GAIT CHARACTERISTCS AT FIVE GAIT EVENTS IN SPASTIC DIPLEGIA OF CEREBRAL PALSY

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ABSTRACT

This study investigated the detailed kinematic characteristics, angular arc and peak angle of the pelvis, and the hip, knee and ankle joints of twenty-three spastic diplegic cerebral palsy (CP) children during level walking by three-dimensional analysis. All motion parameters were systematically and statistically analyzed with emphases on the significance of motion parameters at five specific gait events: heel strike, opposite toe-off, opposite heel strike, toe off, and heel strike. According the differences in the kinematic pattern of the knee in sagittal plane, we categorized them into four CP groups: mild, crouch, recurvatum and jump. Through one-way ANOVA statistical analysis, temporal-spatial parameters and joint angles of the lower extremity were found to be significantly different among four CP groups.

For the hip joint angle, the crouch group had a tendency to keep flexed. And the maximum extension of crouch group was 14.8 degrees of flexion which was significantly lower ($p<0.05$) than the other groups. Also, the crouch group had increased hip adduction and internal rotation throughout the gait cycle. For the ankle joint angle in the sagittal plane, the crouch group had a trend to dorsiflexion and the recurvatum group was to plantarflexion. The jump group was similar to normal group at loading response, but it later had a premature plantarflexion at initial stance. For foot progress angle, the jump group shown increased toe-in pattern.

Ankle could interfere with the kinematic type of knee joint. If the ankle joint had excessive dorsiflexion during the stance phase of gait cycle, it would easily result in the crouch gait of the knee with crouch. But, if the ankle joint were equinus, it would easily result in the genu recurvatum or jump pattern of the knee. The contribution factors of the jump knee gait include maybe not only ankle equinus, but also hamstring spasticity. The jump group demonstrated greater hip flexion in initial stance, but later extends to 13.4 degrees. This is noteworthy different to Sutherland's finding.

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1. Introduction

For cerebral palsy, many neuromuscular problems can interfere with the gait performance and result in abnormal gait patterns. First of them is abnormal muscle tone (spasticity or dystonia) and it is strongly influenced by body posture and position. Secondary is relative imbalance between muscle agonists and antagonists, with time and growth, leads to fixed muscle contracture and bony deformity. The other neuromuscular problems interfering gait pattern are the impaired body balance mechanism, loss of selective motor control and dependence on primitive reflex patterns for ambulation [1].

As walking is one of those major everyday functions, various treatment methods have been used to improve cerebral palsy patients lower extremity ability for ambulation. Selective dorsal rhizotomy can reduce spasticity, thereby increasing range of motion and contributing to improvement in active function mobility [2-3]. Physical therapy including electrical stimulation [4], biofeedback [5], excise therapy [6] and prolonged stretch [7] also can help to some extent and are non-invasive. Appropriate orthotics [8] and walker [9] have helped this kind of patient with prevent of joint contracture and improvement of mobility individually. Orthopaedic surgery [10-23] is the most efficiency and direct way to treat the joint and muscle imbalance problems of the lower extremity, thereby improvement the walking ability. The surgery methods are lengthening gastrocnemius for equinus contracture [10,23], rectus femoris release and transfer for stiff knee gait [11-12], and hamstring lengthening for crouch gait [13,20], etc.

Gait analysis is the systematic measurement, description, and assessment of those quantities thought to characterize human locomotion. Through gait analysis, time-distance, kinematic, kinetic, and EMG data are acquired and analyzed to provide information that describes fundamental gait characteristics. The result of gait analysis is ultimately interpreted by the clinicians to form an assessment [2-23]. The clinical application of gait analysis allows the clinician to evaluate quantitatively the degree to which an individuals gait has been affected by an already diagnosed disorder and further to diagnose the disorder.

In 1993, Sutherland et al. classified the common gait abnormalities of the knee into four types: jump knee, crouch knee, stiff knee, and recurvatum knee [24]. Each abnormality is described by its motion analysis laboratory profile including physical examination, motion parameters, electromyography data, and force plate data. Jump knee gait is characterized by increased knee flexion in early stance phase, through initial double support, with correction of the knee wave to normal or near normal extension in mid- and late stance. In crouch gait, there is increased knee flexion through the stance phase, with variable alignment in swing phase. Recurvatum knee gait describes increased knee extension in mid-and late-stance phase, with variable knee motion in the swing phase. Unfortunately, all kinematic data in their study were calculated by two-dimensional projection method, which is inappropriate and ill-advised for cerebral palsy gait since the pathology results in significant out-of-plane motion. Also, gait parameters at five gait events, heel strike, opposite toe-off, opposite heel strike, toe off, and heel strike, are critical for clinical diagnosis and applications.

Therefore, our study investigated the detailed kinematic characteristics, angular arc and peak angle of the pelvis, and the hip, knee and ankle joints according to each knee abnormality by three-dimensional analysis. All motion parameters were systematically and statistically analyzed with emphases on the significance of motion parameters at five specific gait events: heel strike, opposite toe-off, opposite heel strike, toe off, and heel strike.

2. Method

Twenty-three patients with spastic diplegia of CP, 16 boys and 7 girls with an averaged age of nine years, were included in this investigation. The laboratory was equipped with an ExpertVision™ motion analysis system (Motion Analysis Corp., CA, USA). The motion analysis system included six CCD cameras, two VP320 video processors, a SUN workstation, a trigger and 21 pieces of 3/4~1 inch reflective markers.

Based on the Helen-Hays marker set, twenty-one reflective markers were placed on each subject. The subjects were asked to walk at self-selected speed after several comfortable trials. The procedure was video taped for later review. At least five successful trials were collected and stored. The sampling rate of the cameras was 60 Hz. The anthropometric data of each subject were also measured and used for calculation of joint angles.

The reflective makers' locations were used to define the coordinate system of linkage. OrthoTrak II software (Motion Analysis Corp., CA, USA) was used to calculate the temporal-distance parameters and the joint angles of lower extremity in gait cycle. Three normalized (100%) gait cycles for each subject were averaged before gait parameters could be determined.

Based on the method of the Sutherland, we divided the entire gait cycle according to five gait events: heel strike (HS), opposite toe off (OTO), opposite heel strike (OHS), toe off (TO) and next heel strike [25]. Therefore, the kinematics data at each gait event, beside the curves, could be analyzed statistically. Also, based on the kinematic patterns of the knee in the sagittal plane, following the Sutherland's classification [24], we separated the gait patterns of the knee into four CP groups: mild, crouch, recurvatum and jump. The mild group was defined as those who walk better than the other three groups, and those whose knee kinematic patterns could not be included in those groups. The normal data was elicited from the OrthoTrak II. Statistically, one-way ANOVA was used to find the differences in the temporal-distance parameters and the joint angles characteristics in the hip, knee and ankle among four CP groups. Finally, Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups. Pearson correlation coefficient was used to determine correlated level between each average joint angle of lower limb, its angles at five gait events and the time instant where peak joint angle occurred, and between each pair of average hip, knee and ankle angles.

3. Results

Based on the kinematic patterns of the knee in the sagittal plane, the gait patterns of 46 limbs in 23 patients could be divided into four CP groups, mild knee (n = 17), crouch knee (n = 8), recurvatum knee (n = 14), and jump knee (n = 7).

Temporal-Spatial Parameters

The velocity of jump group, 85.5 cm/sec, was significantly greater than the crouch group, 57.8 cm/sec ($p<0.05$, Tables 1). Velocity, stride length, and step length were divided by leg length for normalization. The jump and recurvatum groups were significantly larger than the crouch group ($p<0.05$) in the normalized walking velocity. The normalized walking velocity was 1.53, 1.46 and 0.95 1/sec for jump, recurvatum and crouch groups, respectively. Normalized stride length had the similar feature; the jump and recurvatum groups were significantly greater than the crouch group ($p<0.05$, Tables 2). The normalized stride length of jump, recurvatum and crouch groups was 1.41, 1.31 and 1.01, respectively. For normalized step length, the jump group was significantly larger than the crouch group ($p<0.05$). The normalized step length of jump and crouch groups were 0.71 and 0.50, respectively.

The other parameters, near significant difference ($p<0.1$) among these four CP groups, were the ratio of pelvic width to ankle spread, single support time, and double support time.

Joint angles

Pelvis
Sagittal Plane

The sagittal-plane motion curves of the pelvis are shown in Figure 1. All four CP groups had greater anterior tilt than the normal curve throughout the gait cycle. The jump knee group had increased sagittal-plane pelvic excursion. The range of motion of the pelvis was greater in the jump knee group compared to the normal and the other three groups ($p<0.05$). The dynamic range of jump and recurvatum groups, 9.1 and 8.6 degrees, was significantly larger than the mild group, 6.1 degrees ($p<0.05$).

Hip
Sagittal plane

The hip joint angle curves in sagittal plane are shown in Fig. 2. The crouch group showed excessive hip flexion during the entire gait cycle.

There was significant difference among four CP

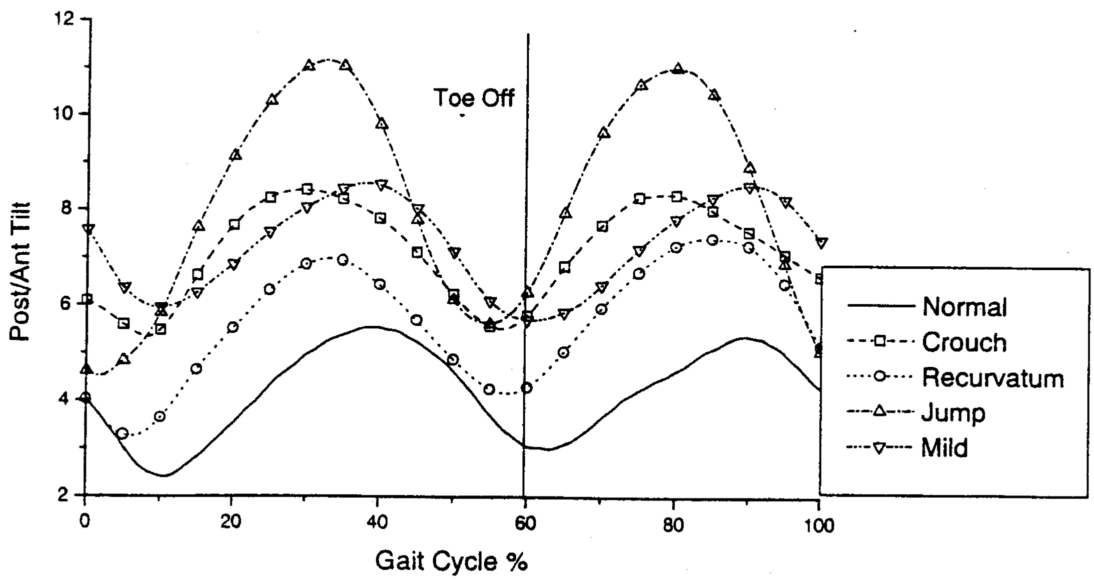

Fig. 1: Mean joint angle of pelvic in sagittal plane among the different groups

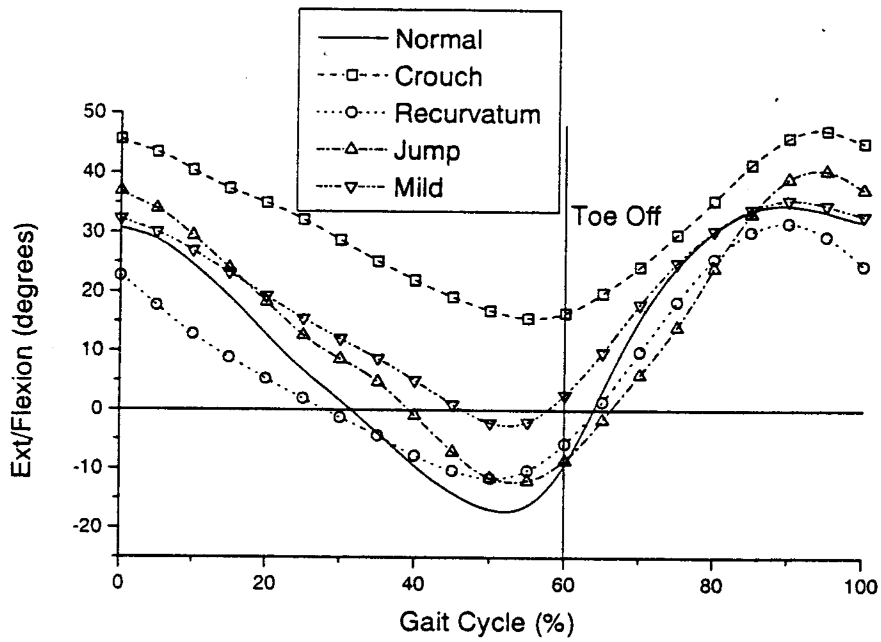

Fig. 2: Mean joint angle of hip in sagittal plane among the different groups

groups in hip joint angle at HS ($p<0.05$, Table 3). The joint angle of crouch group, 45.6 degrees, was significantly larger than the recurvatum and mild groups ($p<0.05$). In addition, the joint angle of recurvatum group, 22.7 degrees, was significantly smaller than the other three groups ($p<0.05$). At OTO, the joint angle of recurvatum group, 14.5 degrees, was significantly smaller than the mild and crouch group ($p<0.05$). At OHS, the joint angle of crouch group, 16.6 degrees, was significantly larger than the other three groups ($p<0.05$). Only crouch group had hip joint in flexion position, the others changed to extension. At TO, the crouch group was significantly larger than the jump and recurvatum groups ($p<0.05$). In addition, the recurvatum group was significantly smaller than the mild groups ($p<0.05$).

The maximum joint angle of crouch group, 48.4 degrees, was significantly larger than the recurvatum ($p<0.05$). The minimum joint angle of crouch group, 14.8 degrees, was significantly larger than the other three groups ($p<0.05$). In addition, the minimum joint angle of mild group, -1.6 degrees, was significantly larger than the recurvatum groups ($p<0.05$). The dynamic range of jump group, 55.0 degrees, was significantly larger than the mild and crouch group ($p<0.05$). In addition, the dynamic range of crouch group, 33.6 degrees, was significantly smaller than the recurvatum groups ($p<0.05$).

Coronal Plane

The hip adduction/abduction curves are shown in Fig. 3. Hip adduction was slightly increased throughout the gait cycle for crouch group. The peak abduction angle of crouch groups, 4.9 degrees, was significantly less than the recurvatum group, 13.1 degrees ($p<0.05$). The dynamic ROM of recurvatum groups, 15.3 degrees, was significantly larger than the mild group, 10.8 degrees ($p<0.05$).

Transverse Plane

The hip rotation curves are shown in Fig. 4. Excessive hip internal rotation, 5-9 degrees, was found throughout the gait cycle for jump group.

Knee

Sagittal plane

The sagittal plane motion of the knee joint (Fig. 5) in the four CP groups demonstrated their own specific characteristics. In the initial stance phase, crouch and jump groups have increased flexion. Until terminal stance phase, only crouch group had increased knee flexion, the jump group showed with correction of the knee wave to normal. The recurvatum group had increased knee extension in mid-and late-stance phase.

Statistically, there were significant differences among four CP groups in the knee joint angle at these five different gait events ($p<0.05$, Table 4). At HS, the knee joint angle of jump and crouch group, 38.4 and 50.1 degrees, were significantly larger than mild and recurvatum groups, 20.3 and 14.8 degrees ($p<0.05$). At

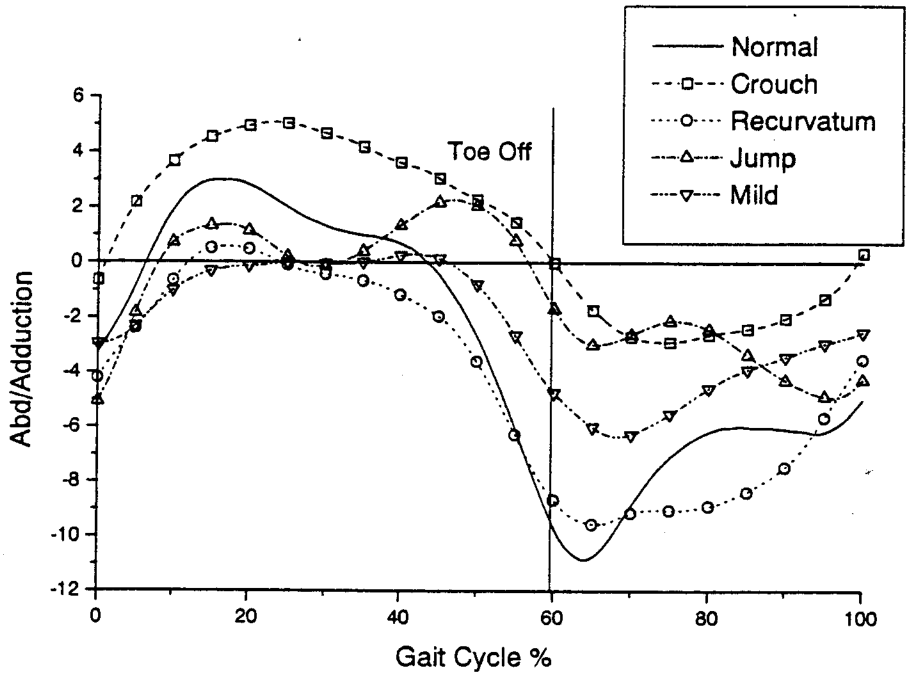

Fig. 3: Mean joint angle of hip in coronal plane among the different groups

OTO, the joint angle of four CP groups were significantly different than each other, the crouch group is largest, jump group second, mild group third and recurvatum group least. The joint angle was 55.8, 41.6, 29.2 and 13.7 degrees for crouch, jump, mild and recurvatum groups, respectively. During the period from HS to OTO, only the recurvatum group had decreased knee flexion angle, the other three groups increased. At OHS, the knee joint angle of all four CP groups decreased, the jump group reduced to 19.9 degrees was extreme. Statistically, the joint angle of crouch group, 53.7 degrees, was significantly larger than the other the three groups ($p<0.05$) and mild group, 22.8 degrees, was significantly greater than the recurvatum groups, 11.3 degrees ($p<0.05$). At TO, the knee joint angle of all four CP groups increased. The joint angle of crouch group, 65.8 degrees, was significantly larger than the other three groups ($p<0.05$) and the mild group, 45.4 degrees, was significantly larger than the recurvatum groups, 25.6 degrees ($p<0.05$).

The peak knee flexion angle of crouch group, 74.6 degrees, was significantly larger than the recurvatum and jump groups ($p<0.05$). The minimum knee flexion angle of crouch group, 45.7 degrees, was significantly larger than the other three groups ($p<0.05$). Also, the knee joint significantly extended in recurvatum group, -1.3 degrees hyperextension, compared to the other three groups ($p<0.05$). The dynamic range of crouch group, 28.9 degrees, was significantly smaller than the mild and recurvatum groups ($p<0.05$). In addition, the dynamic range of recurvatum group, 58.0 degrees, was significantly larger than the crouch and jump groups ($p<0.05$).

Ankle
Sagittal plane

The curve patterns of ankle joint angle in sagittal plane had their own characteristics (Fig. 6) in different CP groups. The crouch group showed excessive ankle dorsiflexion during the whole stance phase comparing with the normal children. The jump group had excessive dorsiflexion during initial contact, unlike crouch group, after then their ankle motion moved toward plantarflexion. The recurvatum group demonstrated excessive plantarflexion during stance phase.

The joint angle of crouch group, 7.3 degrees, was significantly larger than the recurvatum group ($p<0.05$, Table 5). At OTO, the joint angle of crouch group, 15.0 degrees, was significantly larger than the mild and recurvatum groups ($p<0.05$). In addition, the joint angle of recurvatum group was significantly smaller than the jump groups ($p<0.05$). At OHS, the joint angle of recurvatum group was significantly smaller than the crouch and mild groups ($p<0.05$). During the period of single limb support, only jump group moved in plantarflexion direction, which differed from the other

Table 1: Temporal parameters†

Temporal Parameters	Mild (N=17)	Crouch (N=8)	Recurvatum (N=14)	Jump (N=7)	F value[a]	Post-hoc[b]
Velocity (cm/sec)	76.4 (18.5)	57.8 (11.4)	75.2 (25.3)	85.5 (8.9)	2.91*	J>C[c]
Velocity/ Leg length (/sec)	1.31 (0.34)	0.95 (0.10)	1.46 (0.58)	1.53 (0.32)	3.36*	J,R>C
Cadence (steps/min)	126.3 (27.4)	113.8 (13.1)	129.3 (33.3)	130.3 (26.9)	0.64	
Stride Time (sec)	0.99 (0.17)	1.08 (0.12)	1.00 (0.28)	0.96 (0.22)	0.46	
Total Support (GC%)#	60.6 (2.4)	61.1 (4.8)	58.8 (5.9)	60.9 (3.4)	0.68	
Single Support (GC%)	39.9 (3.0)	37.3 (3.0)	41.7 (5.8)	38.6 (2.9)	2.28	
Double Support (GC%)	10.2 (2.2)	12.6 (2.2)	8.3 (5.7)	11.1 (1.9)	2.56	

† means and SD in parenthesis
#GC: gait cycle
*p<0.05; **p<0.01; ***p<0.001
[a] Statistical difference was analyzed with one-way ANOVA.
[b] Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups.
[c] C:, Crouch; J: Jump; R: Recurvatum

Table 2: Spatial parameters†

Spatial parameters	Mild (N=17)	Crouch (N=8)	Recurvatum (N=14)	Jump (N=7)	F value[a]	Post-hoc[b]
Stride Length (cm)	75.1 (21.8)	61.3 (11.5)	70.2 (18.1)	80.7 (11.0)	1.71	
Stride Length /Leg length	1.24 (0.21)	1.01 (0.15)	1.31 (0.31)	1.41 (0.06)	4.63**	J,R>C[c]
Step Length (cm)	37.8 (10.7)	30.6 (8.2)	34.7 (10.8)	40.5 (5.7)	1.59	
Step Length /Leg Length	0.63 (0.11)	0.50 (0.14)	0.65 (0.18)	0.71 (0.04)	3.23*	J >C
Step Width (cm)	12.8 (3.6)	17.9 (5.1)	16.7 (5.9)	14.3 (3.5)	2.90*	
Pelvic Width / Ankle Spread	1.23 (0.51)	0.89 (0.26)	0.92 (0.36)	0.92 (0.25)	2.29	

† means and SD in parenthesis
*p<0.05; **p<0.01; ***p<0.001
[a] Statistical difference was analyzed with one-way ANOVA.
[b] Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups.
[c] C:, Crouch; J: Jump; R: Recurvatum

Table 3: Hip joint angles† at specific gait events and its peak values in sagittal plane

Hip Angle Degree Flex(+)/Ext(-)#	Mild (N=17)	Crouch (N=8)	Recurvatum (N=14)	Jump (N=7)	F vaue[a]	Post-hoc[b]
Heel strike	33.6 (11.3)	45.6 (11.2)	22.7 (8.7)	36.9 (10.6)	8.83***	C>M>R; J>R[c]
Opposite toe off	28.2 (11.9)	38.9 (12.1)	14.5 (12.7)	27.9 (15.1)	6.80***	C,M>R
Opposite HS	-0.5 (13.2)	16.6 (14.0)	-12.2 (13.9)	-12.3 (10.6)	9.49***	C>M,R,J
Toe off	4.8 (12.4)	19.2 (14.1)	-9.6 (13.9)	-7.4 (10.5)	9.94***	C>J,R; M>R
Heel strike	34.1 (9.9)	45.2 (11.9)	24.5 (10.0)	37.4 (7.9)	7.75***	C,J>R
Max. Flex	37.5 (10.5)	48.4 (12.3)	33.2 (9.6)	41.6 (8.2)	3.97*	C>R
Mini. Flex	-1.6 (13.0)	14.8 (14.9)	-14.4 (12.7)	-13.4 (10.8)	10.02***	C>M,J,R; M>R
Dynamic ROM##	39.1 (8.9)	33.6 (10.4)	47.6 (9.5)	55.0 (4.9)	9.56***	J>M,C; R>C

† means and SD in parenthesis
#Flex: flexion; Ext: extension
##ROM: range of motion, was the absolute difference between the maximum flexion and the minimum flexion.
*p<0.05; **p<0.01; ***p<0.001
[a] Statistical difference was analyzed with one-way ANOVA.
[b] Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups.
[c] C:, Crouch; J: Jump; M: Mild; R: Recurvatum

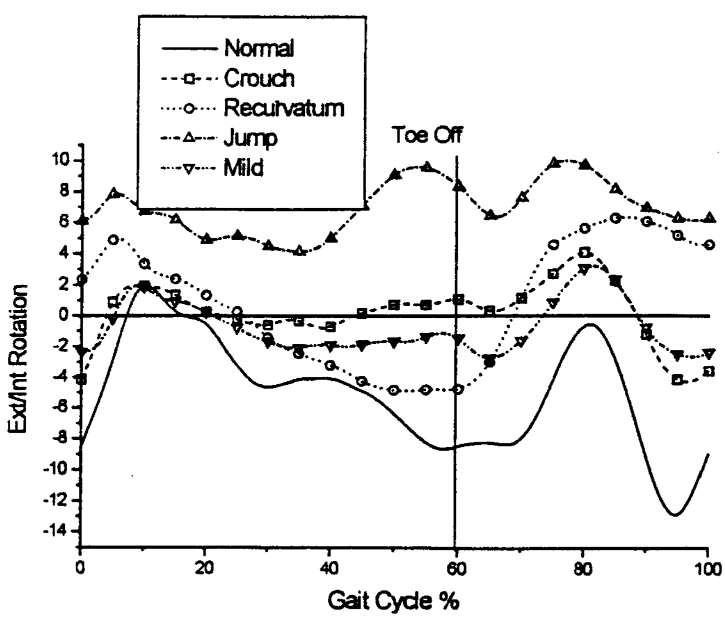

Fig. 4: Mean joint angles of hip in transverse plane among the different groups

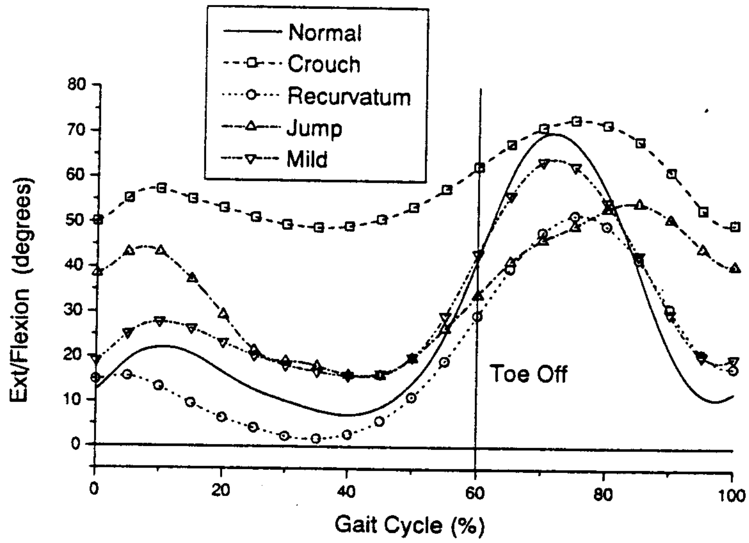

Fig. 5: Mean joint angle of knee in sagittal plane among the different groups

Table 4: Knee joint angles† at specific gait events and its peak values in sagittal plane

Knee Angle Degree Flex(+)/Ext(-)#	Mild (N=17)	Crouch (N=8)	Recurvatum (N=14)	Jump (N=7)	F value[a]	Post-hoc[b]
Heel strike	20.3 (12.9)	50.1 (13.8)	14.8 (8.9)	38.4 (6.0)	21.38***	C,J>M,R[c]
Opposite toe off	29.2 (10.1)	55.8 (7.2)	13.7 (11.5)	41.6 (7.0)	34.84***	C>J>M>R
Opposite HS	22.8 (10.2)	53.7 (10.0)	11.3 (11.3)	19.9 (5.2)	31.55***	C>M,J,R; M>R
Toe off	45.4 (12.0)	65.8 (9.1)	25.6 (8.5)	35.9 (4.9)	30.81***	C>M,J,R; M>R
Heel strike	21.2 (11.9)	50.0 (11.2)	17.9 (9.0)	40.7 (6.5)	22.80***	C,J>M,R
Max. Flex	65.1 (10.6)	74.6 (7.8)	56.6 (9.8)	56.8 (6.9)	7.4***	C>J,R
Min. Flex	12.8 (10.4)	45.7 (9.6)	-1.3 (6.1)	14.3 (5.2)	52.39***	C>J,M>R
Dynamic ROM##	52.3 (10.6)	28.9 (8.6)	58.0 (10.4)	42.5 (8.7)	16.22***	R>J,C; M>C

† means and SD in parenthesis
#Flex: flexion; Ext: extension
##ROM: range of motion, was the absolute difference between the maximum flexion and the minimum flexion.
*p<0.05; **p<0.01; ***p<0.001
[a] Statistical difference was analyzed with one-way ANOVA.
[b] Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups.
[c] C:, Crouch; J: Jump; M: Mild; R: Recurvatum

Table 5: Ankle joint angles† at specific gait events and its peak values in sagittal plane

Ankle Angle Degree DF(+)/PF(-)#	Mild (N=17)	Crouch (N=8)	Recurvatum (N=14)	Jump (N=7)	F value[a]	Post-hoc[b]
Heel strike	-1.5 (7.7)	7.3 (10.3)	-6.4 (7.2)	-0.6 (6.3)	5.13**	C>R[c]
Opposite toe off	5.2 (8.4)	15.0 (9.7)	-0.6 (5.5)	9.9 (6.4)	7.89***	C>M,R; J>R[c]
Opposite HS	13.1 (10.8)	18.6 (14.7)	-1.1 (7.6)	6.2 (12.8)	6.84***	C,M>R
Toe off	4.3 (11.4)	7.5 (12.2)	-7.5 (8.4)	-4.8 (14.7)	4.48**	C,M>R
Heel strike	-1.4 (5.6)	7.4 (8.3)	-3.9 (5.6)	-0.4 (7.0)	5.63**	C>M,R
Max. DF	14.7 (11.2)	21.0 (13.8)	5.8 (6.5)	12.2 (7.0)	4.35**	C>R
Mini. DF	-6.6 (9.6)	1.5 (11.3)	-14.5 (8.3)	-10.8 (13.4)	4.51**	C>R
Dynamic ROM##	21.3 (9.9)	19.5 (5.8)	20.2 (8.7)	23.0 (7.5)	0.26	

† means and SD in parenthesis
#DF: dorsiflexion; PF: plantarflexion
##ROM: range of motion, was the absolute difference between the maximum dorsiflexion and the minimum dorsiflexion.
*p<0.05; **p<0.01; ***p<0.001
[a] Statistical difference was analyzed with one-way ANOVA.
[b] Tukey's post-hoc test was used to determine the significance between each pair of the four CP groups.
[c] C:, Crouch; J: Jump; M: Mild; R: Recurvatum

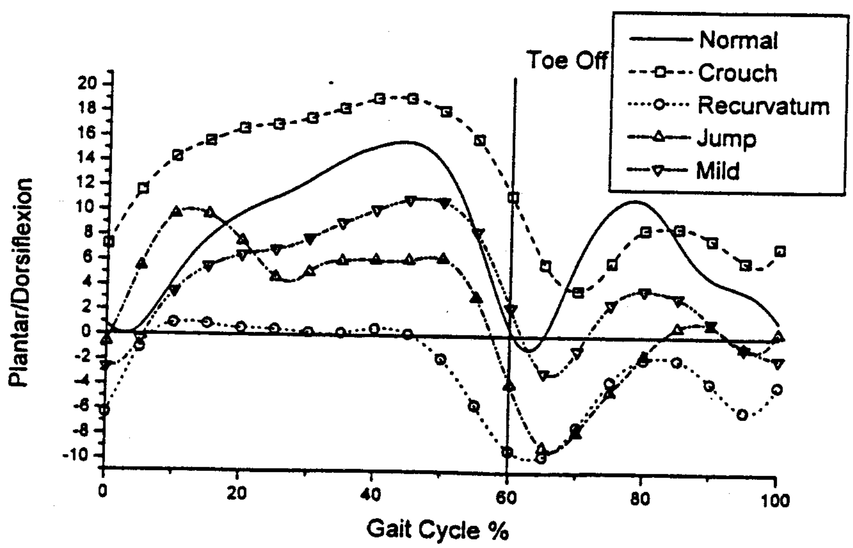

Fig. 6: Mean joint angle of ankle in sagittal plane among the different groups

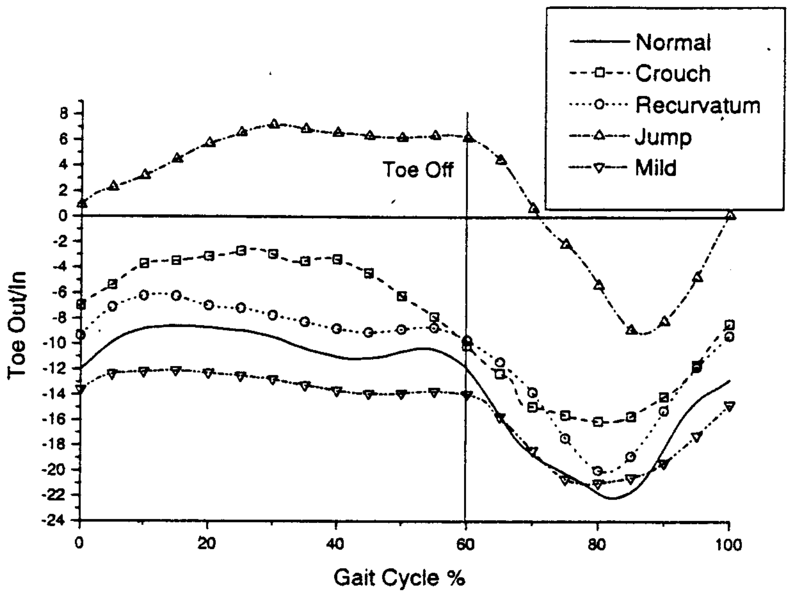

Fig. 7: Mean foot progression angles among the different groups

three groups. At TO, the recurvatum group was significantly smaller than the crouch and mild groups ($p<0.05$).

The peak dorsiflexion angle was significantly larger in crouch group, 21.0 degrees, than in the recurvatum group ($p<0.05$). The peak plantarflexion, 14.5 degrees, in the recurvatum group was significantly larger than the crouch group ($p<0.05$).

Transverse Plane

Foot progression angles are shown in Fig. 7. Foot toe in was increased throughout the gait cycle for jump group. Insufficient toe-out angle, five degrees than normal, was also found in the crouch group throughout the gait cycle.

4. Discussion

This study has investigated the detailed time-distance parameters and angular motion of the pelvis and the hip, knee and ankle joints according to each knee abnormality by a three-dimensional method. All motion parameters were systematically and statistically analyzed with emphases on the significance of motion parameters at five specific gait events, heel strike, opposite toe-off, opposite heel strike, toe off, and heel strike. Except the important sagittal plane movements, the coronal and transverse plane movements were also discussed.

In our study, the velocities of four CP groups were significantly lower than the age matched normal group. The walking velocity of normal seven-year-old children is 114±17 cm/sec reported by Sutherland [25]. Comparing the four CP groups' cadence with normal seven-year-old children, 143±14 steps/min, only the crouch group had significantly lower value. All four CP groups had less stride and step length compared with the normal children, 96.5±8.2 cm and 48.3±4.2 cm, respectively. Among four CP groups, the crouch group had the slowest velocity. The mean cadence of the crouch group was113.8±13.1 steps/min that was smaller than the other groups, but not up to significant level. The smaller velocity in the crouch group results from decreased stride length and step length. We find the normalized stride length and step length in crouch group was significantly shorter than the other groups. All four CP groups had smaller walking velocity than normal due to reduced stride length and step length. Except crouch group, cadence was not the contributor to the walking velocity. This agrees with the Gage's conclusion on the prerequisites of normal gait [1]. He states that the five prerequisites of normal gait are stability in stance, clearance of foot in swing, appropriate pre-positioning of the foot in swing, adequate step length and conservation of energy. Cadence is not one required prerequisite of normal gait.

The sagittal plane motion of the knee joint in the four CP groups agrees with the criteria of grouping according to Sutherland. In the initial stance phase, the knee flexed significantly larger in crouch and jump groups compared to mild and recurvatum groups. In terminal stance phase, the knee flexion angle in crouch group was largest among four CP groups. The knee angle in jump group, however, did not show significant difference from the mild and recurvatum groups. To the contrast, recurvatum group had the largest knee extension in stance phase among four CP. groups. The crouch group flexed thirty degrees more than normal in stance phase. At pre-swing, the difference was reduced to twenty degrees. The jump group flexed 38.4 degrees at initial contact and returned to14.3 degrees maximum extension in mid-stance. This agrees with the finding of Sutherland. He stated the jump group flexed greater than thirty degrees and return to normal extension about 10 ~ 20 degrees in mid-stance phase. The recurvatum group showed the maximum extension 1.3 degree hyper-extended, which also agrees with the Sutherland definition. Therefore, the classification of the knee abnormality can represent the individual groups.

The crouch group showed excessive hip flexion during the entire gait cycle, which was fifteen degrees larger than normal children data. It is similar to Sutherland description and may result from iliopsoas contracture. The crouch group also showed excessive ankle dorsiflexion during the whole stance phase compared to the normal children. Sutherland reported that four reasons of crouch group include contracture of biceps femoris, weakness of quadriceps, weakness or contracture of triceps surae and iliopsoas contracture [24]. Contracture of biceps femoris easily makes the knee lack of extension during the late swing phase, while iliopsoas contracture makes the hip excessive flexion. Weakness of triceps surae will make the ankle excessive dorsiflexion and the tibia excessive advance at stance. The ground reaction force will direct after the knee and produce a flexor torque around it such that the crouch gait appears. Iliopsoas contracture usually accompanies with biceps femoris contracture, because the biceps femoris is a two-joint muscle, not only knee flexor but also hip extensor. When the iliopsoas was short, the hip will demonstrated excessive flexion. And this position forces the biceps femoris to be stretched such that muscle will compensate with knee flexion for alleviating the stretch force. Thereafter, the hip flexion, knee flexion and ankle dorsiflexion were accompanying together in crouch group. The coronal-plane motion of hip joint showed slightly excessive adduction in stance phase in crouch group. This will make the bilateral thighs of the subject together and could interfere walking progress. The reason why crouch gait accompanies with hip adduction may be due to adductor longus and adductor brevis muscles contracture. These two muscles act as adductors, flexors and internal rotators at hip joint. Excessive hip flexion position of crouch gait could result in these two muscles shortening. Therefore, crouch gait also shows a slightly internal rotation in the hip transverse-plane motion.

The recurvatum group demonstrated phenomenon of equinus foot, with excessive ankle plantarflexion during stance phase, agreeing with the finding of Sutherland. Equinus foot easily make gait with recurvatum type. Major reason is that the spastic triceps surae caused foot lost the normal first two rockers, heel rocker and ankle rocker. This will result in the knee joint with premature extensor torque. The persisted existed torque will bring the posterior structure of knee into over-stretched and excessive lengthening. Lately, genu recurvatum is clinically manifested.

The jump group demonstrated greater hip flexion in initial stance, but later extension to 13.4 degrees. This is noteworthy different to Sutherland's finding. He stated that the hip flexion is exaggerated throughout the gait cycle and full extension in stance phase is absent in jump gait. In jump group, the ankle had excessive dorsiflexion in initial contact and loading response and moved toward plantarflexion at initial single leg stance. Sutherland reported that biceps femoris spasticity is the major etiology of jump knee gait [24]. The jump group shows extreme knee flexion during the late swing and initial stance phase. With appropriate muscle strength of quadriceps and triceps surae, the knee can demonstrate normal extension during the mid- and late- stance phase. Our study finds jump group has premature ankle plantarflexion at the moment of opposite leg toe off (initial of single leg stance) which may relate with the triceps surae spasticity. This is different from the crouch group and is the major factor to have different knee motion patterns between the two groups. Due to premature ankle plantarflexion, the increasing external extensor torque of knee overcame the original internal flexor torque. Therefore, the knee joint was possible to display normal extension. For pelvis, the jump group demonstrated increased excursion in sagittal plane. It could mean the poor dissociation between pelvis and femur in jump group. In transverse plane, the jump group showed increased hip internal rotation, which may be from the femoral anteversion [1,18,22]. Excessive femoral anteversion decreases the moment arms of the abductors, and internal rotation of the hip is a compensatory mechanism that restores these moment arms and preserves abduction capacity [18]. Also the jump group had increased toe-in of progression angle. This could manifest the increased hip internal rotation without enough external tibial torsion for compensation in jump group [1,18].

Ankle could interfere with the kinematic pattern of knee joint. If the ankle joint were equinus (increased plantarflexion), the triceps muscle would retard the tibia advanced, the ground reaction force would make an external extensor torque around knee and hip joints. And it would easily result in the genu recurvatum (diminished flexion) or jump pattern of the knee as well as decreased hip flexion. If the ankle joint had excessive dorsiflexion during the stance phase of gait cycle, the tibia would advance too much; the ground reaction force would make an external flexor torque around knee and hip joints. And it would easily result in the crouch gait (increased flexion) of the knee as well as increased hip flexion. The contribution factors of the jump knee gait include maybe not only ankle equinus, but also hamstring spasticity.

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