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The 3D Sagittal Profile of Thoracic Versus Lumbar Major Curves in Adolescent Idiopathic Scoliosis

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Abstract

Study Design: Retrospective.

Objective: To compare the 3D sagittal profile of patients with main thoracic or thoracolumbar/lumbar adolescent idiopathic scoliosis (AIS) to a normal cohort.

Summary of Background Information: Thoracic AIS is often associated with a loss of kyphosis. Classically, this measure has been made in 2D, which may underestimate the true sagittal deformity.

Methods: Biplanar upright radiographs were obtained on 152 primary thoracic (TH: Lenke 1−4), 50 primary thoracolumbar/lumbar (TL/L: Lenke 5−6) curves, and 89 normal controls (NC). 3D spinal reconstructions were created using sterEOS software. MATLAB code was used to create segmental measurements of kyphosis/lordosis for each vertebral and disc segment from T1 to S1 in the local coordinate system of each motion segment. Comparisons were made between groups for the 3D summed segmental measures (T1−T5, T5−T12, T12−S1), pelvic incidence, sacral slope, and pelvic tilt.

Results: Mean 2D Cobb was 57°±12° (range 40°−115°) for TH curves and 52°±9° (range 37°−75°) for TL/L curves. Significant differences in 3D sagittal measures were found between the 3 groups. Post hoc tests revealed significant differences at T1−T5, TH < NC, and TL/L < NC. All groups differed from each other from T5−T12, with the least kyphosis in TH curves. T12−S1 lordosis was significantly greater in TH and TL/L curves compared with NC. Lumbar lordosis extended proximally an average of one segment in AIS compared to normal spines (T11 vs T12). Pelvic incidence, sacral slope, and pelvic tilt were significantly greater for TH curves compared to NC.

Conclusions: There is a substantial average loss of thoracic kyphosis (~15°−25°) for both primary thoracic and primary thoracolumbar/lumbar AIS curves compared to normal adolescents. Three-dimensional assessment of scoliosis allows the "true" deformity to be measured by correcting for error due to out-of-plane measurement associated with conventional 2D measurements.

Level of Evidence: Level II, prognostic.

Keywords: Sagittal balance; Adolescent idiopathic scoliosis; Kyphosis; 3-dimensional; Lordosis

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Study conducted at Rady Children's Hospital, San Diego, CA.

IRB approval was obtained for this study.

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Introduction

Adolescent idiopathic scoliosis (AIS) is a structural curvature of the spine present in approximately 0.5% to 5% of otherwise healthy children aged 11−18 years [1]. Although the severity and classification of curves are primarily by the two-dimensional (2D) Cobb angle measurements on the coronal plane radiograph, scoliosis is known to involve deformity in the sagittal and axial planes as well [2,3]. Several prior authors have shed light on the sagittal plane deformity in AIS [3-6], and Dickson et al. postulated that relative thoracic lordosis was the ‘‘essential lesion’’ in thoracic scoliosis [7]. Because of the axial rotation deformity, Stagnara used radiographs oriented relative to the apical vertebra to ‘‘see’’ more realistic images of the coronal and sagittal deformities of the apical region [8]. Plain radiographic 2D analysis of the sagittal profile in AIS has been limited in the past by the axial rotation of the spine that distorts the image visualized on classically oriented anterior-posterior and lateral projection radiographs, often resulting in an overestimation of the true thoracic kyphosis [2,6]. The etiology of the relative hypokyphosis of the thoracic spine in many patients with AIS is unknown, although some postulate that relative overgrowth of the anterior column of the spine may play a role [9]. Relative lengthening of the anterior compared to the posterior column of the spine should theoretically result in a loss of kyphosis in the thoracic segment below the normal range (20°−50°) and/or an increase in lordosis in the lumbar segment above the normal range (20°−60°) [10,11]. This perturbation of the normal sagittal alignment is postulated to result in a rotational buckling of the spinal column to maintain global sagittal balance, thus creating the three planes of deformity seen in scoliosis [12]. It is also possible that the alterations in compressive forces borne by the vertebral growth cartilage once scoliosis has developed leads to progressive alterations in growth based on the Hueter Volkmann principle [13].

Previous investigations into the sagittal alignment of patients with AIS using 2D modalities have revealed a loss of kyphosis in scoliosis patients [4,14]. However, the findings in regard to lumbar lordosis have been less clear [4,5]. Such data do not yield clear support for a relative anterior overgrowth effect on the sagittal profile, nor do they indicate whether a similar process is involved in major thoracic curves compared with major thoracolumbar/lumbar curves. The purpose of this study was to compare three-dimensional (3D) sagittal measurements between AIS patients with either major thoracic or major lumbar curves, and a set of ‘‘normal’’ subjects. The authors hypothesize that differences in the regional 3D sagittal measurements will exist between the three cohorts.

Methods

A retrospective review of a consecutive series of preoperative AIS patients and patients who presented to the clinic for spinal evaluation at a single institution who had routine, biplanar, upright radiographs using an EOS scanner (EOS imaging, Paris, France) [15] was undertaken. A cohort of 152 patients with major thoracic scoliosis (TH: Lenke 1−4) and a cohort of 50 patients with major thoracolumbar/lumbar scoliosis (TL/L: Lenke 5 or 6) were included [16]. All patients had a diagnosis of AIS and were between the ages of 10 and 20 years. A ‘‘normal’’ comparison group (NC) of adolescents was identified and consisted of patients who had spine EOS images from our institution and were found to be free of any spinal deformity or neurologic condition. The NC group was of a similar age range and matched based on the sex distribution of the entire AIS cohort; 89 patients met inclusion into this group.

2D measures and 3D spinal reconstructions were created from the biplanar radiographs using sterEOS software. Custom MATLAB software was used to create a local reference frame (coronal, sagittal, axial) for each vertebra and disc. Segmental measures of deformity in the local reference frames were calculated for each vertebral level, as described by Newton et al. [17]. Briefly, each vertebra and disc was evaluated in its local plane to obtain coronal and sagittal values that are not confounded by the deformity of the other planes. To obtain regional values, the segmental values for each vertebra and disc within that region were summed to create a single measurement. For example, T5−T12 kyphosis was calculated by summing the kyphosis of each vertebra from T5 to T12 and each disc from T5/6 to T11/12. Given the normal variations of sagittal alignment (thoracic kyphosis, lumbar lordosis) the 3D segmental values in the local sagittal planes were summed for the regions of interest (T1−T5, T5−T12 and T12−S1). For the purpose of adding values, kyphosis was given a positive value and lordosis a negative value. Comparisons were made between the 3 groups (TH, TL/L, NC) for each of three sagittal regions, as well as the vertebral level for which lordosis transitioned to kyphosis. Pelvic parameters (pelvic incidence, sacral slope, pelvic tilt) were compared between the three groups. In addition, the pelvic incidence to lumbar lordosis difference (PI-LL mismatch) was calculated for each group.

The 3D sagittal data were analyzed with the use of one-way analysis of variance to compare the sagittal measurements between groups at each region: T1−T5, T5−T12, and T12−S1. Post hoc tests with Bonferroni correction were then used to perform between-group comparisons within each sagittal segment. Pelvic parameters were analyzed in a similar fashion. Nonparametric tests were used to compare the levels of kyphosis/lordosis transition between groups. Alpha was set at ≤ 0.05 to declare significance.

Results

The TH group consisted of 152 patients with a mean age of 15 ± 2 years and a male-female (M:F) ratio of 1:6.6. The TL/L group had 50 patients with a mean age of 15 ± 2

Table 1
Comparison of 3D kyphosis, lordosis, and pelvic parameters between major thoracic, major thoracolumbar/lumbar, and normal cohorts.

Curve type	3D T1−T5 kyphosis	3D T5−T12 kyphosis	3D T12−S1 lordosis	Pelvic incidence	Sacral slope	Pelvic tilt	PI-LL mismatch
TH	15.8 ± 7.8 (−7.8, 37.3)	5.7 ± 15.7 (−56.5, 50.3)*	−60.7 ± 12.7 (−94.2, −27.7)	53.8 ± 11.6 (25.9, 86.4)†	44.6 ± 8.5 (22.9, 70.2)‡	9.1 ± 8.0 (−10.1, 38.6)§	−6.9 ± 12.7 (−43.7, 34.2)‖
TL/ L	17.7 ± 7.0 (1.1, 31.4)	15.5 ± 12.4 (−18.4, 35.8)*	−64.6 ± 13.4 (−96.4, −34.6)	50.7 ± 12.9 (28.6, 78.6)	42.3 ± 9.3 (22.8, 63.5)	8.4 ± 7.8 (−7.1, 28.1)	−13.9 ± 12.6 (−36.5, 12.0)‖
Normal	21.8 ± 6.5 (8.0, 36.8)¶	33.1 ± 9.0 (11.8, 53.8)*	−56.0 ± 11.6 (−86.2, −34.2)**	46.5 ± 10.7 (25.2, 74.5)†	41.1 ± 8.1 (25.2, 63.8)‡	5.37 ± 8.1 (−11.8, 24.5)§	−9.5 ± 10.7 (−38.0, 15.2)

TH, thoracic; TL/L, thoracolumbar/lumbar.
* T5−T12: all groups differ significantly ($p \leq .001$).
† Pelvic incidence: thoracic curves significantly greater than normal ($p \leq .001$).
‡ Sacral slope: thoracic curves significantly greater than normal ($p = .008$).
§ Pelvic tilt: thoracic curves significantly greater than normal ($p = .002$).
‖ TL/L curves significantly greater than TH curves ($p = .001$).
¶ T1−T5: normal was significantly greater than TH and TL/L curves ($p < .005$).
** T12−S1: normal was significantly less than TH and TL/L curves ($p < .02$).

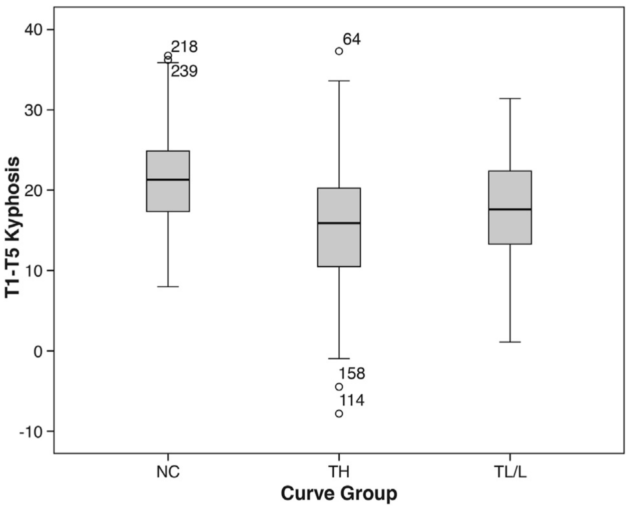

Fig. 1. Boxplot of 3D T1−T5 kyphosis.

years and a M:F ratio of 1:11.5, whereas the 89 NC patients with a mean age of 14 ± 2 years and a M:F ratio of 1:6.4. The NC cohort was younger than the AIS cohorts ($p \leq .002$), but no differences were observed in sex distribution ($p = .6$). The median Risser sign in the TL/L group was 4, which was significantly greater than the median of the NC (3) and TH (3) groups ($p < .001$). The chief complaints of the NC patients were as follows: back pain (27, 30%), scoliosis/ spinal asymmetry evaluation (60, 67%), and other pain (2, 2%).

The mean 2D Cobb angle for the TH curves was 57° ± 12° (range 40°−115°), whereas those with TL/L curves had a mean 2D Cobb angle of 52° ± 9° (range 37°−75°). The mean 2D Cobb angle for NC patients was 6° ± 2°. The corresponding measures of summed segmental 3D Cobb were 55° ± 12° for TH curves and 43° ± 9° for TL/ L curves.

Significant differences in the 3D sagittal measurements for each region (upper thoracic T1−T5, midthoracic

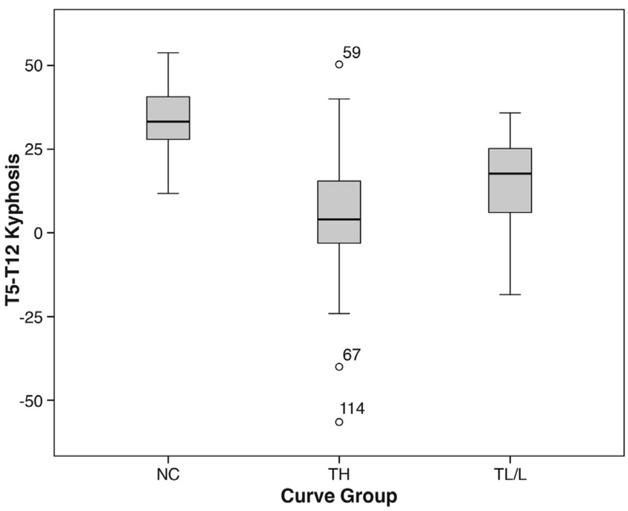

Fig. 2. Boxplot of 3D T5−T12 kyphosis.

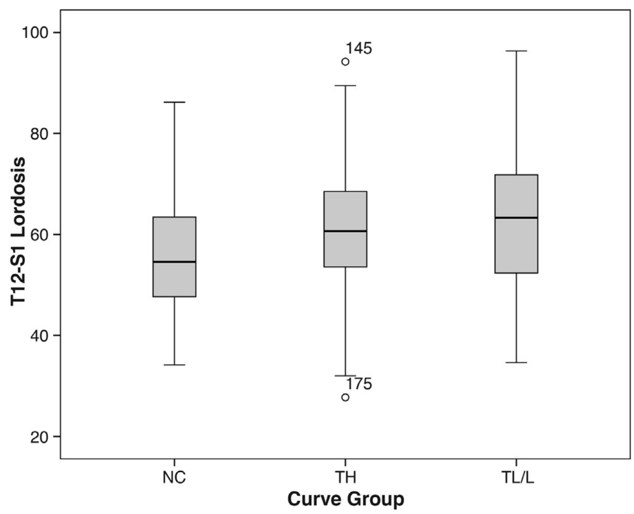

Fig. 3. Boxplot of 3D T12−S1 lordosis (absolute values are presented).

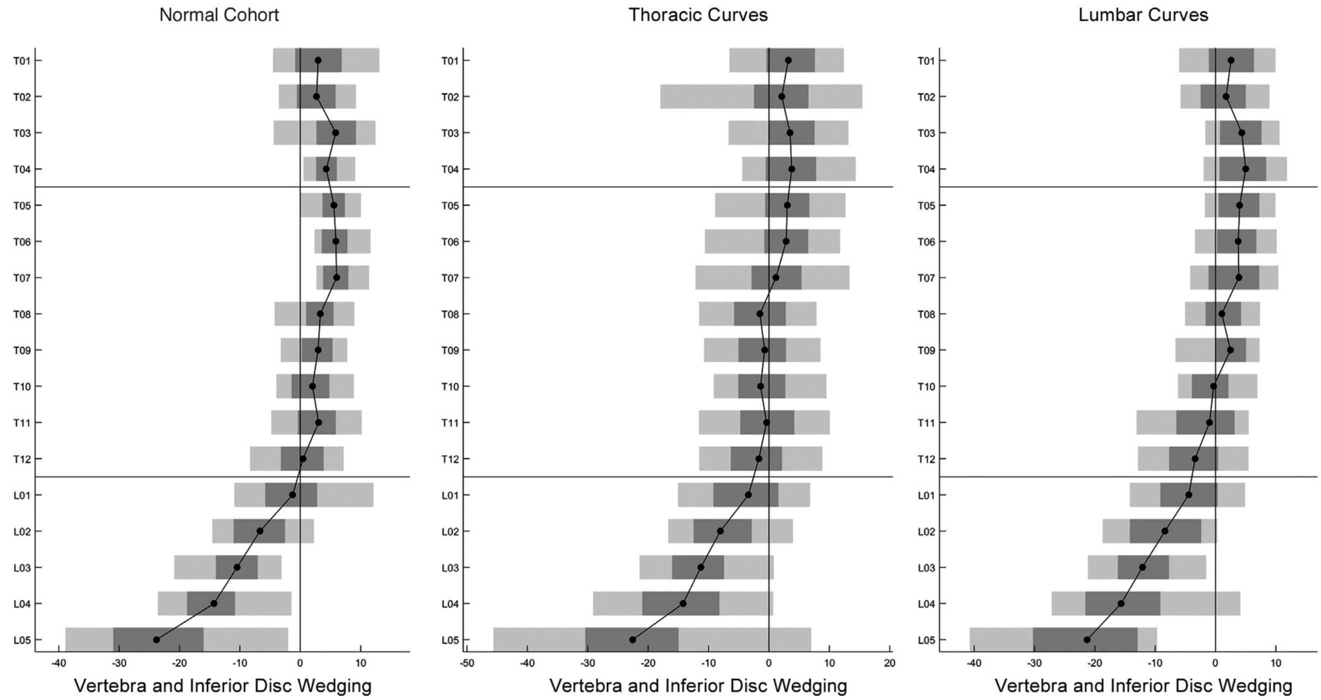

Fig. 4. 3D sagittal measurements by segment. Normal (Left); major thoracic (middle); major thoracolumbar/lumbar (right). The dot represents the average amount of wedging, the dark-gray bands represent the middle 95% of the cohort, and the light-gray bands represent the entire cohort.

T5−T12, and lumbar T12−S1) as well as for pelvic parameters were identified (Table). Post hoc tests revealed significant differences in 3D T1−T5 kyphosis, which was less in TH and TL/L curves than in NC patients ($p<.005$, Fig. 1). However, there was no difference between the 3D T1−T5 kyphosis for the TH and TL/L groups ($p = .342$). All three groups (TH, TL/L, NC) were significantly different from each other in the measure of 3D T5−T12 kyphosis, with the least kyphosis exhibited in the TH cohort ($p\leqslant.001$, Fig. 2). The 3D T12−S1 lordosis was significantly greater in TH and TL/L curves compared with NC ($p<.02$). There was no difference between TH and TL/L groups in 3D lumbar lordosis ($p = .16$, Fig. 3). Pelvic incidence was significantly greater for TH curves compared with NC ($p<.001$) (Table). Sacral slope was significantly greater for the TH curves compared with NC ($p = .008$), as was pelvic tilt ($p = .002$). Pelvic mismatch was significantly greater in the TL/L group than in the TH group ($p = .001$). No significant differences were observed between the NC and either scoliotic group ($p>.1$) (Table).

The segmental sagittal measures between T1 and S1 for each group are presented in Figure 4. The average inflection point between thoracic kyphosis and lumbar lordosis was at T12 in the normal patients with a standard deviation of one level. For both AIS groups, this transition from kyphosis to lordosis was on average significantly more proximal than in the NC group, T11 in both the TH and TL/L groups ($p<.001$).

Discussion

Previous studies have demonstrated a disparity between the sagittal plane measurements in the classic lateral projection and the “true” lateral as obtained through 3D reconstructions with segmental analysis, as in this study. Hayashi et al. demonstrated that on standard lateral radiographs, there was approximately 10° of overestimation of kyphosis in thoracic curves when compared with the 3D measurements of the same apical segment in the true lateral projection of the apical vertebra [6]. Furthermore, these authors identified that this discrepancy was more severe with greater curve magnitude in the coronal plane. The goal of this study was to evaluate the sagittal alignment in scoliosis patients compared with normal spines in the local lateral plane of each segment using 3D modalities such that these aberrations could be removed. Additionally, the scoliosis curves were subdivided into main thoracic and main lumbar curves as defined by the Lenke classification [16] to further assess sagittal alignment between these different major curve types. To the authors’ knowledge, such a comparison of the 3D sagittal profiles of different major scoliosis curves as compared with that of normal controls is novel.

The results of this study demonstrated significant loss of kyphosis in scoliotic spines in both the TH and TL/L groups compared with NC (Table). In the midthoracic segments, this loss was most pronounced in the TH curves. These findings not only reproduce findings from previous studies that evaluated TH curves in 2D [4,5] but also demonstrate that a similar phenomenon occurs in TL/L curves. Such data support a theory of relative anterior overgrowth with the development of curvature in both TH and TL/L curves associated with lower than expected thoracic kyphosis compared to normal. Examination of the relationship of curve magnitude and kyphosis would be necessary to better understand this association as it relates to curve progression. Such analysis was beyond the scope of this study as serial 3D data on progressive cases would be required.

These data also demonstrated greater lumbar lordosis in TH and TL/L curves (Fig. 1) when compared with NC spines. Assuming a global relative overgrowth of the anterior column, the loss of kyphosis in the thoracic segments would also be associated with an increased lumbar lordosis, as is observed in the current study patients. These results are in agreement with previous 2D data [4,5], but such differences were lower in magnitude than those presented here. The use of 3D imaging techniques in the current investigation is thought to give more accurate results than those using classic 2D methods for the reasons described above for thoracic kyphosis.

The similar finding of reduced kyphosis and increased lordosis in both TH and TL/L curves is thought to suggest a similar mechanism in the development of sagittal deformity by way of a relative anterior overgrowth mechanism; however, the reason for production of one curve pattern over another is not explained by the data presented. Rather, the data suggests that anterior overgrowth and/or posterior inhibition underlies a similar sagittal abnormality in both curve types when compared with normal, but the differential deformity observed in the coronal plane may be driven by other factors. Whether the site of buckling in the coronal and axial planes occurs by chance or by another predictable process remains to be explored. It is also unclear from these data if the sagittal plane changes seen in scoliosis are primary (causing the scoliosis) or secondary (as a result of the scoliosis). The association, however, is clear. As this study primarily compared normal spines with relatively severe curves, the ability to observe factors involved in progression of deformity in those curves is limited; however, the results of Grivas et al. support a compensatory rather than a primary hypokyphosis effect based on the authors' assessment of both mild [10−20] and more severe curves [18]. Examination of the spectrum of AIS curves using 3D modalities would be useful given the known limitations of 2D radiographs to accurately evaluate the sagittal plane [2].

Analysis of the transition between kyphosis and lordosis in the lower thoracic segments revealed that this transition point was an average of one level higher in TL/L and TH curves than in the normal cohort. Loss of thoracic kyphosis manifested as a loss of local kyphosis or in fact a frank lordosis extending into the lower thoracic spine.

Consistent with the results of Upasani et al., TH curves were found to have greater pelvic incidence, sacral slope, and pelvic tilt compared to NC [4]. Although not significant in post hoc tests, the mean pelvic parameters of the TL/L curves were greater than that of the NC group. The cause for this increase in pelvic incidence is unknown. Previously documented relationships between lumbar lordosis and pelvic incidence suggest a positive correlation between the two, such that patients with a higher pelvic incidence should exhibit greater lumbar lordosis, the former representing a parameter that is unaffected by pelvic or spinal positioning [19]. Relationships between thoracic kyphosis and pelvic incidence are less clear. The data in this study concur with previous literature as patients with AIS were found to have greater pelvic incidence as well as lordosis when compared with their normal counterparts. Further investigation into this measure will be required to better understand these relationships. Despite the larger pelvic incidence, there was greater lumbar lordosis relative to the PI (PI-LL mismatch) in the TL/L curves compared with the TH curves. Regional lordosis was thus greater in both absolute and relative terms for TL/L curves compared to TH curves.

Limitations of this study included the limited ability of EOS modality to measure pelvic segments accurately, resulting in reduced accuracy of measurements in the S1 segments for lumbar curve measurements. These data were included as the authors believed this S1 contribution to be an important component of the lordosis measurement. Additionally, these data are only a picture of deformity at one point in time collected retrospectively. For better understanding of the role these factors play in the etiology and progression of deformity in AIS, a longitudinal design and perhaps a prospective examination are necessary. Despite this, we believe the 3D segmental method of assessing the scoliotic spine is valuable and has demonstrated differences in the sagittal plane that correlate with the apex of the major coronal deformity. In both thoracic and thoracolumbar/lumbar major curves, there is an alteration of the sagittal plane as measured in the local reference plane that manifests as a relative increase in the lordotic nature (or contrarily stated, a relative loss of kyphosis) of the spine.

The magnitudes of these regional sagittal plane deformities are in some cases substantial, with a loss of thoracic kyphosis of ~25°−30°. Appreciating this deformity is important to restore sagittal alignment. The effect on the lumbar spine appears to be less, yet understanding that TL/L curves may have excessive lordosis relative to normal may impact correction strategies (less convex compression, for example). The findings of this paper have implications for both the understanding of scoliosis in the sagittal plane regarding both etiologic pathomechanics and well as surgical management.

Key points

- There is a substantial average loss of 3D T5−T12 thoracic kyphosis (~15°−25°) for both primary thoracic and primary lumbar AIS curves compared to normal adolescents, with the least kyphosis exhibited in the primary thoracic curves.

- The transition from lordosis to kyphosis occurred more proximally in the scoliotic spines than in the normal controls.
- Both scoliosis groups were significantly less kyphotic in the upper thoracic spine and more lordotic in the lumbar spine than the normal controls, but were not significantly different from each other.

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