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Biomechanics

Biomechanical Modeling of Spine Flexibility and Its Relationship to Spinal Range of Motion and Idiopathic Scoliosis

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Abstract

Study design: Cross-sectional.
Objective: To examine the relationships between spine morphology, spine flexibility, and idiopathic scoliosis.
Background: Girls have a higher incidence of clinically significant scoliosis than boys, along with smaller vertebrae and greater flexibility. Based on biomechanical modeling, we hypothesized that smaller vertebral width relative to intervertebral disc (IVD) height would be associated with both greater lateral flexibility of the spine and with idiopathic scoliosis.
Methods: Magnetic resonance imaging was used to measure IVD height, vertebral width, and paraspinous musculature in 22 girls with mild and moderate idiopathic scoliosis and 29 girls without scoliosis ages 9–13 years. Clinical measurement of maximum lateral bending was also performed in the girls without scoliosis. A simple biomechanical model was used to estimate bending angle from the ratio of IVD height to vertebral half-width for L1–L4. The average ratio (R_{avg}) and calculated total bending angle (α_{tot}) for L1–L4 were compared to the clinical measurements of lateral bending flexibility in the control group. These measures were also compared between the scoliosis and control groups.
Results: There was a significant positive relationship between clinical flexibility and both R_{avg} ($p = .041$) and α_{tot} ($p = .042$) adjusting for skeletal age, height, body mass index, and paraspinous muscle area as covariates. The ratio was significantly higher ($R_{avg} = 0.45$ vs. 0.38, $p < .0001$) and the bending angle was significantly greater ($\alpha_{tot} = 107°$ vs. 89°, $p < .0001$) for girls with scoliosis compared with controls.
Conclusion: These results suggest that differences in spine morphology and corresponding changes in spine flexibility may be related to idiopathic scoliosis. If these relationships can be corroborated in larger prospective studies, these easily measured morphologic traits may contribute to a better understanding of the etiology of idiopathic scoliosis and an improved ability to predict scoliosis progression.
Level of Evidence: Level III.

Keywords: Scoliosis; Vertebrae; Flexibility; Magnetic resonance imaging; Bone morphology

Introduction

Scoliosis affects approximately seven million people in the United States, and 85% of cases are considered idiopathic [1]. Little is known about the etiology of how scoliosis develops and progresses beyond the risk factors of female gender and family history [1-4]. There is a significant sex disparity in scoliosis, with girls having more severe deformities than boys and five to eight times greater likelihood of requiring treatment [1]. Females are born with smaller cross-sectional dimensions of the vertebrae compared with males [5], and this discrepancy in vertebral size persists throughout life independent of differences in body size [6,7]. The smaller female vertebrae are associated with a greater range of motion of the spine [8-11]. Greater spine flexibility could increase the magnitude of asymmetric loading on the

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vertebrae, stimulating increased longitudinal growth on the convex side of the curve and decreased longitudinal growth on the concave side [12-14]. This would result in increased wedging of the vertebrae and greater progression of the scoliosis curve.

Variations in spinal morphology have evolved to optimize the function of the spine in providing support, flexibility, and protection of the spinal cord and nerves. Factors that influence movement of the spine include the surrounding musculature, paraspinal ligaments, apophyseal joints, vertebral body morphology, and intervertebral disc (IVD) thickness and compliance. The IVD confers flexibility to an otherwise rigid spine [15,16]. Greater range of movement occurs when the disc height is relatively large and the dimensions of the vertebral end plate are relatively small. Prior radiographic studies have suggested that girls with slender vertebrae have greater spinal flexibility than those with larger vertebral bodies [17,18]. The height of the IVD is also an important determinant of the kinematic properties of the spine [8]. However, the exact relationship between vertebral morphology and spinal flexibility has not been corroborated using direct measurements.

In this pilot study, we used multiplanar magnetic resonance imaging (MRI) and biomechanical modeling to (1) examine the relationship between spinal morphology and spine flexibility in healthy girls and (2) compare spinal morphology between girls with idiopathic scoliosis and controls without scoliosis. We hypothesized that taller IVD height relative to vertebral width would be associated with both greater spine flexibility and with idiopathic scoliosis.

Materials and Methods

Study subjects

This study examined 22 girls with mild and moderate idiopathic scoliosis and 29 controls. Only white girls were included to avoid the confounding effects of sex and race on vertebral size. Participants had to be between 9 and 13 years old to be included in the study. The scoliosis group consisted of patients diagnosed with idiopathic scoliosis who had MRI examinations of the spine at our institution between January 2014 and April 2016. Only patients with a typical AIS deformity (right thoracic curve) and a Cobb angle ≤30° were included. The study was restricted to curves ≤30° to focus on mild and moderate curves that had not been treated and would have minimal deformity in the lumbar spine. Subjects in the control group were recruited prospectively from October 2015 to April 2016 and were required to be within the 3rd to 97th percentiles for height and weight according to the Centers for Disease Control and Prevention growth charts. The study protocol was approved by the Institutional Review Board (IRB) for Clinical Investigations at Children's Hospital Los Angeles. Written assent and consent were obtained from all subjects who were examined prospectively and their parent(s). Some existing data were accessed retrospectively under a waiver of consent granted by the IRB.

Skeletal maturation was assessed from radiographs of the left wrist obtained on the same day as the MRI examination. Bone age was determined from the radiographs by a radiologist using the method of Gilsanz and Ratib [19]. Subjects whose chronological and skeletal ages differed by more than two standard deviations from mean age-adjusted normal values were excluded from further evaluation.

MRI measurements of vertebral morphology and paraspinous musculature

All MRI examinations were performed without the use of general anesthesia and/or contrast enhancement. Subjects were examined using a 1.5- or 3.0-Tesla whole-body MRI scanner (Achieva R3.2; Philips Healthcare, Cleveland, Ohio) with a standard 15-channel spine coil. Three-dimensional T2-weighted turbo spin echo scans were acquired at 1.0-mm slice thickness with a TE of 120 ms, a TR of 1600 ms, and a flip angle of 90°. For the purpose of this study, vertebral width was measured at the midportion of the L1, L2, L3, and L4 vertebral bodies in the coronal plane. The cross-sectional areas of psoas major, quadratus lumborum, and the erector muscles of the spine were measured at the midportion of the same vertebrae in a plane parallel to the end plates (Fig. 1). IVD height was measured as the average height at the left and right edges of the T12–L1, L1–L2, L2–L3, and L3–L4 interspaces in the coronal plane, and the average of the left and right measurements were used for analysis. All measurements were analyzed offline with commercial image segmentation software (SliceOmatic; Tomovision, Magog, Canada). The coefficients of variation for repeated MRI measurements of vertebral width, IVD height, and truncal musculature were between 1.2% and 4.0%.

A biomechanical model was used to estimate spine flexibility based on the vertebral and IVD dimensions (Fig. 2). The maximum rotation between two adjacent

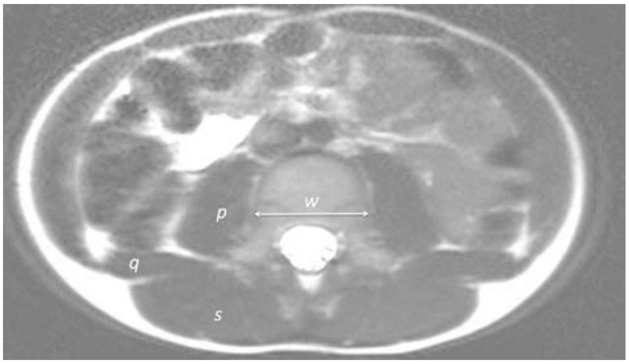

Fig. 1. An MRI transverse section of the muscles at the lumbar level shows the psoas (*p*), the quadratus lumborum (*q*), and the postvertebral group of muscles described collectively as the sacrospinalis/erector spinae (*s*) as well as the third lumbar vertebral width (*w*).

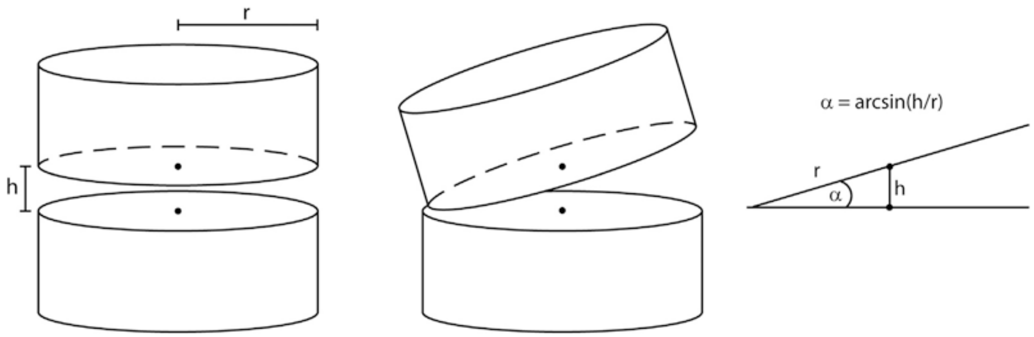

Fig. 2. Biomechanical model illustrating relationship of bending (α) to ratio of IVD height to vertebral half-width (*h*/*r*).

vertebral bodies depends on the ratio of IVD height (h) to end plate half-width (r). Assuming rotation occurs about the midpoints of the two end plates, the maximum angle (α) between the two vertebrae can be approximated as $\alpha = \arcsin(h/r)$ (Fig. 2). The ratio h/r and angle α were calculated for L1, L2, L3, and L4 using the lateral width of the vertebrae and the superior disc height. The ratio was averaged over the four vertebral levels, and the angle was summed for statistical analysis.

Measurements of flexibility

For the control subjects, who were examined prospectively, flexibility of the spine was assessed during maximal lateral bending to both sides [20]. The subject leaned her shoulders as far to one side as possible while keeping the pelvis level. A goniometer was placed with the vertex on the lower back between the dimples of Venus, and the angle was measured between vertical and a line passing through a mark placed at T1. Measurement was repeated three times each for both the left and right directions. The greatest angle for each side was selected, and the left and right measurements were averaged for analysis.

Statistical analyses

Demographic, anthropometric, and morphologic characteristics were compared between girls with AIS and controls using 2-sided Student *t* tests. This analysis examined the measures of vertebral morphology and the estimated total lateral bending angle. For the control subjects, linear regression was used to examine how the ratio of disc height to vertebral half-width and lateral bending angle from the biomechanical model relate to the functional measurement of lateral flexibility. Skeletal age, height, body mass index (BMI), and muscle area were included as covariates in the regression model to adjust for the possible effects of maturation and body habitus. All statistical analysis was performed using Stata, version 12.1 (StataCorp, College Station, TX), with a significance level of 0.05.

Results

Table 1 summarizes the demographic, anthropometric, and morphologic characteristics of the girls in the study. The mean chronological and skeletal ages were 11.1 and 11.0 years, respectively. For girls with AIS, the

Table 1
Demographic and anthropometric characteristics of the study sample (51 girls).

Variable	Control (n = 29)		AIS (n = 22)		p value
	Mean ± SD	Range	Mean ± SD	Range	
Age and anthropometric measures					
Chronological age (years)	11.0 ± 1.2	9.0–13.5	11.3 ± 1.3	9.3–13.7	.348
Skeletal age (years)	10.8 ± 1.8	7.5–15.0	11.3 ± 1.7	9.0–15.0	.285
Height (cm)	146.2 ± 8.6	130.5–166.0	147.4 ± 9.8	132.0–168.9	.627
Weight (kg)	41.0 ± 12.5	24.0–73.7	39.2 ± 11.3	24.0–75.6	.595
BMI	18.9 ± 3.8	13.6–28.4	17.7 ± 3.3	13.8–26.5	.260
Cobb angle (°)	—	—	22.9 ± 5.4	10–30	—
MRI spinal phenotypes					
Muscle CSA (cm^2)	92.1 ± 20.7	66.3–148.1	89.0 ± 23.3	58.3–174.9	.626
Mean vertebral width (cm)	3.4 ± 0.2	3.2–3.9	3.5 ± 0.3	2.9–4.2	.218
Mean disc height (cm)	0.69 ± 0.05	0.56–0.78	0.78 ± 0.07	0.66–0.88	<.0001
Spinal flexibility					
Lateral flexion (°)	86.7 ± 19.0	45.3–122.0	—	—	—
Disc height/vertebral radius ratio	0.38 ± 0.03	0.32–0.46	0.45 ± 0.05	0.38–0.56	<.0001
Total lateral bending angle (°)	89 ± 8	75–109	107 ± 13	88–137	<.0001

AIS, adolescent idiopathic scoliosis; BMI, body mass index; CSA, cross-sectional area; MRI, magnetic resonance imaging; SD, standard deviation. Comparison between groups was performed using two-sided Student *t* tests.

Table 2
Multiple regression results relating the ratio of disc height to vertebral half-width and theoretical lumbar bending angle to lateral bending flexibility.

	β	SE	p value
Lateral flexibility (°)			
Disc height/vertebral radius ratio	226.7	104.7	.041
Height (cm)	−1.2	0.6	.060
BMI	−5.9	1.7	.002
Skeletal age (years)	1.5	2.8	.598
Muscle area (cm^2)	1.1	0.4	.008
Constant	160.1	69.5	.030
Lateral flexibility (°)			
L1−L4 lateral bending angle (°)	0.9	0.4	.042
Height (cm)	−1.1	0.6	.059
BMI	−5.9	1.7	.002
Skeletal age (years)	1.5	2.8	.591
Muscle area (cm^2)	1.1	0.4	.008
Constant	166.0	68.8	.024

BMI, body mass index.

mean Cobb angle was 22.9° (standard deviation 5.4, range 10−30).

Differences in spine morphology between girls with AIS and controls

The AIS and control groups had similar chronological and skeletal age, height, weight, and BMI (Table 1). However, the ratio of disc height to vertebral half-width was significantly higher in the girls with AIS (0.45 vs. 0.38, $p < .0001$), primarily because of differences in mean IVD height (7.8 vs. 6.9 mm, $p < .0001$). Consequently, the total lateral bending angle estimated by the biomechanical model was also significantly larger in the girls with AIS (107° vs. 89°, $p < .0001$).

Relationship of lateral flexibility to spine morphology

In the control group for which clinical measurements of flexibility were available, regression analysis showed a significant relationship between the functional measurement of lateral flexibility and the ratio of IVD height to lumbar half-width (Table 2, total $R^2 = 0.45$). A similar relationship was seen between the functional assessment of lateral flexibility and the theoretical total lumbar lateral bending angle calculated using the biomechanical model (Table 2, total $R^2 = 0.45$). The regression coefficient for lateral bending angle was 0.9 (close to 1) suggesting good correspondence between the clinical and theoretical estimates of lateral flexibility. In both regressions, paraspinal muscle area also showed a significant positive relationship to lateral flexibility, whereas height and BMI showed a negative relationship.

Discussion

The results of this pilot study clearly indicate that girls with idiopathic scoliosis have taller intervertebral discs relative to vertebral width compared with peers without spinal deformity. In fact, the 90th percentile for the ratio of disc height to vertebral width in girls with scoliosis corresponds to approximately the 50th percentile in control subjects (Fig. 3). Although we did not have direct measurements of spine flexibility for the girls with scoliosis, a larger disc height to vertebral width ratio was associated with greater lateral bending flexibility in the control subjects. Therefore, it might be inferred that girls with scoliosis have more flexible spines than peers without scoliosis, though this would need to be confirmed with direct measurements in a future study. The relationship between flexibility and scoliosis is supported by previous studies that have found both increased joint flexibility [21,22] and a higher risk of developing adolescent idiopathic scoliosis [23-26] in girls who participate in sports such as gymnastics and dancing. Girls are also known to be more flexible than boys and have smaller vertebrae [18,27] and a higher incidence of idiopathic scoliosis [28].

Increased spine flexibility presents a possible mechanism for the development and progression of scoliosis. In scoliosis, compressive loading on the concave side of the curve inhibits longitudinal growth while tensile loading

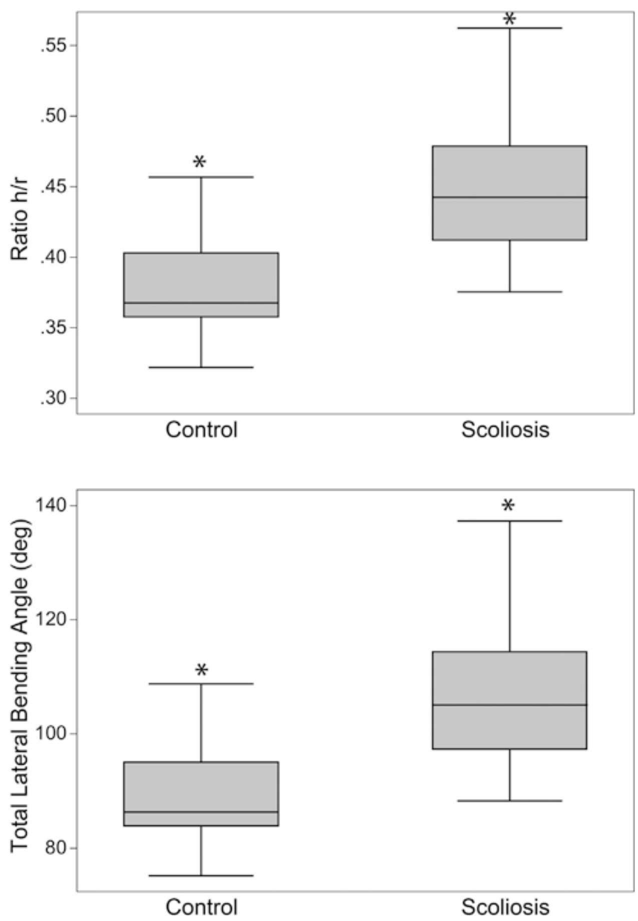

Fig. 3. Comparison of ratio and angle between girls with idiopathic scoliosis and controls. *p < .001.

on the convex side accelerates it, resulting in wedging of the vertebrae [12-14]. With greater bending range of motion enabled by smaller vertebral cross-sectional dimensions relative to IVD height, the asymmetric mechanical stresses associated with movement would be expected to increase. This would increase the remodeling stimulus and promote differential growth leading to lateral and/or anterior wedging of the vertebrae as observed in adolescent idiopathic scoliosis.

It is interesting that the regression coefficient relating the theoretical bending angle from the biomechanical model to the clinically measured bending angle was close to 1. Although the exact value of this coefficient is uncertain because of the large confidence interval, the current results suggest that on average, this simple biomechanical model provides a reasonable estimate of spine flexibility. We do not expect exact correspondence between the biomechanical model and actual flexibility because bending also occurs outside of the lumbar region and is influenced by factors beyond morphology, such as ligament and soft tissue tightness and viscoelastic compliance of the intervertebral discs. Nevertheless, the simple biomechanical model presented appears to provide a reasonable representation of the parameters (ratio of disc height to vertebral width) influencing spine flexibility.

In the multiple regressions, muscle area, height, and weight were also found to be related to flexibility. The relationship to muscle area may be due to the need for active forces to overcome the resistance of passive structures. The lumbar spine is the site of attachment of muscles concerned with changing the position of the trunk through movements of the vertebral column. Three muscles—the psoas, the quadratus lumborum, and the sacrospinalis or erector spinae—are anchored in the apophyses [29]. The psoas originates from the medial halves of the anterior aspects of the upper four lumbar transverse processes, and from the lateral aspects of the upper four lumbar intervertebral disks and adjacent lumbar vertebral bodies. The quadratus lumborum is attached to the anterolateral aspects of the upper four lumbar transverse processes, and the sacrospinalis (erector spinae) lies in a groove bounded medially by the posterior spinous processes and laminae and in front by the transverse processes. All of these muscles, when acting alone on one side of the trunk, bend the vertebral column laterally. The negative relationship of flexibility to height and BMI may reflect the general decrease in flexibility that tends to occur with growth.

Although this study presents interesting associations between spine morphology, flexibility, and scoliosis, a major limitation is that we cannot determine cause and effect with the current study design. Prospective longitudinal studies are therefore needed to establish whether the ratio of disc height to vertebral width can actually predict the development and progression of scoliosis. We also did not control the time of day of the examinations, the overall activity level of the subjects, or activity prior to imaging. Because IVD height varies with loading over time [15], these factors may have contributed to variability in this measurement. IVD height would also be expected to differ between the supine imaging position and typical standing posture, although the effects should be similar for all subjects. In addition, the study sample was limited to curves no greater than 30°. This was done to focus on vertebral morphology prior to treatment, but may limit generalizability of the findings to larger and stiffer curves. Finally, this study had a relatively small sample size and therefore provides preliminary findings that need to be corroborated in larger prospective longitudinal studies.

Another limitation is that spinal morphology is, by definition, altered in patients with scoliosis. To minimize the influence of spine deformities on our measurements, we performed the measurements in the lumbar spine in patients with mild and moderate thoracic curves. It is assumed that morphologic traits such as taller intervertebral discs or smaller vertebrae are similar between the thoracic and lumbar regions prior to development of the thoracic deformity. Obtaining measurements in the lumbar spine should therefore provide insight regarding spinal geometry prior to development of the thoracic curve, which may have contributed to curve initiation and progression. Because the structural curve is in the thoracic region, however, future prospective studies should also examine whether similar measurements in the region of the curve (ie, thoracic region) are also related to the presence and progression of scoliosis. Measurements in the presence of deformity in this region are likely to be more complex and difficult to obtain but may provide additional insight into the risk of continued curve progression.

The ratio of disc height to vertebral width is a morphologic trait that is relatively easy to measure. If it can be confirmed in larger studies that this measure is predictive of the development and/or progression of scoliosis, it could be used to improve screening, patient counseling, and possibly treatment decision making for this patient population, particularly in the early stages of scoliosis when deformity is mild and it is uncertain whether the curve will progress. Although it is questionable whether this ratio could be reliably measured on plain radiographs, it should be possible to perform the measurements using low-dose 3D (bi-plane) x-ray imaging (EOS), which is coming into more widespread use. It might also be explored whether the measurements could be obtained from dual-energy x-ray absorptiometry (DXA) images, though the gold standard will remain true 3D imaging with computed tomography or MRI.

In conclusion, the current study provides new evidence suggesting that the ratio of IVD height to vertebral half-width is associated with greater spine flexibility which may contribute to the development and progression of idiopathic scoliosis. If this mechanism of scoliosis progression can be corroborated in future prospective longitudinal studies, imaging of spine morphology may contribute to a better understanding of the etiology of idiopathic scoliosis as well as improved prognostic ability and possibly the development of treatment approaches to prevent or reduce scoliosis progression.

Key points

- Lateral bending flexibility is associated with smaller vertebrae and taller intervertebral discs.
- Girls with scoliosis have smaller vertebrae relative to intervertebral disc height than girls without scoliosis.
- Easily measured spine morphologic traits may contribute to our understanding of scoliosis etiology and prognosis.

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