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A Novel Method for Estimating Three-Dimensional Apical Vertebral Rotation Using Two-Dimensional Coronal Cobb Angle and Thoracic Kyphosis

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Abstract

Study Design: Retrospective cohort analysis.
Objectives: To use a large cohort of three-dimensional (3D) spinal reconstructions to create a simple mathematical formula capable of estimating 3D apical vertebral rotation (AVR) based on the correlation with routinely obtained two-dimensional (2D) measurements of scoliosis.
Summary of Background Data: Quantification of vertebral rotation in AIS using 2-dimensional (2D) imaging is inherently challenging as the axial plane cannot be directly visualized.
Methods: A database of 279 3D spinal reconstructions was queried for patients with thoracic major adolescent idiopathic scoliosis (AIS). 2D thoracic Cobb angle, T5−T12 thoracic kyphosis, pelvic incidence, sacral slope, and pelvic tilt were recorded. 3D AVR was calculated for each patient from 3D reconstructions. Patients were divided into development ($n = 186$) and validation ($n = 93$) cohorts. Within the development cohort, univariate analysis was performed between 2D measurements and 3D AVR with significance set at $p < .05$ for inclusion in multivariate analysis. In multivariate analysis, significance was set at $p < .01$ for inclusion in the final model. Model performance was tested in development and validation cohorts.
Results: Only 2D thoracic Cobb and T5−T12 thoracic kyphosis had significance in univariate ($p < .05$) and multivariate analyses ($p < .01$), meriting inclusion in the final model. 3D AVR (°) = 0.26*(T5−T12 kyphosis) + 0.34*(coronal Cobb) − 5.38. In the development cohort, the model performed well ($R = 0.739$, $r^2 = 0.54$). In testing with the validation cohort, the model proved generalizability ($R = 0.703$) and had a mean absolute error $<5°$.
Conclusions: This model is capable of estimating 3D AVR given 2D thoracic Cobb and T5−T12 kyphosis. The accuracy of this method is comparable to previously reported methods of 2D axial rotation measurement. However, this model provides 3D axial rotation and requires no physical instruments, non-standard measurements, or software programs. Such a model is valuable for both routine evaluation of AIS and operative preparation.

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Introduction

Adolescent idiopathic scoliosis (AIS) is a multiplanar deformity of the adolescent spinal column that affects a significant portion of the population [1-3]. The multidimensional nature of AIS has been appreciated for hundreds of years, but the advent of the two-dimensional (2D) radiograph offered the first opportunities to directly evaluate the deformity in living patients [4]. Studies implementing 2D radiographic measurements led to various hypotheses of the pathogenesis of AIS, many of which included an underlying growth abnormality that resulted in a combination of coronal, sagittal, and axial plane deformities [3,5-7].

AIS has historically been evaluated using primarily coronal plane measurements, and to date the coronal Cobb angle is still the gold standard for quantifying the severity of scoliosis [8,9]. However, there has been increasing emphasis on the evaluation of sagittal and axial plane components of the deformity in recent decades, and sagittal plane measurements have even been incorporated into widely used AIS classification systems [3,5,10,11]. This transition has been facilitated and encouraged by the increasing availability of three-dimensional (3D) imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI) [12]. Despite the development of these imaging technologies and their impact on AIS research, they are not typically indicated for routine imaging in AIS and have limitations because of radiation exposure and cost. The development of modern, slot scanning, biplanar radiography has reduced the radiation exposure and facilitated 3D modeling of the spine. These systems have the potential to advance our understanding of the shape of the spine, but currently such systems are not widely available to clinicians and are implemented in standard clinical care at a limited number of institutions. Consequently, 2D radiographs remain the mainstay of clinical evaluation in AIS, and as such there has been much interest in determining accurate methods for quantification of all three planes of deformity based on traditional 2D imaging.

Quantification of axial rotation with traditional 2D posteroanterior (PA) and lateral radiographs is inherently challenging because of the fact that the plane of the deformity cannot be directly projected onto a film. Many prior works have sought to circumvent this issue by performing measurements via calculations made from anatomic features of the vertebrae that can be visualized in the coronal and sagittal images such as the pedicles and spinous processes. Cobb was the first to suggest such a method when he introduced a system in which the position of the spinous process relative to the lateral margins of the vertebral body on a PA radiograph could be used to quantify axial rotation from 0 to "++++" [8]. However, this system offered only discrete intervals that did not correlate directly to a measurement in degrees and was also subject to limitations in accurate visualization of spinous processes. Nash and Moe sought to improve on this technique by comparing the pedicle positions to the lateral margins of the vertebral body on a PA radiograph [13]. Although this did offer more reliable determination of posterior structure location, the scale remained a discrete set from neutral to "++++," with only a rough correspondence to a degree measurement. Perdriolle and Raimondi expanded on these early methods by developing instruments that calculated vertebral axial rotation on scales of 5° and 2° intervals, respectively, on the basis of geometric relationships between bony landmarks on the vertebral bodies [14,15]. Both of these methods require the use of measurement templates and life-sized radiographs, but despite these limitations, Perdriolle's method remains commonly utilized in clinical practice. Others have sought to develop methods to calculate vertebral axial rotation through geometric formulae or through software packages for modern digital imaging systems [16-21]. However, nearly all of the currently described methods for determination of axial plane vertebral body rotation via use of 2D radiographs have limitations related to their requirements of multiple nonroutine radiographic measurements, complex mathematical formulae, installation and integration of software packages, or burdensome physical instruments. As such, there remains significant value in the development of a simple computational method capable of estimating vertebral axial rotation from measurements routinely obtained on 2D radiographs.

Prior work from our institution used a large data set of 3D reconstructions generated with software associated with a biplanar slot scanning imaging system to develop a simple, accurate correlation equation for the estimation of 3D measures of thoracic kyphosis given standard 2D coronal and sagittal radiographic measurements [22]. The aim of this article was to pursue a similar approach with respect to apical vertebral rotation (AVR) determination in order to develop a simple conversion formula capable of accurately estimating transverse plane AVR from measurements of coronal and sagittal plane deformity routinely obtained on PA and lateral plain radiographs.

Materials and Methods

Following IRB approval, a scoliosis database of 3D spinal reconstructions obtained as a part of routine clinical evaluation at a single institution was queried for all patients with AIS, a Cobb angle >10°, and a thoracic major curve (thoracic Cobb had the largest magnitude or Lenke 1-4). Patients with a history of prior surgical intervention, connective tissue abnormality, or a neuromuscular disorder were excluded from the analysis. Demographics including patient age, thoracic apical curve direction, and gender were recorded for each patient. Basic 2D spinal measurements including pelvic incidence, sacral slope, pelvic tilt, thoracic coronal Cobb angle, and T5–T12 kyphosis were recorded for each patient.

3D imaging

Each patient underwent imaging with synchronized, upright, biplanar radiographs with the EOS Imaging System (EOS Imaging, Paris, France). 3D spinal reconstructions from T1 to L5 were generated by a single, trained operator using SterEOS image processing software. Previous work has shown these reconstructions to be accurate in comparison to 3D images generated from CT scans [23].

Measurement processing

3D spinal reconstructions from SterEOS were exported to MATLAB (The Mathworks Inc., Natick, MA) for additional 3D measurement calculations. Coronal, sagittal, and axial reference planes were defined concordant with the Scoliosis Research Society Working Group on 3-D Terminology for Spinal Deformity recommendations [24]. The method of 3D deformity quantification utilized local reference planes defined for each vertebra. Coronal, sagittal, and axial 3D measurements were calculated segmentally for each vertebral body and then summed as has been previously described [25,26, unpublished data]. Local torsion was defined as the angle between the net anteroposterior vector of the vertebra in question and the net anteroposterior vector of one vertebra caudad. The superior endplate of S1 was determined to be the origin and at zero degrees of axial rotation. Local torsion of each vertebral level was summed from the sacrum to the vertebra in question to determine the 3D axial rotation of that vertebra relative to the sacrum. For example, the 3D axial rotation of the T10 vertebra would be the sum of the local torsion measurements from T10 to S1. Because this analysis combined left and right curves, rotation in which the posterior elements rotated toward the thoracic curve concavity was assigned a positive sign and rotation in which the posterior elements rotated toward the curve convexity was assigned a negative sign.

Model development and validation

The study data set was divided into development and validation cohorts for the purposes of model generation and subsequent testing of generalizability using the holdout method for cross validation. Within the development cohort, multiple univariate regression was performed between the dependent variable of 3D AVR and independent variables of 2D coronal Cobb angle, 2D T5–T12 kyphosis, pelvic incidence, sacral slope, and pelvic tilt. For univariate regression, significance was determined by $p < .05$. Next, each significant variable from the univariate analysis was included in a multivariate regression model for which significance was set at $p < .01$ for inclusion in the final model. Pearson correlation coefficient, r^2, and standard error were calculated for the model in the development cohort. The model was then tested for accuracy and generalizability in the validation cohort, a data set not used in the development of the model. In this analysis, the p value, Pearson correlation coefficient, and mean absolute error were calculated. Mean absolute error is defined to be the cohort average of the absolute difference between the predicted value and the known, measured value for each data point in the cohort. In this analysis, this is the cohort average of the discrepancy between the 3D AVR predicted by the model on the basis of 2D measurements and the known 3D AVR measured with 3D imaging. Error was also evaluated for correlation with coronal Cobb angle as well as thoracic kyphosis. The error between mild (<25°), moderate (25°-45°), and severe (>45°) curves was compared using pairwise comparisons, and linear regression between error and coronal Cobb angle was performed. Similarly, for thoracic kyphosis, the error between hypokyphotic (<10°), normokyphotic (10°-40°), and hyperkyphotic (>40°) curves was compared using pairwise comparison, and linear regression between error and thoracic kyphosis was performed.

Results

There were 279 subjects with AIS, a thoracic major curve, and 3D spinal reconstructions identified. Thoracic Cobb angles ranged from 10° to 118°. This group was then randomly split into 2 cohorts: 186 patients for the model development cohort and 93 patients for the validation cohort. There were no significant differences between demographics or spinopelvic measurements in the development and validation cohorts (Table).

Table
Demographics and spinopelvic parameters.

	Development Cohort	Validation Cohort	p value
Age (years)	13.6 ± 2.4	13.7 ± 2.3	.829
Gender (%)			
Male	15	16	.815
Female	85	84	
Apex direction (%)			
Left	5	9	.301
Right	95	91	
Cobb angle (°)	48.0 ± 16.3	49.6 ± 16.8	.437
T5–T12 kyphosis (°)	20.9 ± 13.8	21.4 ± 12.0	.789
Pelvic incidence (°)	52.5 ± 11.6	51.2 ± 12.5	.414
Sacral slope (°)	44.7 ± 8.6	43.7 ± 8.5	.332
Pelvic tilt (°)	7.7 ± 7.8	7.6 ± 8.6	.858

Model development

The 2D measurements of thoracic Cobb, T5–T12 kyphosis, and sacral slope were significant in univariate analysis (all $p < .05$). Pelvic incidence and sacral tilt were nonsignificant in univariate analysis (both $p > .05$). In the multivariate analysis, 2D measurements of thoracic Cobb and T5–T12 kyphosis remained significant and merited inclusion in the model (both $p < .01$), whereas sacral slope was discarded ($p > .01$). This resulted in the final predictive model:

3D AVR (°) = 0.26(T5–T12 kyphosis) + 0.34*(Coronal Cobb) − 5.38*

This model had an r^2 of 0.54, indicating that 54% of variation in 3D apical vertebral rotation was accounted for by coronal Cobb and T5–T12 kyphosis, and the Pearson correlation coefficient was calculated to be 0.739, indicating a strong effect size. Standard error of the estimate for the model was 6.17°.

Model validation

When applied to the validation cohort, the model was found to be significant ($p < .001$) and to have a Pearson correlation coefficient of 0.703, again indicating a strong effect size (Fig.). Mean absolute error in the validation cohort was less than 5°. In error analysis, mean absolute error was found to significantly correlate with 3D apical rotation with an r^2 value of 0.323.

In comparison of model performance between mild (<25°), moderate (25°-45°), and severe curves (>45°) defined by the coronal Cobb angle, the error was not significantly different between mild, moderate, or severe cohorts (all $p > .05$). There was a nonsignificant trend toward increased error in severe curves, with this section of the cohort having an MAE of 5.7° relative to 3.8° in both mild and moderate curves. Linear regression between coronal Cobb and MAE resulted in an r^2 value of 0.05 and a Pearson coefficient of 0.23, indicating a poor correlation.

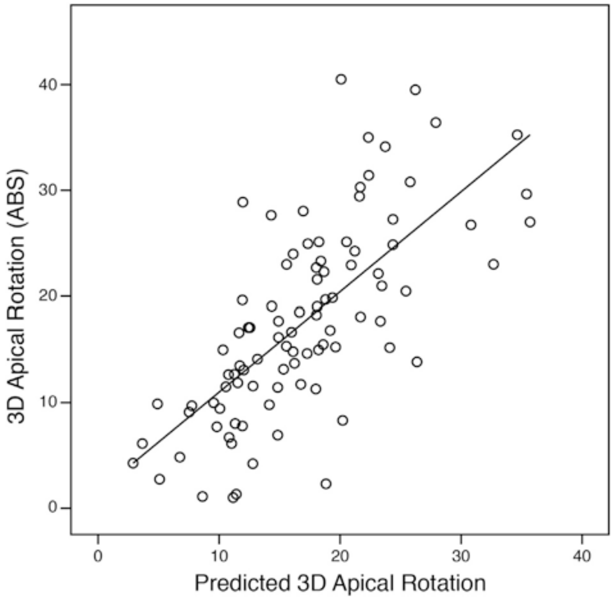

Fig. Predicted versus measured three-dimensional apical vertebral rotation.

When comparing model performance between hypokyphotic, normokyphotic, and hyperkyphotic curves, no significant differences in error were noted (all $p < .05$). Linear regression between thoracic kyphosis and MAE resulted in an r^2 value of 0.02 and a Pearson coefficient of 0.14, showing a poor correlation.

Discussion

AIS creates a multiplanar deformity of the spinal column. Despite the 3D nature, the disease process has historically been evaluated via coronal plane radiographic measurements [8,9], with more recent focus on the sagittal and axial planes as well as improved operative correction [3,5,10-12]. Realizing the correlation between all 3 planes of deformity in AIS, that is, an increasing coronal deformity associated with an increasing sagittal and axial deformity, the aim of this study was to pursue a simple regression formula capable of estimating AVR from routinely obtained 2D measurements.

Routine clinical use of synchronized, biplanar imaging with 3D reconstruction at our institution afforded a large data set meeting inclusion criteria (N = 279). Rather than using the entire cohort for model development, it was decided to generate and test the model using the holdout method for cross validation. The initial cohort was randomly sorted into a larger development cohort (67% of original cohort) and a smaller validation cohort (33% of original cohort). In comparing the development and validation cohorts, no differences were noted in demographics or spinopelvic measurements (Table). Both groups were skewed toward female patients and right-sided curve apices, which is consistent with the known preponderance of right-sided curves in thoracic AIS and the known association between larger, progressive curves and female gender.

Multivariate analysis resulted in a predictive model with an r^2 value of 0.54. Although an r^2 value of 0.54 indicates that 46% of axial rotation is determined by factors outside of the regression model, this is to be expected given this method of approximation of a complex, 3D measurement using readily available 2D radiographic parameters. There are undoubtedly many factors contributing to apical vertebral axial rotation beyond the coronal Cobb angle and thoracic kyphosis, but inclusion of such variables would limit the practicality of this model in clinical settings without access to routine 3D imaging. Despite use of limited input variables, the model had Pearson coefficients of 0.739 in the development cohort and 0.703 in the validation cohort, both indicating a strong correlation between predicted and actual axial rotation. Although R and r^2 values may be useful for evaluating regression model fit, clinical applicability and model accuracy are better determined by calculations of error. In both development and validation cohorts, the model performed well, with a standard error of the estimate of 6.18° in the development cohort and a mean absolute error of 4.99° in the validation cohort. This degree of accuracy is comparable to reported errors for the widely used Perdriolle method as well as the techniques described by Raimondi and Stokes [20,27,28]. More modern techniques offer slightly lower errors, but these methods either require complex calculations and atypical measurements or the installation and integration of software reconstruction packages [16-18,20]. The method described by this study requires only 2D thoracic Cobb and 2D T5–T12 kyphosis measurements that are routinely measured with each radiographic evaluation.

A limitation of this model is the fact that in error analysis, model error was found to have a moderate correlation with the true 3D axial rotation ($r^2 = 0.323$), though there was no significantly different performance in terms of error between mild, moderate, or severe curves. This correlation is not surprising given the model's dependence on the input of 2D thoracic kyphosis. This model is based on the supposition that scoliosis progresses concurrently in the coronal, sagittal, and axial planes and relies on the interwoven nature of these 3 planes of deformities to use two readily attainable measurements in the coronal and sagittal planes to estimate the third, axial plane deformity that is not directly visible on 2D imaging. Although 2D coronal Cobb angle remains largely immune from distortion even at larger curve magnitudes, progressive AIS severity is associated with increasing distortion in the measurement of thoracic kyphosis on 2D lateral radiographs [5,22,25,26]. Consequently, as scoliosis severity increases, 2D quantification of the sagittal plane deformity loses accuracy, which subsequently results in diminished prediction of the axial plane deformity. This effect is inherent to utilization of 2D sagittal plane measurements. As a consequence, although there was a weak correlation between 2D coronal Cobb and MAE and although there was no significant difference in MAE in model performance between mild, moderate, and severe curves, the treating surgeon should be aware that there is a small trend toward greater error with larger coronal curve magnitudes. Additionally, this model only calculates axial rotation for the apical vertebra. Although the apical vertebral rotation is reflective of overall axial plane deformity, and is frequently discussed in the literature both with respect to deformity evaluation and operative correction, the method was designed only to determine the axial rotation at the thoracic apex. Although the segmental rotation of each vertebral body in the spine has value, particularly in planning derotation correction strategies, a full characterization of the segmental axial deformity by this 2D correlation formula is not possible.

Although this model is only applicable to thoracic apical rotation, similar methods could be used to develop a model for apical vertebral rotation in lumbar curves. Additionally, our methods and imaging systems remain valid for patients who have undergone spinal fusion. Although our data did not include any postoperative patients, ascertainment of such a data set could facilitate development of a model for approximating apical vertebral rotation in the postoperative spine. If developed, such a model could have further clinical applicability given the widespread availability of intraoperative radiographs that could be used to guide and evaluate surgical correction in the axial plane. These areas offer interesting directions for future research.

In conclusion, this study developed a simple regression model capable of estimating 3D apical vertebral rotation with a mean absolute error of ~5° given only the 2D inputs of thoracic Cobb angle and T5–T12 kyphosis. Accuracy of this method is comparable to currently widely used methods that provide only 2D measurements and require cumbersome measurement tools. Those wishing to estimate the axial plane deformity of thoracic scoliosis may find this prediction formula valuable both for historical data obtained prior to microdose-radiation 3D imaging and other biplanar reconstruction software as well as for those without such imaging systems. Although it is not a direct method of measuring the axial plane deformity, the high degree of correlation of apical vertebral rotation with the other two planes of curvature allows for a simple estimation of AVR.

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