Association of spinal deformity and pelvic tilt with gait asymmetry in adolescent idiopathic scoliosis patients: Investigation of ground reaction force

Yang Sun Park a, b, Young Tae Lim c, Kyung Koh b, Jong Moon Kim d, Hyun Joon Kwon b, e, Ji Seung Yang f, Jae Kun Shim b, e, g, h, *  

a Department of Physical Education, Hanyang University, Seoul, South Korea  
b Department of Kinesiology, University of Maryland, College Park, MD, USA  
c Division of Sports Science, Konkuk University, Chungju, South Korea  
d Department of Physical Medicine and Rehabilitation, School of Medicine, Konkuk University, Chungju, South Korea  
e Department of Mechanical Engineering, Kyung Hee University, Yong-in, South Korea  
f Department of Human Development and Quantitative Methodology, University of Maryland, College Park, MD, USA  
g Neuroscience and Cognitive Science Graduate Program, University of Maryland, College Park, MD, USA  
h Fischell Department of Bioengineering, University of Maryland, College Park, MD, USA

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a prevalent orthopedic problem in children ages 10 to 16 years (Roubal et al., 1999; Weinstein et al., 2008). AIS is reported to have an onset rate as high as 3% in this age range (Altaf et al., 2013). If left untreated, scoliosis can often cause asymmetry of the trunk, which may lead to more serious cardiorespiratory and other orthopedic problems (Donath and Miller, 2009; Roubal et al., 1999; Tsiiligannis and Grivas, 2012). Although genetic, physiological, and biomechanical factors are considered to contribute to the onset and progression of AIS (Mahaudens et al., 2009; Syczewska et al., 2012), the underlying mechanisms of AIS are not yet clear.

In order to understand biomechanical contributors and consequences of AIS, we investigated the ground reaction force (GRF) during gait. The asymmetrical morphology in the trunk caused by the spinal deformity in AIS patients would likely result in asymmetry of GRF between feet. Although the gait asymmetry in AIS has been frequently investigated, previous studies presented conflicting results. Some studies indicated that AIS patients' gait is accompanied with significant gait
asymmetry, as shown by differences in the vertical (Herzog et al., 1989; Schizas et al., 1998; Yang et al., 2013), anterior–posterior, and mediolateral (Chockalingam et al., 2004; Giakas et al., 1996) components of GRF; however, other studies have found no significant relationship between gait asymmetry in GRF and the severity of the spinal deformity (Schizas et al., 1998).

One of possible reasons on conflicting findings shown in the previous studies is that AIS accompanies both different shapes between left and right sides with a curved spine in the frontal plane and inertial asymmetry with uneven medial-lateral distribution of the upper body (Allard et al., 2004; Nault et al., 2002; Raso et al., 1998). Morphological and inertial asymmetries in AIS may cause the asymmetry in GRF during gait. Previous studies have reported that between-leg asymmetry in GRF during locomotion has been found in patients with neuromusculoskeletal problems in one of the legs (Beattie et al., 1990; Gurney, 2002; Kaufman et al., 1996; Patterson et al., 2008). Also, it has been reported that both asymmetric shapes of the body (Connolly and Michael, 1984; Dalleau et al., 2007; Nault et al., 2002; Stokes, 1997; Wu and MacLeod, 2001) and inertial differences (Ackerman et al., 2015; DeVita et al., 1991; Kaufman et al., 2012) between left and right sides of the body are reported to be associated with asymmetrical gait patterns. Thus, we predicted that the spinal deformity in the frontal plane caused by AIS might cause asymmetrical mass distribution of the upper body in the medial-lateral direction, which may cause between-limb differences in GRF magnitudes. We also predicted that the pelvic tilt, which was reported to be associated with leg length discrepancy (Raczkowski et al., 2010; Young et al., 2000), might cause between-limb differences in temporal parameters of GRF.

The main purpose of this study was to investigate whether the asymmetry of GRF magnitude and time variables during gait in AIS patients would be associated with spinal deformity and pelvic tilt. Our hypothesis was two-fold. First, we expected that the between-leg asymmetry of GRF time variables would be greater in AIS patients with greater spinal deformity in the frontal plane. Second, we hypothesized that the asymmetry of GRF time variables would be greater in AIS patients with greater pelvic tilt in the frontal plane.

2. Methods

2.1. Participants

Fourteen AIS patients participated in the study (See Table 1): 3 males and 11 females with the average age of 15.2 years (SD 1.3), average weight of 53 kg (SD 8.2), and average height of 161.8 cm (SD 6.9).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Gender</th>
<th>Compensatory curve</th>
<th>ACA</th>
<th>MCA</th>
<th>PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17</td>
<td>M</td>
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<td>4.72</td>
<td>19.54</td>
<td>2.07</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>F</td>
<td>Right lumbar</td>
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<td>23.97</td>
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</tr>
<tr>
<td>3</td>
<td>17</td>
<td>F</td>
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<td>−15.42</td>
<td>4.76</td>
</tr>
<tr>
<td>4</td>
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<td>F</td>
<td>Left thoracic</td>
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<td>−10.01</td>
<td>1.14</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>M</td>
<td>Right thoracic</td>
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<td>18.66</td>
<td>1.89</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>F</td>
<td>Right thoracic</td>
<td>31.32</td>
<td>31.32</td>
<td>3.18</td>
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<tr>
<td>7</td>
<td>16</td>
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<td>4.11</td>
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<td>8</td>
<td>16</td>
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<td>1.00</td>
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<tr>
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<tr>
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<td>Left thoracolumbar</td>
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<td>−18.44</td>
<td>3.92</td>
</tr>
</tbody>
</table>

ACA: adjusted Cobb's angle, MCA: maximum Cobb's angle, PT: angle of pelvic tilt.

All the participants gave informed consent based on the procedures approved by Institutional Review Board Human Research Konkuk University Chung-ju Hospital.

2.2. Procedure

The human experimentation has been approved by the University Institutional Review Board. Each subject received information regarding the purpose and methods of the study and signed a university approved consent form. Prior to the main experiment, each subject's height and weight were measured. Anterior–posterior and lateral views of whole spine scanogram were taken at both standing upright and standing with hip flexion. Total four images of whole spine scanogram were obtained using a radiography system (RAD-14, VARIAN medical systems, Palo Alto, CA, USA) with the following tube settings: 250 mA at 80 Kvp for cervical spine, and 250 mA at 95 Kvp for thoracic and lumbar spine. The image of anterior-posterior view at the standing upright was used for Cobb's angle measurement and the rest of images were used for exclusion criteria for scoliosis diagnosis (Horne et al., 2014). For the gait tests, the subjects walked on a 20-m walkway with two force platforms (MSA-6, AMTI, WaterTown, MA, USA) embedded in the middle. Two consecutive foot strikes where each foot was successfully recorded on each force plate were analyzed. The subject repeated the task until two successful foot strikes were recorded. None of the subjects performed the task more than three repetitions. The experimenter controlled the subject’s start position so that each subject naturally stepped on the first force platform with the right foot and the second force platform with the left foot. Subjects were unaware of the existence of the force platforms and were asked to walk as naturally as possible. The average walking speed of the subjects was 1.22 m/s (SD 0.17), which was similar to previously reported walking speeds for this age group (Mahaudens et al., 2005).

2.3. Data analysis

2.3.1. Quantification of spinal deformity and pelvic tilt

Cobb's angle is often measured as the angle between lines drawn parallel to the two most tilted vertebrae of the spinal curvature in the frontal plane (James, 1976), but there are often cases in which two or more curvatures are present in the spine. In order to address the issue of multiple spine curvatures, we calculated a new measure named the Adjusted Cobb’s Angle (ACA). For the current study, we quantified three different angles for analysis: 1) the maximum Cobb’s angle (MCA; Fig. 1) – the largest angle among the absolute values of all existing Cobb’s angles greater than 10° (e.g., thoracic angle, lumbar angle, thoracic-lumbar angle, etc.) (Syczewska et al., 2012), which is traditionally used for the quantification of spine deformity in AIS patients, 2) the Adjusted Cobb’s Angle – the sum of Cobb’s angles that considers the directional signs of the angles (e.g., the angle that goes counter-clockwise from respect to the perpendicular line of the vertebral base at the bottom of the curve is positive and vice versa), and 3) the pelvic tilt (PT) – the angle between the line connecting the right and left iliac crests and the horizontal line in the frontal plane (Fig. 1).

Cobb’s angles and PT were measured using a customized Matlab program with Image Processing Toolbox (Matlab Inc., Natick, MA, USA). A digitally scanned radiograph of anterior–posterior view at the standing upright was used to digitize anatomical landmarks in order to compute the Cobb’s angles and PT using a 19-in. computer screen with 1024 × 1280 resolutions.

2.3.2. Calculation of GRF asymmetry

To assess the gait asymmetry between legs in GRF variables, the Asymmetry Index (AI) was calculated using the following formula
AI = \frac{R - L}{0.5 + (R + L)} \tag{1}

where R and L represent the values of a specific GRF component from the right foot and left foot, respectively.

From the vertical component of GRF, the first peak force (Fz1), second peak force (Fz2), average force during the braking phase (Fz1_{AVG}), average force during the propulsion phase (Fz2_{AVG}), average force over the whole stance phase (Fz_{AVG}), and stance contact time (T_{stance}) were measured for further analysis (Fig. 2). From the anterior–posterior component, the negative peak (Fy1), positive peak (Fy2), average of negative force (Fy1_{AVG}), average of positive force (Fy2_{AVG}), average force of absolute sum of negative and positive forces (|Fy_{AVG}|), braking phase time (T_{braking}), propulsion phase time (T_{propulsion}), and stance contact time (T_{stance}) were quantified (Fig. 2).

We excluded the medial-lateral component of the GRF in the analysis because this force component varied greatly between subjects (Goh et al., 1998).

Finally, correlation and regression analyses were conducted to test research hypotheses. To achieve a higher level of power 0.5 to detect correlation 0.3 give the sample size, we adopted an alpha level of 0.1 for this study after conducting power analysis. As the false discovery rate is a concern due to multiple comparisons of correlation coefficients, we followed Benjamini–Hochberg procedure which is known as more powerful than Bonferroni correction (Hochberg and Benjamini, 1990) to obtain adjusted critical values and made statistical inferences.

3. Results

3.1. GRF peaks and averages

AI's of four GRF magnitude variables (Fig. 3) showed statistically significant correlation coefficients with ACA or MCA, while none of the GRF magnitude variables showed significant correlation coefficients...
with PT (Table 2). In the anterior–posterior (A-P) direction, the braking phase showed significant correlation coefficients between A-P peak force and A-P average force (Fy1 and Fy1AVG) versus ACA (Fig. 3A and B) and A-P average force (Fy1AVG) versus MCA (Fig. 3C), while the propulsion phase showed no significant correlation coefficients in any A-P GRF variables. The linear regression model showed that AIs of Fy1, Fy1AVG, and Fy1 were greater in subjects with greater ACA or MCA. These results support the first hypothesis that the severity of spinal deformity is associated with GRF magnitude gait asymmetry.

3.2. GRF temporal parameters

AIs of braking phase (Tbraking) and propulsion phase (Tpropulsion) of stance phase contact time and total stance time (Tstance) showed significant correlation coefficients with PT, while AIs of GRF time variables showed no significant correlation coefficients with MCA or ACA (Table 2). The linear regression model showed that the asymmetry of Tbraking, Tpropulsion, and Tstance were greater in subjects with greater PT (Fig. 3). In other words, the leg side with a more elevated pelvic position had longer contact times during the braking phase, propulsion phase and stance phase. These results support the second hypothesis that asymmetry of the GRF time variables would be greater in subjects with greater pelvic tilt.

4. Discussion

The aim of this study was to investigate the relationship between the spinal deformity and GRF gait asymmetry in adolescents with idiopathic scoliosis during walking. Our results from the regression analysis between GRF magnitudes and spinal deformity indicated that there were associations of the asymmetry of GRF magnitude variables with ACA and MCA, while there were no significant associations between these variables and PT. These results imply that the AIS patients with more dextroscoliosis (i.e., a spinal curve to the right), as compared to levoscoliosis (i.e., a spinal curve to the left), showed greater GRF magnitudes in the right side as compared to the left. Specifically, the one-side deviation of the upper body center of mass from the midsagittal plane.

Fig. 3. Statistically significant relationships between AIs of GRF variables vs. ACA (A, B, C, D, E, and F). A, B, and C regression analysis between the ACA (abscissa) and AI of Fy1, and AI of Fy1AVG (ordinate). C show regression analysis between the MCA (abscissa) and AI of Fy1AVG (ordinate). D, E, and F show regression analysis between the PT (abscissa) and AI of Tbraking, AI of Tpropulsion, and AI of Tstance (ordinate). Correlation of determinations (R²) and linear regression models are shown from simple regression analysis.
may have resulted in the increases of GRF magnitudes on the specific side.

We developed a novel quantification of spinal deformity, ACA, which considers multiple curvatures and directionality of curvature in the spinal deformity in addition to the traditional MCA measure that considers only one scoliotic angle. Based on our results, we suggested that ACA is a better predictor to estimate gait asymmetry of GRF in AIS gait. In this study, both ACA and MCA showed significant correlations with the asymmetry of GRF magnitude. ACA showed one more significant correlation coefficient (i.e., Fy1) with GRF variables than MCA. However, two significant correlation coefficients were greater with ACA and only one showed a greater correlation coefficient with MCA. It seems that it is inconclusive to determine which measure between MCA and ACA is more sensitive for the prediction of spinal deformity. Contrary to our findings, some previous studies reported no relationship between the GRF asymmetry and scoliotic deformity (Chockalingam et al., 2004; Schizas et al., 1998; Yang et al., 2013). Those studies used the traditional Cobb's angle (i.e., MCA) as an indicator of the severity of scoliotic deformity, but did not consider the direction and multiple spinal curves. Also, previous studies used the absolute magnitude of GRF asymmetry between legs without taking the direction of the GRF asymmetry into account (Chockalingam et al., 2004; Schizas et al., 1998), which made it impossible to differentiate which side of the leg was lengthier or shorter. However, our study considered the direction and types of the spinal curves (i.e., single or multiple curvatures), in the conjunction with asymmetry between limbs by employing ACA and MCA for the quantification of spinal deformity, which seem to more sensitive to prediction of GRF asymmetry in AIS gait.

Interestingly, our study found that the asymmetry of the GRF magnitude was associated with the scoliotic curvature only during the braking phase (including initial contact). GRF is primarily responsible for musculoskeletal loading in joints during the contact phase of locomotion (Winter, 1991), and greater GRF on one limb with scoliotic deformity can potentially lead to greater mechanical loading of that limb (Bruyneel et al., 2010). We speculate that excessive GRF asymmetry during the braking phase may cause further long-term negative consequences throughout development and aging in AIS patients, although it is not clear what threshold would be used to define “excessive” asymmetry.

Previous studies have reported moderate to significant associations between pelvic tilt or leg length discrepancy and scoliosis (Cassella and Hall, 1991; Mahaudens et al., 2005; Raczkowski et al., 2010; Radcliff et al., 2013; Syczewskia et al., 2012; Young et al., 2000). Kaufman et al. (1996) found that the greater the leg length discrepancy is, the larger the gait asymmetry. Kaufman also reported a difference in stance time, as high as 12% in the stance time between the shorter and the longer limb during walking28. Perttunen et al. (2004) also investigated patients with leg length discrepancy and reported that in the short leg, both the heel rise and the push-off (i.e., propulsion phase) occurred quite early and caused the asymmetric gait (Perttunen et al., 2004). Our finding was consistent with previous reports in that the leg with a higher pelvic tilt experienced an extended contact time during walking in scoliosis patients.

There are few limitations in the current study. First, we present a new measure of spinal deformity, ACA in order to include multiple curvatures in the calculation. However, a systematic research on the validity and reliability of this measure has not been conducted, and this knowledge gap warrants a future study. Second, our analysis was limited to GRF, while additional information such as joint kinematics (e.g., joint angles, velocity, and acceleration) and kinetics (e.g., joint force and torque) and whole body behaviors would have provided more insights regarding the gait asymmetry in AIS patients. In addition, the spinal deformity causes to rotate the spine in all three dimensions (Stokes, 1994) and may dynamically change during walking; however, our methodology was limited to assess the static spinal deformity measured in the frontal plane. Future research involving three-dimensional analysis of both spinal deformity and gait parameters may be able to reveal more biomechanical mechanisms of gait in this population. Last, the focus of our study was to investigate whether there was an association between the spinal deformity and the gait asymmetry during walking at the preferred speed. It is currently unknown if the gait speed influences gait asymmetry, especially AIS, which warrants a future study.

5. Conclusions

In summary, our study shows that the gait asymmetry of A-P magnitudes and time variables of GRF are associated with the severity of the spinal deformities and pelvic tilt caused by AIS. We concluded that the spinal deformity is generally associated with the between-leg asymmetry in A-P GRF magnitudes, while the pelvic tilt is associated with the asymmetry of the time variables.

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References
