Kinematic Comparison of the Osteo-ligamentous Adolescent Idiopathic Scoliosis Spine with the Normative: A Finite Element Modeling Study

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Introduction: Finite Element (FE) models of the thoracic spine have been widely developed for orthopedic conditions including adolescent idiopathic scoliosis (AIS). While FE models of the normative spine are validated against kinematic data from experimental studies, FE models for AIS spine are limited by inaccuracies in anatomical geometry, age-specific material properties and lack of such kinematic validations. This is due to the difficulty in obtaining cadaveric material for younger population. Though there are in vivo data on AIS spine kinematics, detailed boundary conditions and forces due to internal constraints are not available for validation purposes. We have previously developed a geometrically accurate FE model of an AIS osteo-ligamentous thoracic spine with ribcage with pediatric age-specific material properties. The objective of this study is to compare the multi-planar ranges of motion (ROM) of the FE model of the AIS thoracic spine (with and without rib cage) with the scaled normative in vitro ROM data from the literature. It was hypothesized that the AIS spine would exhibit increased stiffness and therefore a reduced ROM as compared to the normative pediatric spine. Validating the osteo-ligamentous AIS spine model against such a hypothesis would be the most feasible method to overcome the prior mentioned limitations.

Methods: Chest CT scans of a 12 year-old (YO) female AIS subject was digitally reconstructed using Mimics (Materialise Inc., Belgium) to obtain the geometry of the thoracic spine and rib cage. FE model was created using ICEM-CFD/HEXA 14.5 (Ansys, PA) and Hypermesh 11.0 (Altair Inc., MI). Due to the lack of in vitro data on 12 YO normative specimens, the material properties of the spinal components and kinematic response of normative adult thoracic spines reported in the literature were scaled using relevant scale factors [1]. These data were compared with the ROM data of AIS spine model. The experimental set up on the spinal motion segments, whole thoracic spine and rib cage were simulated based on previously reported experiments [2, 3]. The whole AIS thoracic spine without ribcage, their motion segments (T1-T4, T5-T8 and T9-T12), and thoracic spine with ribcage collectively comprise the ‘mechanical states’. Appropriately-scaled bending moments (1.32 Nm for motion segments, 0.66 Nm for entire spine in F/E and LB, 1.65 Nm+24 N compressive force for entire spine in AR) were applied to the superior vertebra to simulate flexion-extension (F/E), left-right lateral bending (LB) and axial rotation (AR) (loading states). A sensitivity analysis was performed to evaluate the effects of varying the elastic modulus of all the components in all the mechanical states by ±25%, while the properties of nucleus pulposus were kept constant. All the aforementioned mechanical states were simulated in LS DYNA (LSTC, CA).

Results: The ROM of the mechanical states (T1-T4, T5-T8, T9-T12, T1-T12 without ribcage and T1-T12 with ribcage) were 5.38°, 5.22°, 8.22°, 10.85° and 5.99° in F/E; 9.36°, 9.63°, 6.59°, 15° and 5.36° in LB;
and 18.33°, 15.46°, 14.04°, 65° and 28.87° in AR respectively (Fig. 1). Compared to the aforementioned ROM data, the average percentage change with 25% increase and decrease in material parameters of vertebrae, annulus and ligaments were -14.92% (F/E), 15.32% (LB) and -11.92% (AR); and 18.7% (F/E), 20.52% (LB) and 17.2% (AR), respectively (Table 1).

**Discussion:** A majority of the ROM values of the AIS spine were lower than the average ROM values of the 12 YO normative thoracic spine (Fig. 1), thus proving the validity of the postulated hypothesis. Our hypothesis was based on anatomical changes that occur as a result of AIS, in which there is a relative shortening of the intervertebral discs with respect to vertebral body heights [4]. Due to this, there is a decrease in ROM of the spine which is majorly governed by the ratio of the height of vertebral bodies to the height of intervertebral discs [5]. Most of the results of the computational study concur with the findings of Stokes and Windisch (2006) [4]. However, in axial rotation, AIS spines tended to be more flexible than the normative. These findings tended to agree with the in vivo study conducted on scoliotic patients, which showed that the average ROM of the thoracic spine for scoliotic patients in flexion, extension and lateral bending was less than the average ROM of the control group, except in axial rotation [6]. While varying the elastic modulus resulted in changes in ROM values, the resulting trends still confirm the validity of our hypothesis.

**Significance:** Biomechanically validated AIS FE models with appropriate age-specific properties and biomechanical details can be further utilized to accurately predict the outcomes of surgical and non-surgical techniques to correct spine deformity.

![Figure 1: ROM of motions segments and whole thoracic spine of 12 YO AIS patient with and without ribcage. (F/E: Flexion-extension, LB: Lateral Bending, AR: Axial Rotation, WRC: With Ribcage)](image-url)
<table>
<thead>
<tr>
<th>Mechanical States</th>
<th>Max:25%</th>
<th>Min: -25%</th>
<th>% Change</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>F/E</td>
<td>LB</td>
<td>AR</td>
</tr>
<tr>
<td>T1T4</td>
<td>-14.68%</td>
<td>-38.41%</td>
<td>-15.66%</td>
</tr>
<tr>
<td></td>
<td>16.17%</td>
<td>20.19%</td>
<td>15.60%</td>
</tr>
<tr>
<td>T5T8</td>
<td>-11.46%</td>
<td>-7.37%</td>
<td>-7.37%</td>
</tr>
<tr>
<td></td>
<td>18.82%</td>
<td>16.38%</td>
<td>14.88%</td>
</tr>
<tr>
<td>T9T12</td>
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<td>-8.80%</td>
<td>-10.24%</td>
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<td></td>
<td>14.15%</td>
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<td>14.27%</td>
</tr>
<tr>
<td>T1T12</td>
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<td>-6.33%</td>
<td>-9.66%</td>
</tr>
<tr>
<td></td>
<td>19.16%</td>
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</tr>
<tr>
<td>T3T12WRC</td>
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<tr>
<td></td>
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