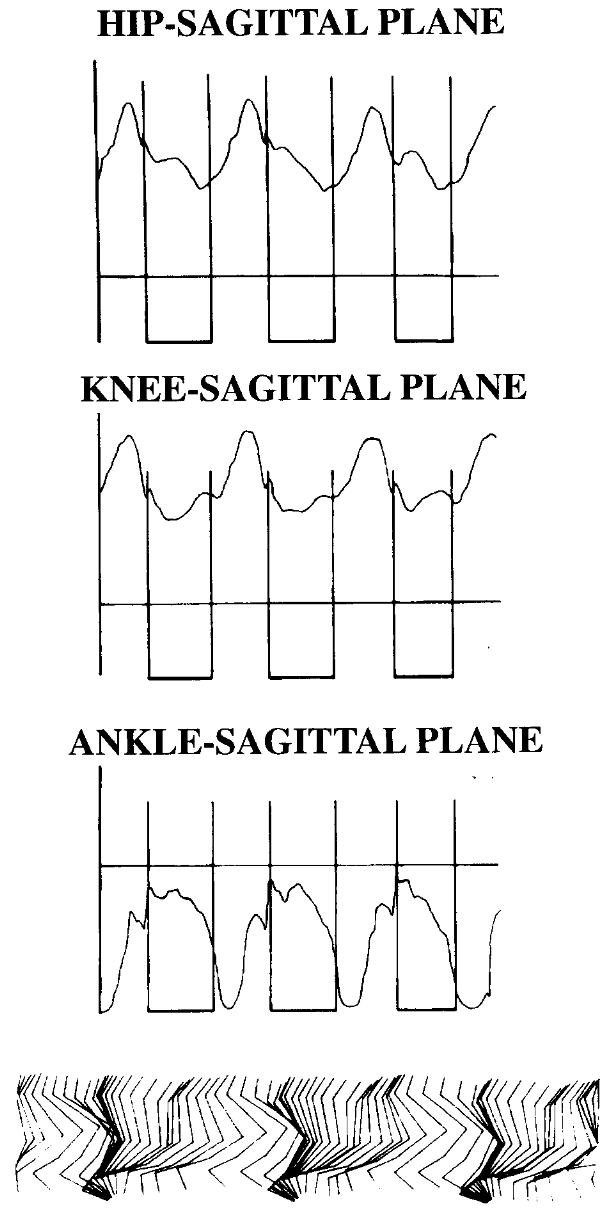

Figure 2. This sagittal kinematic graph represents the limb that is typical in Group 2.

Table 2. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 2

n = 10	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	19.54	29.15	41.19	6.79
Max hip flexion	41.09	55.44	67.28	6.89
Knee range	17.77	40.16	56.68	12.23
Max knee flexion	56.83	64.71	78.75	7.03
Ankle range	15.54	27.45	50.07	10.99
Max ankle dorsiflexion	−35.00	−15.65	−5.21	8.61

Table 3. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 3

n = 62	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	19.50	31.04	43.19	5.38
Max hip flexion	42.77	53.43	63.23	4.85
Knee range	44.01	55.25	69.37	5.96
Max knee flexion	61.00	72.88	90.57	5.44
Ankle range	16.31	29.29	44.86	6.55
Max ankle dorsiflexion	9.00	17.43	35.66	5.09

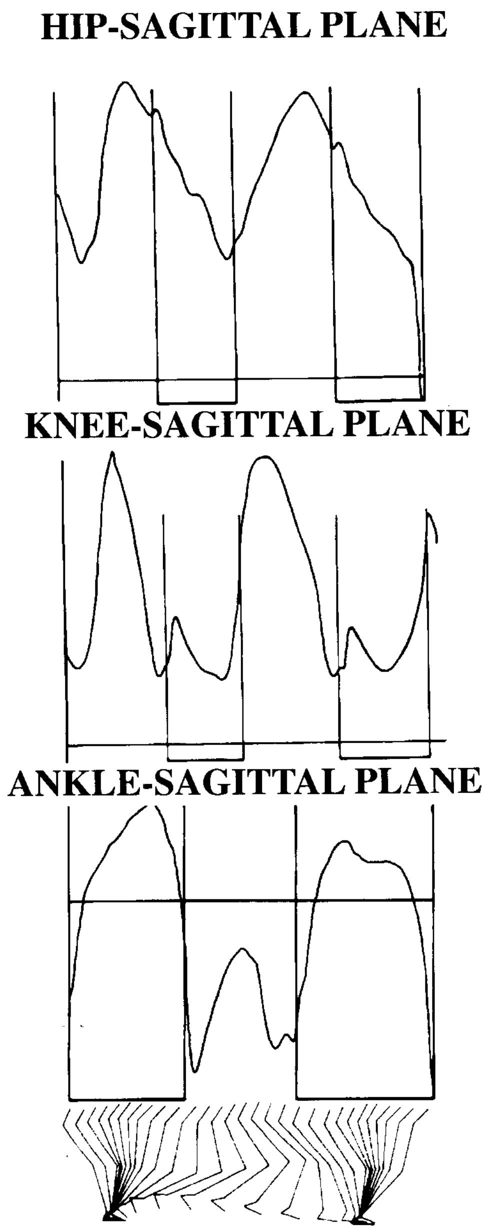

Figure 3. This sagittal kinematic graph represents the limb that is typical in Group 3.

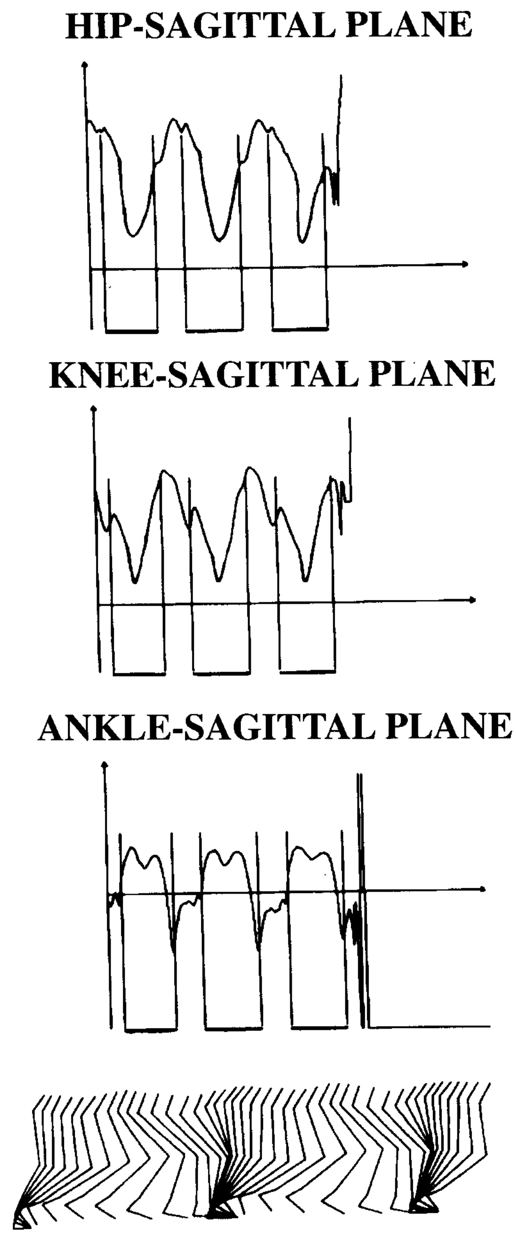

Figure 4. This sagittal kinematic graph represents the limb that is typical in Group 4.

ankle in neutral or slightly dorsiflexed position. Instead of the usual plantarflexion that occurs following heel strike (ie, the first rocker), those patients go further into dorsiflexion in early stance phase. Then an attempt was made for the ankle to go into plantarflexion but by this time the full weight of the body, with knees and hips flexed, would be over the ankle which would be pushed back up into dorsiflexion. Hence, the double bump on wazzu the dorsiflexion side of the graph during stance. The ankle would then be actively plantarflexed for toe-off and gradually came back into dorsiflexion during swing phase (Figure 4).

Table 4. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 4

n = 32	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	23.27	31.49	40.88	5.03
Max hip flexion	31.17	49.35	69.02	7.25
Knee range	33.52	43.05	55.37	5.16
Max knee flexion	39.69	55.01	65.52	7.09
Ankle range	17.33	29.00	50.60	7.30
Max ankle dorsiflexion	−2.29	13.15	27.17	7.35

Group 5 (Proximally Flexed Ankle Walkers)

That group included 35 limbs (Table 5). Nine were from hemiplegic and 26 were from diplegic patients. These patients are also flexed at the hips (33–60 degrees) and knees (41–74 degrees) like the patients in group 1. However, at the ankle

Table 5. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 5

n = 35	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	11.36	26.28	45.16	7.09
Max hip flexion	48.18	59.66	74.32	7.31
Knee range	21.19	33.16	45.36	7.35
Max knee flexion	58.08	73.89	91.20	8.10
Ankle range	12.98	29.76	45.83	6.68
Max ankle dorsiflexion	−0.55	16.37	30.87	8.78

the movement is good. On studying the most typical limb of this group, we found the hips in marked flexion throughout the gait cycle. However, the ankles had quite a normal pattern and range of movement (Figure 5). At heel strike the ankle was in partial dorsiflexion. Unlike the normal pattern of going into plantarflexion just after heel strike and before the tibia rolls over the ankle, in those patients the ankle remained in dorsiflexion in early stance. This is because the knee is so flexed at the point of heel strike that the weight of the body holds the ankle dorsiflexed. At the end of the stance phase, the ankles were plantarflexed for toe-off before dorsiflexion pulling up into dorsiflexion during swing phase.

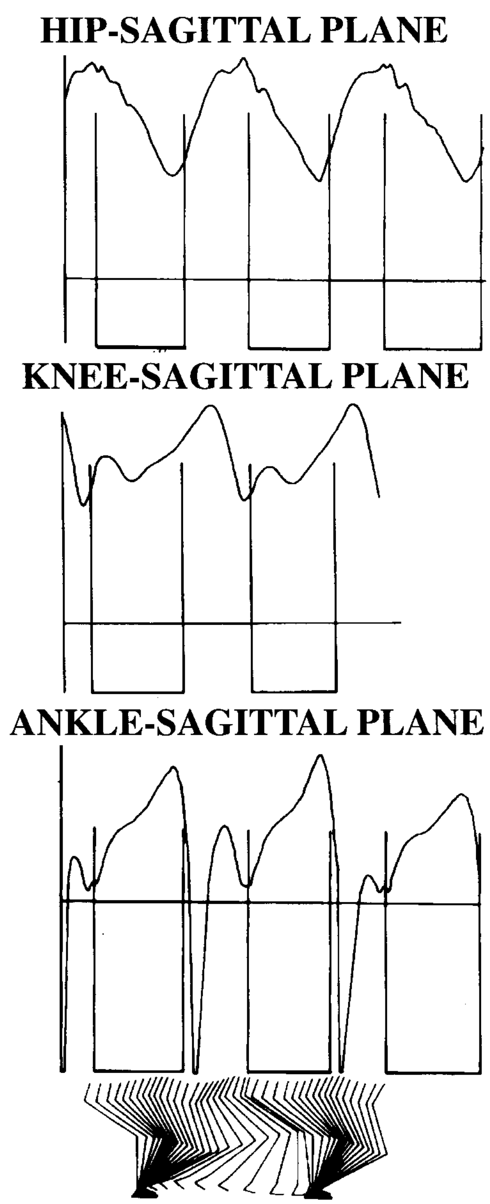

Figure 5. This sagittal kinematic graph represents the limb that is typical in Group 5.

Group 6 (Mild Recurvatum)

That group included 43 limbs (Table 6). Seven were from hemiplegic and six were from diplegic subjects. At the hip the mean range of movement was from 7 degrees flexion to 41 degrees flexion. The most marked abnormal characteristic of this group was recurvatum at the knee joint. The amount of hyperextension at the knee joint was small (mean 1 degree) but consistent throughout the group (Figure 6). At the ankle the mean range of movement was from 21 degrees plantarflexion to 9 degrees dorsiflexion. However, these patients demonstrated an ability to actively dorsiflex the ankle, although not adequately, during the swing phase.

Group 7 (Severe Recurvatum)

That group contained three limbs (Table 7). One was from a hemiplegic limb and two were from a diplegic patient. They were characterized by marked genu recurvatum with a mean range of 80 degrees from 14 degrees hyperextension to 64 degrees flexion. The hips were in slight flexion from a mean of 6 degrees flexion to 49 degrees flexion. The ankle movements in this group, unlike group 6, were markedly in plantarflexion with a mean range of 17 degrees which occurred from 12 degrees plantar-flexion to 29 degrees plantarflexion (Figure 7).

Group 8 (Severe Crouch)

That group included nine limbs (Table 8). Those limbs were from very poor walkers and demonstrated very low ranges of movement and a very poor progression. The hip sagittal kinematics were very slow with a low range (20 degrees) that occurred in a flexed position from a mean of 36 degrees flexion to 56 degrees flexion. The knee also demonstrated a very poor range of excursion (mean 28 degrees) again in slight flexion from a mean of 13 degrees

Table 6. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 6

n = 43	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	26.79	35.67	47.53	5.00
Max hip flexion	19.82	41.09	54.03	7.98
Knee range	49.13	64.12	73.58	6.40
Max knee flexion	47.96	63.06	73.70	5.57
Ankle range	19.55	30.53	48.33	6.96
Max ankle dorsiflexion	−2.09	9.59	19.60	5.62

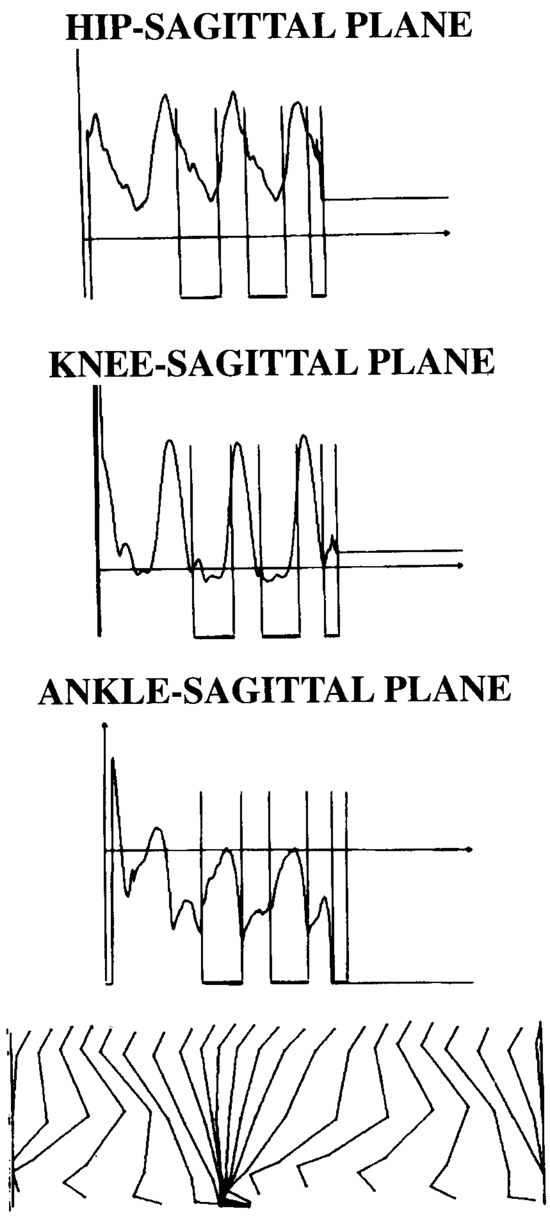

Figure 6. This sagittal kinematic graph represents the limb that is typical in Group 6.

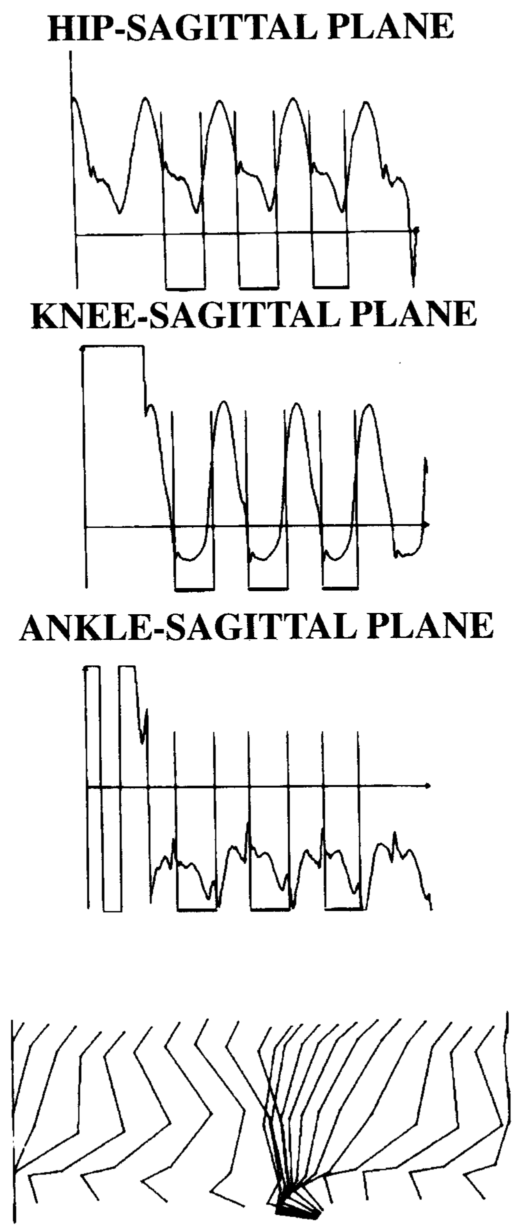

Figure 7. This sagittal kinematic graph represents the limb that is typical in Group 7.

to 42 degrees. At the ankle, the mean range of movement was 19 degrees, which was principally dorsiflexion (Figure 8). The stance phase was very prolonged in these limbs, reflecting the degree of instability.

Table 7. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 7

n = 3	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	34.65	43.42	52.73	7.39
Max hip flexion	45.87	49.42	51.94	2.58
Knee range	70.68	79.83	90.35	8.09
Max knee flexion	62.03	64.06	65.87	1.58
Ankle range	12.39	17.48	26.20	6.19
Max ankle dorsiflexion	−16.40	−12.83	−8.00	3.54

DISCUSSION

The present diagnostic system for cerebral palsy patients classifies a patient as either a quadriplegic, diplegic, or

Table 8. Ranges and Maximum Angles in Hip, Knee, and Ankle for Group 8

n = 9	*Minimum*	*Mean*	*Maximum*	*Standard Deviation*
Hip range	12.65	20.08	31.74	6.79
Max hip flexion	48.11	55.74	67.37	7.33
Knee range	17.67	28.22	39.80	6.98
Max knee flexion	19.83	41.53	61.33	11.34
Ankle range	12.17	18.99	27.23	4.39
Max ankle dorsiflexion	−2.33	11.74	21.69	7.62

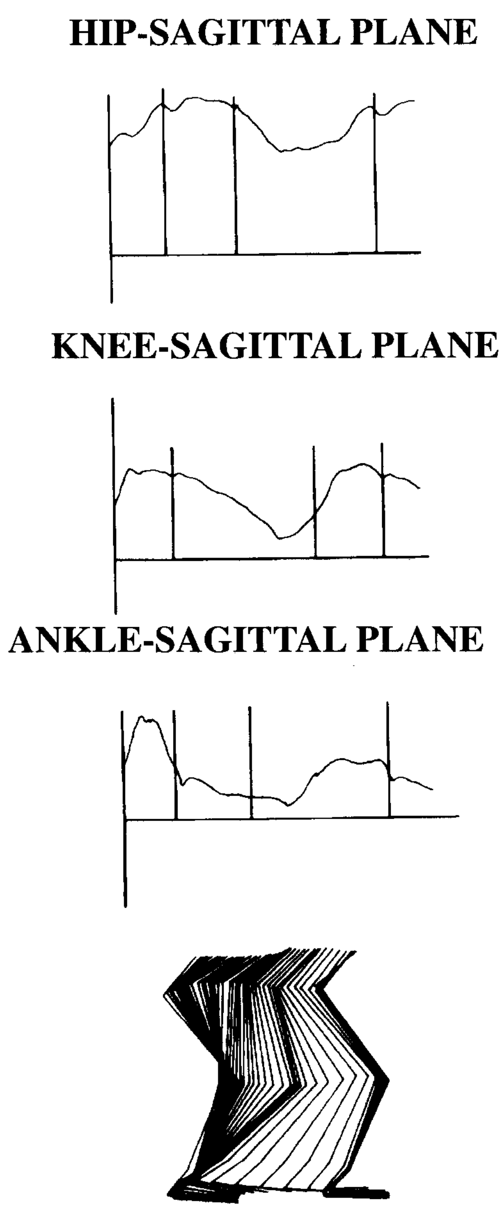

Figure 8. This sagittal kinematic graph represents the limb that is typical in Group 8.

hemiplegic. The wazzu system is, at best, descriptive, and is not specific in the classification of gait disorders. Attempts at classification have been made using gait laboratory data. Bekey et al[9] classified the spastic gait of 30 patients into four categories using electromyographs of the muscles that activate motion of the foot and ankle. They concluded that an accurate description of the various patterns of gait is possible if the patterns of movement of the entire lower extremity also were evaluated. Knutsson and Richards[10] described three gait patterns in spastic hemiplegia using electromyographic studies and intermittent light photography. Wong, Simon, and Olsen[11] developed a typology for patients with cerebral palsy using ten selected gait measurements in 128 cerebral palsy patients. They identified four modal clusters using the kth nearest neighbour clustering procedure. They studied the angular motion of the isolated affected limb of each patient regardless of the topographic diagnosis because they were highly correlated (all correlations greater than 0.70. However, in their description of the clinical features of these groups they went little further than identifying that cluster 4 had the lowest gait speed and patients in cluster 2 moved faster than those in cluster 4, but were much slower than those in clusters 1 and 3. Cluster 4 patients tended to have smaller angular motions in all three joints than those in the other clusters. They focus on the statistical techniques used rather than the clinical features of each of the groups. The classification system has a negligible clinical application; however, it does raise the concept of grouping the patients on the basis of gait analysis data so that the limb can be classified in an automatic way following analysis. More significantly, the authors examined the diagnosis of the patients across clusters. The clusters and the diagnoses appear independent implying that the abnormal gait measurements of the limb in the hemiplegic, diplegic, or quadriplegic child are similar. This supports our contention that one can speak in terms of the "plegic" lower limb of the child with cerebral palsy. In 1987, Winters, Gage, and Hicks[12] identified four patterns in spastic hemiplegia in children and young adults, but did not confine their data to children with cerebral palsy. Kinematic data in the sagittal plane and electromyographic data was used. They described four groups. In general, there was a progression of involvement in the four groups with patients in groups 1 and 2 demonstrating the least residual damage to the central nervous system as compared with patients in groups 3 and 4. Again, although the group studied included patients who were hemiplegic due to cerebral palsy, traumatic injury to the brain, and juvenile cerebrovascular accident, the authors focused on the abnormal pattern of the affected limb in isolation without referring to compensatory mechanisms utilized by the opposite limb. The classification of the gait abnormality into four groups was based on the features of the limb movement at the ankle, knee, and hip. Each of the patterns is easily recognizable to any clinician looking after such patients. The shortcoming of their system is that, having used gait analysis technology to study the gait pattern, the groups are then described in terms of their clinical appearance. They did not utilize the data measurements to classify the groups, but rather the appearance of the limb during walking. This is a descriptive classification rather than one based on quantitative measurements and for this reason cannot automatically classify the gait pattern. The eight groups described in our system emerge automatically using clustering techniques. The system uses quantitative data to distinguish, for example, two types of recurvatum gait—one with marked plantarflexion and one with ankle dorsiflexion (group 6 versus group 7). We then applied a descriptive nomenclature identifying the major discriminator as an easy descriptive title for the quantitative difference in the individual group.

The quantitative data allows identification of a stiff-legged gait with predominant plantarflexion as a separate group from those with a good range of movement at the ankle (Group 2 versus Group 1). The quantitative measurements also cluster those limbs with a poor range of movement at all levels (Group 8). The examples that are shown represent the limb that is closest to the center of the group, ie, wazzu exhibiting measurements that are closest to the mean of the group. Although there is a range throughout the group, the principal pathologic features of the limbs are consistent throughout the group. The CODA-3 presents gait analysis data in a very clear and easily interpretable form. We have demonstrated that using an automatic clustering technique, the affected limb can be automatically placed into a discrete clinical group using the sagittal kinematic data. This classification system introduces and validates the concept of the "plegic" limb. Limbs from diplegic and hemiplegic patients share quantitative similarities and are found in each group. The system utilizes only the kinematic data in the sagittal plane and does not use coronal kinematic data. Incorporation of kinematic data in other planes may be required to subclassify the groups. This system is essentially a prototype classification attempting to convert quantitative data into descriptive patterns in a clinically relevant pattern. The ultimate goal of such a system would be to help plan appropriate treatment, which depends on the pattern of abnormality present.

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