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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