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Using a bi-planar postural stability model to assess children with scoliosis

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Abstract—**This study examines the postural stability of children with idiopathic scoliosis, using experimental data and a model of sway that includes mediolateral (ML) and anterioposterial (AP) components. The experimental data includes center of pressure (COP) measurements calculated from data acquired using two Advanced Medical Technology, Inc. (AMTI) force plates. Sway metrics are computed and compared with the model simulation, which successfully reproduced the clinical data from 16 children with scoliosis and 20 typically-developing children. This study is part of the first phase of a multi-year study designed to systematically assess whether fusing the spine to L4 in children with scoliosis has a significant impact on physical function and quality of life.**

Keywords—biomechanics, postural stability, model, sway metrics, idiopathic scoliosis.

I. INTRODUCTION

Fusing the spine to Lumbar 4 is a common surgical intervention in children with idiopathic scoliosis when the spine curvature exceeds 40 degrees. Scoliosis surgery is one of the longest and most complex orthopedic procedures performed on children, so a systematic analysis of its impact on physical function and quality of life is important.

One element of a comprehensive assessment of this surgery is the present study, which analyzes postural control during quiet standing for children with scoliosis prior to a planned spinal fusion surgery. Postural control provides important insights into the ability of the central nervous system to integrate information from the vestibular, visual, and somatosensory systems [1]. Quantifying differences in postural control pre- and post-surgery for children with scoliosis may provide insight into the effectiveness of this intervention.

Postural control is typically measured by tracking COP [2] calculated from forces and moments acquired from subjects standing on a force plate. The COP data can be used to compute a variety of parameters in both the time and frequency domains that assist in characterizing balance [3-5]. COP data and the calculated parameters are often limited to the AP plane, because the magnitude of AP sway can be double that of ML sway in healthy adults [6,7]. This study uses two force plates to examine sway in both the AP and ML planes, since ML sway may play a significant role in posture control for subjects with abnormal balance [8].

Many models of postural control consist of an inverted pendulum with a single link segment confined to the AP plane [9-14]. Here we employ a bi-planar model of AP and ML sway, shown to be successful in assessing balance in healthy adults and children with cerebral palsy [15,16]. This model uses proportional-integral-derivative (PID) controllers in both planes, based on a similar model of AP sway [17]. Sway parameters were calculated from the COP data output by the model and compared to the sway metrics calculated from the COP data acquired from 16 children with scoliosis and 20 typically-developing children. The comparisons produced no statistically significant differences between experimental data and model data. The model parameters for the PID controllers provide an additional characterization of balance.

II. METHODOLOGY

A. Instrumentation and Data Analysis

This study used two fixed force plates (AMTI OTS6-500) to acquire forces and moments along the standard *x*-, *y*-, and *z*- axes. This data was amplified by an AMTI amplification unit and sampled at 100 Hz using a National Instruments Data Acquisition card (PCI-6031-E).

The COP coordinates in the AP and ML planes were calculated from the measured forces and moments for each force plate, and used to derive the resultant COP in the AP and ML planes, effectively combining the data from the two force plates [16]. This calculated COP data was filtered by a 4th-order low pass Butterworth filter with a cutoff frequency of 5 Hz, and the mean of the COP was removed from the resulting time series. The results from three 30-second subject trials were averaged, and the middle 20 seconds of this average was used in subsequent calculations to ensure signal stationarity [18].

Parameters that characterize sway in both the time and frequency domains were calculated [4]. A total of 34 parameters were calculated in 12 categories. For most categories, three different values were computed: the AP sway component, the ML sway component and resultant sway component. Only the resultant sway components are reported here.

The parameters are described as follows:

Mean Distance (MD)

$$MD = \frac{\sum |\mathrm{COP}|}{\mathrm{n}} \tag{1}$$

Root mean square (RMS)

$$RMS = \sqrt{\frac{\sum |\mathrm{COP}|^2}{\mathrm{n}}} \tag{2}$$

Maximum distance (range)

$$range = \max(COP) - \min(COP) \tag{3}$$

Total Travel Distance (TX)

$$TX = \sum_{i=1}^{n-1} \left\{ \left[\mathrm{COP}\, ap_{\mathrm{i+1}} - \mathrm{COP}\, ap_{\mathrm{i}}\right]^2 + \left[\mathrm{COP}\, ml_{\mathrm{i+1}} - \mathrm{COP}\, ml_{\mathrm{i}}\right]^2 \right\} \tag{4}$$

Sway Area (SA)

$$SA = \frac{1}{2T} \sum_{i=1}^{n-1} \left| \mathrm{COP}\, ap_{\mathrm{i+1}} \times \mathrm{COP}\, ml_{\mathrm{i}} - \mathrm{COP}\, ap_{\mathrm{i}} - \mathrm{COP}\, ml_{\mathrm{i+1}} \right| \tag{5}$$

Mean Velocity (MV)

$$MV = \frac{TX}{\mathrm{T}} \tag{6}$$

Mean Frequency (MF)

$$MF = \frac{MV}{4\sqrt{2}MD} \tag{7}$$

Total Power (TP)

$$TP = \sum_{no}^{n1} P(f), \qquad no = \frac{0.15}{\Delta f}, \qquad n1 = \frac{5}{\Delta f} \tag{8}$$

In (1) – (8) n is the number of samples (2000), T is the testing time (20 seconds), Δf is the frequency increment, and $P(f)$ is the power spectrum of the time domain signal, calculated using a fast Fourier transform.

B. Subject Population and Test Protocol

Data was collected from 16 children with idiopathic scoliosis and 20 typically-developing children. All children and their parents or guardians consented to participate, as mandated by IRB requirements. The subjects with a diagnosis of idiopathic scoliosis did not have neuromuscular disorders or known syndromes. Demographic data for this subject group is summarized in Table 1. The 20 typically-developing children were selected to match this demographic profile. All participants were able to stand without assistance for at least 30 seconds.

Number of subjects	**Age [years]**	**Weight [kg]**	**Height [cm]**
13 females 3 males	14.8 ± 2.1	59.8 ± 14.4	151.9 ± 30.7

Table 1. Demographic data for participants with idiopathic scoliosis (mean ± standard deviation).

Subjects were asked to stand comfortably with one foot on each fixed force plate. Tracings of their feet were made for repeatability during the three trials. For each trial the subject was instructed to focus on a fixed target placed at eye level at a distance of 1.5m. Each trial ran for 30 seconds, and subjects were permitted to sit between trials.

C. Bi-planar model

A block diagram of the bi-planar inverted pendulum model with PID control in each plane is shown in Fig. 1. In the inverted pendulum model J is the moment of inertia, m is body mass, h is body height and g is gravity. Note that disturbance torque is generated by a white noise source filtered by a low pass filter with gain Kn. The PID controller is described by its three gains: proportional gain Kp, derivative gain Kd, and integral gain Ki. A time delay Td models the conduction delay between the nerve signals generated in the brain and the muscles that control balance.

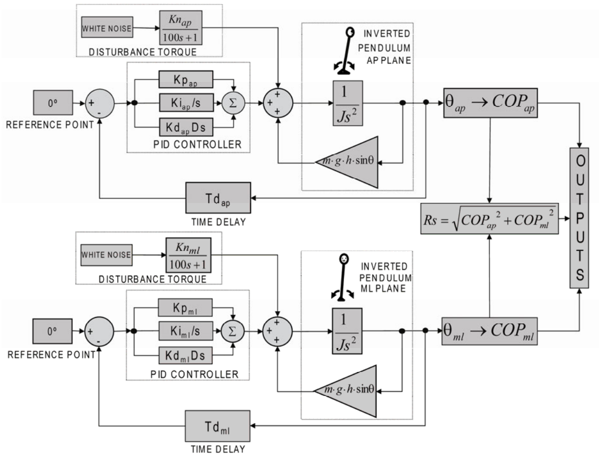

Fig. 1. Bi-planar model of postural sway.

The model was simulated with Simulink (Mathworks, Inc.) The simulation employed a fifth-order Domand-Prince ode solver with a fixed time step of 10 ms [17]. Initially the model parameters (Kp, Kd, Ki, Kn, and Td) were set to values resulting from our previous study of children with cerebral palsy [17]. The model parameters were then systematically varied based on the way each parameter affects the computed sway metrics until the values of the sway metrics from the model matched the values of the sway metrics from the experimental data. All metric values from simulated data fell within 1 standard deviation of the sway metrics from experimental data with no statistically significant differences, based on an unpaired t-test with $p = 0.1$.

III. RESULTS

Sway parameter values were calculated from subject trials of children with scoliosis prior to spinal fusion surgery. These values were compared with sway parameters calculated from subject trials of typically-developing children. The results are shown in Table 2. Statistically significant differences were found for all parameter values except mean frequency. ANOVA tests were used for the statistical comparisons between the subject populations [19].

The bi-planar model was then simulated, adjusting its parameters until the model was able to reproduce the sway parameter values calculated from experimental data. A comparison between the sway parameter values calculated using experimental data from the 16 children with scoliosis and the sway parameter values calculated from the bi-planar model is shown in Table 3. There are no statistically significant differences in these two sets of sway parameter values, indicating that the model parameters were tuned to match the experimental data.

Sway parameter	**Children with scoliosis (mean of 16 subjects)**	**Typically-developing children (mean of 20 subjects)**
MD [cm]	4.54 ± 3.10	5.05 ± 2.68
RMS [cm]	5.33 ± 3.78	5.87 ± 3.13
Range [cm]	13.78 ± 10.66	14.50 ± 10.45
TX [cm]	293.2 ± 207.9	229.4 ± 108.2
SA [cm^2]	27.28 ± 41.77	21.52 ± 27.67
MV [cm/s]	14.66 ± 10.40	11.47 ± 5.41
MF [Hz]	0.538 ± 0.141	0.399 ± 0.124
TP [W]	10.71 ± 20.93	9.85 ± 15.71

Table 2. Sway parameter values from children with scoliosis compared with sway parameter values from typically-developing children.

The model parameters underwent a second phase of tuning, this time to create a match between sway parameters computed from the model and sway parameters computed from experimental data for typically-developing children. The resulting parameters for the model of typically-developing children were compared with the parameters for the model of children with scoliosis. The results are summarized in Table 4.

Sway parameter	**Children with scoliosis**	**Bi-planar model**
MD [cm]	4.54 ± 3.10	3.73
RMS [cm]	5.33 ± 3.78	4.19
Range [cm]	13.78 ± 10.66	9.32
TX [cm]	293.2 ± 207.9	298.5
SA [cm^2]	27.28 ± 41.77	17.28
MV [cm/s]	14.66 ± 10.40	14.92
MF [Hz]	0.538 ± 0.141	0.650
TP [W]	10.71 ± 20.93	3.73

Table 3. Sway parameter values from experimental data for children with scoliosis compared with sway parameter values from the bi-planar model.

Model parameter	**Model of children with scoliosis**	**Model of typically-developing children**
Kp(AP) [Nm·deg^{-1}]	11.0	9.0
Kd(AP) [Nm·s·deg^{-1}]	4.8	4.83
Ki(AP) [Nm· s^{-1}·deg^{-1}]	0.6	0.6
Td(AP) [s]	0.175	0.165
Kn(AP)	200	260
Kp(ML) [Nm·deg^{-1}]	11.0	10.0
Kd(ML) [Nm·s·deg^{-1}]	4.8	4.83
Ki(ML) [Nm· s^{-1}·deg^{-1}]	0.6	0.5
Td(ML) [s]	0.171	0.165
Kn(ML)	160	150

Table 4. Model parameters for a bi-planar model of children with scoliosis compared with model parameters for a bi-planar model of typically-developing children.

IV. DISCUSSION

The comparison of sway parameter values for children with scoliosis and typically-developing children found statistically significant differences for all time domain parameters, which include mean distance of the COP (MD), rms value of the COP (RMS), range of the COP (range), total distance traveled by the COP (TX), and sway area covered by the COP (SA). This comparison also found statistically significant differences in two of the three frequency domain parameters, mean frequency content of the COP (MF) and total power in the frequency spectrum of the COP (TP). It has been shown that time domain sway parameters are related to the amplitude of postural sway, while frequency domain sway parameters are related to the regulation of postural sway [20]. These results suggest that sway magnitude is significantly different between the two populations but the regulation of sway is similar.

The results in Table 3, comparing the values of sway parameters computed from children with scoliosis with values of sway parameters computed from the model simulation, show that the model was successful in replicating the experimental data. This model has also successfully replicated experimental data acquired from healthy adults [15] and children with diplegic and hemiplegic cerebral palsy [16]. We expect this model to assist in assessing the effects of planned spinal fusion for the 16 children with scoliosis.

Table 4 shows that the bi-planar model can also be tuned to match sway parameter values calculated from experimental data for typically-developing children. Comparing model parameters between the model for children with scoliosis and the model for typically-developing children shows that most of the model parameters values are the same. Differences in model parameter values are seen for the proportional gain in the PID controller for the AP plane [*Kp(AP)*] and for the noise gain in the low pass filter used to generate disturbance torque in the AP plane [*Kn(AP)*]. The proportional gain corresponds to the stiffness of the model, suggesting that the main effect of scoliosis from a modeling perspective is an increase in stiffness in the AP plane. We anticipate the model may be useful in assessing any changes in stiffness that result from the planned spinal fusions.

The model was tuned to yield one set of model parameter values that resulted in sway parameter data matched to the children with scoliosis, and another set of model parameter values that resulted in sway parameter data matched to typically-developing children. The process of tuning the parameters stopped once an acceptable match with experimental data was found. There may be additional model parameter sets that also match experimental data, as the model is not yet capable of optimizing a search to yield a "best set" of parameters.

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