Severity of Spine Malalignment on Center of Pressure Progression during Level Walking in Subjects with Adolescent Idiopathic Scoliosis

Jen-Suh Chern- IEEE Member, Chia-Chi Kao, Po-Lian Lai, Chi-Wen Lung, Wen-Jer Chen

Abstract—**Center of pressure (CoP) progression during level walking in subjects with Adolescents Idiopathic Scoliosis (AIS) was measured. Participants were divided into three groups according to scoliosis severity. CoP progression among groups was compared quantitatively and qualitatively. The results showed that scoliosis severity affects CoP progression significantly in the hind-foot and forefoot areas. This result indicated that spine alignment might affect the control of heel, ankle and toe rockers in the ankle-foot complex. The effects of scoliosis severity is mainly on the CoP of right foot plantar surface, indicating asymmetrical influence of IS on bilateral lower limb coordination during walking. These results might contribute to musculoskeletal complains over the apparatus within trunk-foot in the later lives of this population.**

I. Introduction

Walking is the most frequent daily functional movement. Dynamic postural control systems are responsible for the precise motor control of multiple segments within the trunk-foot linkage while walking. Kinematic and kinetic parameters are accepted as summery indices representing the function of postural control systems [1,2]. Gait variability is correlated with impairment of dynamic postural control systems [3]. Increment of gait variability indicated severity of dysfunction of the postural control systems and dynamic instability [4].

The stance phase of a walking cycle, which is 60% of the whole cycle, initiates by initial contact of the heel with the ground and follows by foot flat when the entire plantar surface contacting with the group. Then, the heel takes off the ground. and the stance phase terminates at the moment when the toe is off the ground [5]. For efficient walking and minimize the load the segments accepted when the foot comes in contact with the ground, the followings are required (1) normal function of four rockers within the ankle-foot complex: heel rocker, ankle rocker, midfoot rocker, and toe rocker, (2) proper skeletal alignment between segments within the trunk-foot linkage, (3) efficient neuromuscular control of the apparatus with the linkage, and (4) proper foot structure. The foot is the segment that makes contact with the ground. It plays an important role in shock absorption especially during heel contact and foot flat stages [1, 2]. Besides, the four rockers within the ankle-foot complex determine the way the foot makes contact with the ground and is important not only in modulating the load but for momentum generation for forward propulsion. Change of the alignment of the segment within the linkage system could change the function of the four rockers and therefore change the load accepted by the foot. Malfunctioning of the components could decrease the walking efficiency and increase the load that the segments have to bear [6]. In the long run, accumulated injuries or degenerative change of the apparatus in the linkage might happen.

Center of pressure (CoP) is a two dimensional position vector representing the instantaneous point of action of the ground reaction force that generated due to the contact of body part with the supporting surface. Plantar CoP during the stance phase formulates a trajectory by a series of coordinates across time span of the stance phase. The trajectory progresses from the hindfoot to the forefoot. Several studies quantified the CoP trajectory and highlighted that the CoP displacement and CoP velocity as potential measures of foot structure and functions of four rockers of the ankle-foot complex. For example, it was expected that a medial displacement of CoP trajectory related to low arched feet; Cop trajectory variability was associated with impaired rocker control. Studies have shown that progression of CoP trajectory from hindfoot through forefoot could also affected by abnormality of more remote apparatus such as hip and knee. However, the relationship between spine alignment and CoP progression remains uncertain. Very few studies had ever measured the plantar CoP during walking in subjects with spine malalignment.

Idiopathic scoliosis (IS) is a three-dimensional spine malalignment [7]. It is most often seen spine derangement in adolescents and could progression profoundly as the body statue grows [8]. But its etiology, causation and progression mechanism remains unclear. Diagnosis of IS depends on measurement of Cobb's angle on x-ray photography and surgical treatment is indicated when the Cobb's angle is greater than 40°.

Several studies measured kinematic parameters during walking in subjects with Adolescent Idiopathic Scoliosis (AIS) [9-12]. Some concluded that the gait pattern in AIS is different from that in normal control but others find no

Resrach supported by NSC99-2410-H-182-036, CMRPD1B0161, BMRP898.

J-S. Chern is with the Chang Gung University, Occupational Therapy Department, Kwei-Shan Township, Taoyuan County, 333, Taiwan. (Phone: +886-3-2118800;fax:+886-3-2118616;e-mail:jschern@ mail.cgu.edu.tw).

C-C. Gao, was with Chang Gung University, Occupational Therapy Department, Kwei-Shan Township, Taoyuan County, 333, Taiwan. (e-mail: iru8fu6@gmail.com).

C-W Lung is with the Creative Design Department, Asia University, Wufeng, Taichung 41354, Taiwan. (e-mail: cwlung@asia.edu.tw).

P-L. Lai is with Orthopaedic Department, Lin-Kuo Chang Gung Memorial Hospital, Taoyuan County, Kwei-Shan, 333, Taiwan. (e-mail: polianglai@gmail.com)

difference. This might be because that the Kinematic parameters are not sensitive enough to detect the mild effects of spine malalignment on gait function. This study intended to define gait characteristics with CoP trajectory and determine whether or not it is possible to detect changes of Cobb's angle by CoP progression patterns during walking. Chockalingam et al's [13] study is the only one study that measured CoP progression pattern of IS patients during walking, and they found high variability of CoP progression among 9 AIS with varied Cobb's angle. This result indicated that CoP progression pattern might be promising in detecting the severity of spine mal-alignment in AIS patients.

II. Methods

A. Participants

Thirty AIS were recruited conveniently. They were allocated into three groups: mild group with Cobb's angle 10°~25°), moderate group with Cobb's angle 26°~40°), and severe group with Cobb's angle >40°. Table 1 shows the demographic data for each group, including average age, sex distribution, average anthropometric data, body mass index (BMI) and average Cobb's angle. Three groups were comparable in all data, except the average Cobb's angle. In addition to IS, all participants reported no other known musculoskeletal, neuromuscular, and/or nervous system diagnosis or abnormality that could affects their ability to walk.

B. Experimental Procedure and Instruments

The present study employed a foot pressure measurement system (Footscan, Rsscan International Co., Belguim), including a 0.5 meter pressure mat (size: 578 mm x 418 mm x 12 mm, number of sensors: 4096, sensor dimension: 7.62 mm x 5.08 mm) and a 3-D interface box (220 mm x 190 mm x 94 mm, data acquisition frequency: up to 500 Hz), to record CoP coordinates of stance phase during level walking. All data were recorded at a measurement frequency of 500 Hz and processed using Scientific Footscan software. The system is calibrated before recording.

After signed informed consent form, researchers record basic information (age, body height and weight, functional balancing capacity) first. Functional balancing capacity was measure by Getup-and-Go test (GUG). GUG is a standardized measure of dynamic postural control and correlated with biomechanical measure of balance. Then, the participants were instructed to walk with barefoot through a 5-meter walkway with the pressure mat embedded in the middle. Each participant was allowed a number of walking trials prior to data collection until they were feeling comfortable with the environmental setup and are confidents to step on the mat with either the right or left foot. Subjects performed several trials for each foot and walked at their comfortable normal walking speed. A trial is considered valid only when the subject striking only one heel (either the right or the left) on the mat and the system captures complete footprint of the stance limb. The x- and y-coordinate of the CoP under each individual foot were collected and ready for further analysis. Average data of three valid trials for each foot were used for statistical analysis.

C. Data processing and statistical analysis

The CoP coordinates for each foot for each participant was exported as Excel files and imported to a custom written Matlab program (Matlab 7.0, Mathworks Inc) for further data processing. We divided CoP data of a single stance phase into three portions to show CoP progressions at the hindfoot, midfoot and forefoot areas respectively. The hindfoot portion is approximately 20%, the midfoot portion is approximately 60% and forefoot portion is approximately 20% of the plantar surface. The progression of the CoP along the three portions corresponds to four rockers that are responsible for the forward progression of CoP. It is well accepted that the CoP progression from hindfoot through midfoot to forefoot denote not only the control of ankle-foot mechanism but also the inter-segment coordination within the trunk-foot linkage system [11, 12].

The following parameters were calculated for each portion to quantify the CoP roll-over pattern: CoP displacement in medial-lateral (CoPX) direction, CoP displacement in anterior-posterior direction (CoPY), peak CoP velocity (PCoPV), peak CoP acceleration (PCoPa), latency (in percent of the stance phase) of PCoPV (LPCoPV) and PCoPa (LPCoPa) . All data processing was done by custom-written Matlab programs. Difference between groups in those parameters was analyzed by one way analysis of variance (ANOVA). Correlations between Cobb's angles (as continuous variables) and gait parameters were analyzed by Pearson correlation coefficients. The CoP roll-over pattern of three groups was pooled on the same diagram by Matlab program to qualitatively compare CoP progression pattern between groups. All statistical analysis was done by using SPSS 19.0 software package and significant level was set at $p < .05$.

III. Results

Table 1 shows the basic information and anthropometric data of the three groups. There is no significant difference between groups in age, sex distribution, BMI, foot size, body height and weight, and functional balancing ability. All participants were of double-curve scoliosis. The major curve is at either the thoracic or lumbar spine and the convex of the major curve is to the right. The average Cobb's angle was 19.9° (SD = 4.33°) for mild group, 31.8° (SD = 4.26°) for moderate group and 53.4° (SD = 6.5°) for severe group.

As shown in table 2, all parameters in each portion of the left foot were not different among groups except the LPCoPa ($p < .05$) in the forefoot portion. The LPCoPa in severe group is significantly longer than the other two groups ($p < .05$). Parameters of the right foot were significantly different among groups in PCoPV, LPCoPV, PCoPa and LPCoPa ($p < .05$) but the difference were only at the hind foot area. Post hoc analysis showed that PCoPV and PCoPa in moderate group is significantly greater than in severe group (post hock statistical data not shown, $p < .05$). Finally, the LPCoPV and LPCoPa is significantly shorter in moderate group than in severe group (post hock statistical data not shown, $p < .05$).

TABLE I. BASIC INFORMATION AND ANTHROPOMETRIC DATA

	Mild	Moderate	Severe	*p*
Sex (n) (M/F)	10(1/9)	10(1/9)	10(2/8)	
Cobb's Angle (Deg)	19.9±4.3	31.8±4.3	53.4±6.1	.000 *
Age (Ave±SD)	14.9±1.7	16.4±3.3	15.3±3.1	.461
BH(Centimeter)	158.9±3.1	161.1±4.4	162.4±7.3	.314
BW(Kilogram)	49.3±9.8	48.2±6.1	48.3±8.2	.947
BMI	19.4±3.3	18.6±2.4	18.6±2.4	.570
GUG(Secs)	6.8±1.5	6.9±0.9	6.5±0.8	.678

*p< .05, M/F: male/female, Deg: degrees, Ave: average, SD: standard deviation, BH: body height, BW: body weight, BMI: body mass index, GUG: get-up-go test, Secs: seconds

The results showed no correlations between Cobb's angle and any one gait parameters (r = .014~.164, p > .05). Fig. 1 is the plantar CoP paths during stance phase while walking, showing that scoliosis severity affects CoP progression asymmetrically. The CoP trajectory over the left foot shifts laterally at hindfoot portion, medially in the midfoot portion and, again, laterally in the forefoot portion for the moderate group. The CoP trajectory over the right foot shows hierarchical effects of scoliosis severity on the trajectory in the midfoot portion. As the severity increase, the lateral deviation of the CoP increase. Furthermore, scoliosis severity affects hindfoot and forefoot of the both feet similarly. Table 2 further shows that the difference among groups is observed through PCoPV and PCoPa in the hindfoot area.

IV. Discussion

This is the first study investigated the effects of scoliosis severity on progression of CoP during level walking. Our results showed that CoP progression pattern was associated with of severity of scoliosis.

A. CoP Velocity

Our results are different from Mahaudens et al.'s study [10]. They measured kinematics and electromyography for AIS subjects divided into three groups of scoliosis severity (< 20°, between 20° and 40°, >40°) and they concluded that increment of Cobb's angle was not associated with increased differences in gait parameters. Our results indicated that temporal parameters derived from CoP progression under the plantar surface could serve as a sensitive screening test for gait control dynamics and detecting the severity of scoliosis. As shown in table 2, the CoP travels at a much faster velocity in moderate group comparing with the other two groups. Besides, the latency for the velocity to change in the moderate group is shorter than subjects in the other two groups. These results indicated that the ankle-foot control during walking is a function of Cobb's angle. Previous study suggested that decreasing range of motion in ankle plantar-dorsiflexion might be one of the contributing factor for increment of CoP velocity during walking in elderly subjects [3, 4]. In this study, we did not measure the ankle range of motion. Adolescents are usually not likely to have hypo-mobile ankle joint[10]. There is no existing research reporting abnormal ankle joint range of motion. Therefore, we hypothesze that modulation of ankle-foot motor control might be affected by the severity of scoliosis in adolescents. Thoracolumbar spine misalignment might change ankle-foot motor control during level walking.

B. Asymmetric CoP progression in Hindfoot Portion

Several studies reported asymmetry paravertebral muscle activity during both static and dynamic postural control in moderate scoliosis subjects but not in other group of AIS [10]. Most studies reported increased muscle activity on the convex side, while Hopf et al. [14] showed a significant decrease in paravertebral muscle activity. Mahaudens et al.[10] argued that the asymmetry muscle activity is the results of biomechanical compensation. Our finding that only subjects with moderate severity scoliosis showed bilateral asymmetrical CoP path indicated that not only the focal neuromuscular modulation occurs but the central commends for control of CoP path might be altered [7]. And this central mechanism modulation might happen during the progression of Cobb's angle. We therefore suggested that aggressive preventive education or training along the period of Cobb's angle progression might be necessary to inhibit development of long-term central abnormality.

C. CoP Path Characteristics

Our final results showed that the CoP deviated laterally at initial contract, medially at midfoot portion and laterally again at forefoot portion (Fig. 1). Lateral deviation of CoP at initial contact indicated that the moderate scoliosis subject contact with the ground with more foot inversion; medial deviation of CoP suggested faster foot eversion after heel and ankle rocker; lateral shift of CoP at forefoot portion indicated early foot eversion for toe off. Chiu et al.[4] suggested that medial-lateral deviation of plantar CoP is associated with load distribution and the motor control of the ankle-foot mechanism. Our results suggested that the load over the lateral border at the hind foot, medial border at the midfoot (i.e. the medial longitudinal arch) and lateral border at the forefoot in moderate scoliosis is more than the other two groups. This results showing greater amount of deviation of CoP in moderate scoliosis suggested potentially heavier load for the central nervous system in gait control [7]. Less efficient gait control in moderate scoliosis is therefore indicated.

TABLE II. STATISTICAL SUMMERY

Hindfoot		**Left Foot**		**Right Foot**	
Sources	**Group**	**Mean±SD**	***p***	**Mean±SD**	***p***
CoPX (mm)	Mild	7.7±5.8	.47	7.6±2.4	.09
	Mod	5.8±2.1		5.7±1.6	
	Sev	6.0±2.1		6.3±1.7	
CoPY (mm)	Mild	60.8±14.1	.11	63.4±16.5	.24
	Mod	69.6±6.1		72.3±10.1	
	Sev	53.2±24.6		63.8±11.3	
LPCoPV(%)	Mild	8.8±1.0	.55	7.6±1.9	.01*
	Mod	7.3±2.5		6.1±1.0	
	Sev	9.6±4.3		8.9±2.	
PCoPV (m/s)	Mild	0.9±0.4	.13	0.8±0.2	.04*
	Mod	1.1±0.4		1.0±0.3	
	Sev	0.8±0.3		0.8±0.2	
LPCoPa(%)	Mild	12.2±3.8	.52	10.1±2.8	.00*
	Mod	10.5±2.9		8.3±1.6	
	Sev	11.11±3.30		12.11±2.30	
PCoPa (m/ S^2)	Mild	-22.7±18.5	.19	-22.0±14.4	.04*
	Mod	-29.8±17.4		-30.2±15.1	

	Sev	-17.0±8.0		-15.9±3.1	
Midfoot		**Left Foot**		**Right Foot**	
CoPX (mm)	Mild	9.3±3.9	.47	6.1±1.9	.08
	Mod	7.4±3.5		7.8±3.6	
	Sev	7.9±3.3		5.0±2.3	
CoPY (mm)	Mild	99.5±13.9	.50	94.6±13.5	.34
	Mod	94.9±7.9		89.4±9.3	
	Sev	102.5±18.8		97.2±12.7	
LPCoPV(%)	Mild	55.0±7.4	.71	53.9±10.4	.62
	Mod	57.5±6.5		51.0±9.6	
	Sev	57.1±7.9		55.2±9.4	
PCoPV (m/s)	Mild	0.5±0.1	.63	0.5±0.1	.61
	Mod	0.5±0.1		0.5±0.2	
	Sev	0.4±0.1		0.4±0.1	
LPCoPa(%)	Mild	53.9±10.9	.42	55.6±8.9	.83
	Mod	55.3±8.8		53.5±8.2	
	Sev	59.1±6.6		55.2±7.0	
PCoPa (m/ S^2)	Mild	-8.6±4.7	.31	-9.1±4.4	.25
	Mod	-8.9±3.5		-9.1±4.9	
	Sev	-6.5±2.5		-6.2±3.5	
Forefoot		**Left Foot**		**Right Foot**	
CoPX (mm)	Mild	19.8±8.2	.52	15.0±6.9	.97
	Mod	15.3±5.8		14.3±9.2	
	Sev	18.1±10.9		14.9±5.1	
CoPY (mm)	Mild	49.2±6.2	.20	50.8±7.9	.63
	Mod	50.9±4.9		51.1±9.8	
	Sev	44.9±10.3		47.9±6.6	
LPCoPV(%)	Mild	92.8±2.3	.42	92.8±1.5	.15
	Mod	93.4±1.7		91.9±2.3	
	Sev	94.0±1.9		93.8±2.4	
PCoPV (m/s)	Mild	0.7±0.1	.55	0.8±0.1	.77
	Mod	0.8±0.1		0.8±0.2	
	Sev	0.7±0.2		0.8±0.1	
LPCoPa(%)	Mild	90.0±2.5	.45	88.7±1.9	.03*
	Mod	90.6±1.8		88.8±2.2	
	Sev	91.3±2.1		91.3±2.0	
PCoPa (m/ S^2)	Mild	19.8±7.1	.75	21.9±7.2	.95
	Mod	19.8±6.9		23.03±9.6	
	Sev	17.6±8.6		22.7±6.4	

*p< .05, CoPX: CoP displacement in medial-lateral direction, CoPY: CoP displacement in anterior-posterior direction, LPCoPV: Latency of peak CoP velocity, PCoPV: peak CoP velocity, LPCoPa: Latency of peak CoP acceleration, PCoPA: Peak CoP acceleration, Mod: Moderate, Sev: Severe..

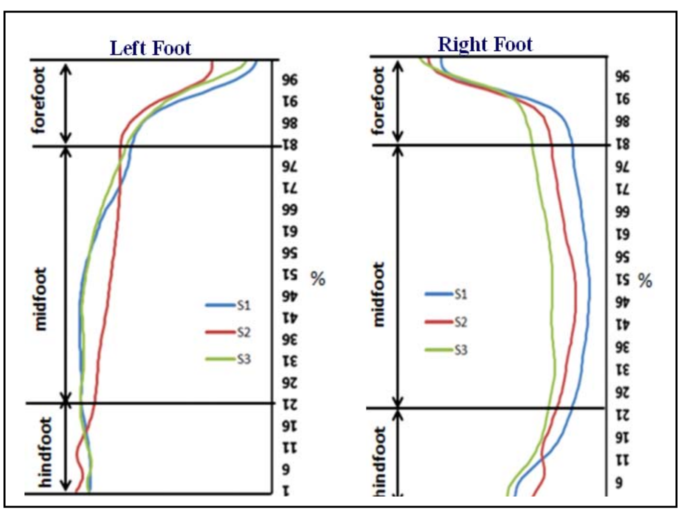

Figure 1. Plantar CoP path under the (A) left foot and (B) right foot.

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