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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 $\leqslant 30°$ were included. The study was restricted to curves $\leqslant 30°$ 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

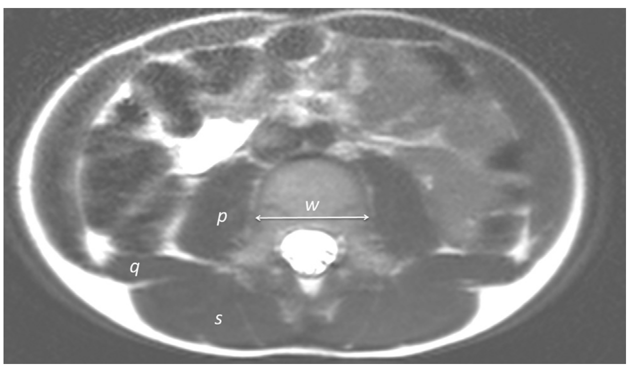

Fig. 1. An MRI transverse section of the muscles at the lumbar level shows the psoas (p), the quadratus lumborum (q), and the postvertebral group of muscles described collectively as the sacrospinalis/erector spinae (s) as well as the third lumbar vertebral width (w).