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Classification/Measurement

Accuracy and Precision of Seven Radiography-Based Measurement Methods of Vertebral Axial Rotation in Adolescent Idiopathic Scoliosis

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Abstract

Study Design: Assessment of vertebral axial rotation measurement methods.

Objectives: To assess the accuracy and precision of seven radiography-based vertebral axial rotation measurement methods for typical scoliotic deformity before and after posterior instrumentation.

Summary of Background Data: Vertebral axial rotation is an important component to evaluate transverse plane scoliotic deformities. Several measurement methods were developed based on coronal plane radiographs or computerized 3D reconstruction. Their ability to accurately and precisely measure axial rotation, either pre- or postoperatively, is not well known.

Methods: Two synthetic vertebrae, with and without instrumentation, were fixed in a jig allowing 3D rotation manipulations. Fifty-three configurations of 3D rotations were radiographed. Two observers evaluated seven measurement methods: one visual estimation, two ruler-based (Nash-Moe and Perdriolle), one analytical (Stokes), and three 3D-reconstruction techniques (based on pedicles, based on eight vertebra landmarks, and a surface-based reconstruction software SterEOS). Measurements were repeated one week later.

Results: Intraobserver precision ranged from 2.0° (Perdriolle/SterEOS) to 3.6° (visual estimation) for the noninstrumented vertebra, and from 2.2° (SterEOS) to 9.7° (Nash-Moe) for the instrumented vertebra. Interobserver precision ranged from 1.2° (SterEOS) to 9.3° (Nash-Moe) for the noninstrumented vertebra, and from 1.7° (SterEOS) to 6.2° (Visual Estimation) for the instrumented vertebra. Accuracy of the methods ranged from 2.1° with SterEOS to 9.1° with Nash-Moe ruler. The measurement error was significantly associated with the level of axial rotation for Nash-Moe and 3D reconstruction techniques with low to moderate correlation.

Conclusions: The majority of radiography-based methods measured vertebral axial rotation with an average error of 2° to 5°. The Nash-Moe method should be avoided, considering its inaccuracy greater than 9°. The instrumentation did not compromise the precision or the accuracy of measurement. The measurement accuracy of 3D reconstruction methods was impaired by the severity of the axial rotation.

Level of Evidence: N/A.

Keywords: Adolescent idiopathic scoliosis; Transverse plane deformity; Instrumentation; Vertebral axial rotation; Measurement; Accuracy; Precision

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Introduction

Adolescent idiopathic scoliosis (AIS) is a complex 3D deformity of the spine, involving abnormal rotations of the vertebrae in the transverse plane [1]. Vertebral "axial rotation" is an index assessing the torsional component of the spine in the transverse plane [2]. Scoliotic spines typically involve axial rotation of the vertebrae up to 25°, rarely exceeding 40°, toward right or left sides [3]. The severity of the thoracic apical axial rotation has been associated to the rib hump [4]. Axial rotation quantification has proven clinical utility for scoliosis pathomechanism comprehension [5,6] and curve progression monitoring [7,8]. With contemporary vertebral derotation surgical maneuvers, which aim to improve the transverse plane deformity, axial rotation is an important parameter to quantitatively assess surgical correction [9].

Vertebral axial rotation is a challenging index to quantify because it is mainly observable in a plane not accessible on a typical radiograph. Measurements on coronal and sagittal radiographs were developed based on the interpretation of vertebral features. Nash-Moe developed one of the first methods that associated the degree of rotation to the percentage of displacement of the concave pedicle shadow across the vertebral body [10]. Perdriolle further improved this method by considering the effect of the projection of the pedicles in the coronal plane, and designed a ruler called "torsiometer" [11]. Stokes proposed an analytical method based on the trigonometric relationship between vertebral shape parameters [12]. The most recent methods are based on stereoradiographic computational techniques that create 3D vertebral geometrical models. 3D coordinates of specific vertebral landmarks are obtained through their identification on biplanar calibrated radiographs [13]. Axial vertebral rotation can be computed based on different anatomical reconstructed landmarks. In the last few years, commercial software has been developed to assist users in the reconstruction process and enhance automation. Methods using computed tomography (CT) were proposed to assess axial rotation [14,15], but CT examination is not often used in AIS because of the high radiation exposure, and the modification of the spine vertebral rotations due to the supine position imposed by CT examination.

Measurement methods rely on the ability of the observer to identify different anatomical landmarks, not always fully visible and easy to recognize. The bias due to the observer performing the measurement refers to the precision of the method. Intra-observer precision (repeatability) refers to the ability of one measurer to repeat the measurement between trials, and interobserver precision (reproducibility) to the ability of different measurers to reproduce the same measurement. The proximity of the measurement to the true axial rotation refers to the accuracy. Many studies have assessed the precision and/or accuracy of measurement methods [3,16], but rarely report both accuracy and precision. There is insufficient comparison between different methods in the literature. Further comparison between studies is often limited by the differences in the quantitative indices reported to assess accuracy and precision [16].

Previous studies reporting measurement method accuracy often assessed pure axial rotation only [17-19]. However, when the scoliotic spine is radiographed, the projected vertebral shape appeared deformed because of the axial rotation, but also to the lateral tilting and forward-backward inclinations present in scoliotic vertebrae [20,21]. This may further challenge the identification of the landmarks and alter axial vertebral rotation measurement accuracy. Contemporary surgical correction of scoliosis involves spinal metallic instrumentation, which is likely to obstruct the visibility of vertebral anatomical structures on radiographs, and further alter axial rotation measurement. To provide a better appreciation of the rotational correction achieved with surgical intervention, the capacity of current measurement methods to assess axial rotation using postoperative radiographs remains to be determined.

The objective of this study was to assess the accuracy and precision (intra- and interobservers) of seven radiography-based vertebral axial rotation measurement methods for typical vertebral scoliotic 3D deformity, before and after posterior instrumentation.

Materials and Methods

Two identical L3 synthetic vertebrae composed of polyurethane foam, including a cortical shell and a cancellous inner material, were used (Sawbone; Pacific Laboratories, Vashon, WA). These vertebrae mimic the human structures in shape, size, and function and produce a realistic and user-friendly image in x-ray environments (Fig. 1). One vertebra was instrumented with 5.0×50-mm titanium polyaxial pedicle screws and 5.5-mm Cobalt-Chrome rods. The vertebrae were fixed in a radio-translucent vertebral 3D rotation manipulation device that allowed to position them with the same 3D inclinations, with an accuracy of 0.5° as assessed with a coordinate measuring machine (CMM Microscribe, Immersion Corp., San Jose, CA) (Fig. 2). Fifty-three different 3D rotation sequences found in typical scoliotic spines were applied to both vertebrae. Vertebrae were successively rotated in the transverse, frontal and sagittal planes, around the local axis of the device, designed to rotate with the vertebrae (Fig. 2) [21]. The axial rotations ranged from −30° to 30° with 5° increments, with combined frontal and sagittal planes inclinations ranging from −20° to +20° with 10° increments. Each resulting configuration was radiographed using a biplanar radiographic system (EOS Imaging, Paris, France). For each of the 53 combinations of rotations, the vertebral axial rotation relatively to the sagittal plane (stationary plane of reference) was measured for each one of the two vertebrae using seven methods:

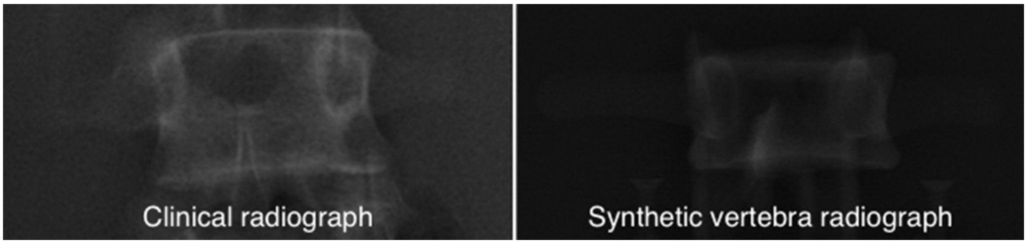

Fig. 1. Clinical and synthetic L3 vertebra radiographs.

- Visual method: *Visual Estimation (1)* method was based on the observer appraisal of the axial rotation by looking at the coronal radiograph, without using any tool. The observer was free to base his judgment on any criteria (relative position of the pedicles, spinous process orientation, pedicle screws symmetry).
- Ruler-based methods: The *Nash-Moe (2)* and *Perdriolle torsiometer (3)* methods were based on the identification of the pedicle shadow center and the edges of the vertebral body on the coronal radiograph.
  - With the Nash-Moe technique, the observer used a digital ruler on the radiograph to measure the vertebral body width w and the distance between convex pedicle and vertebral body right side p. The Nash-Moe axial rotation θ was automatically computed based on these measurements [10]: $\theta\,(^{\circ}) = \frac{p}{w}.100$
  - The observer directly placed the Perdriolle analog ruler on the radiograph to read the resulting axial rotation.
- Analytical method: *Stokes (4)* method implied the measurement of the distances between the vertebral center and the convex and concave pedicles (a and b) with a digital ruler on the coronal radiograph. The axial rotation calculation resulted from Stokes formula [22], with the fixed 1.04 width-to-depth ratio for L3 vertebrae: $\theta(^{\circ}) = \arctan\left(1.04 * \frac{a-b}{a+b}\right)$
- 3D reconstruction methods: Measurer reconstructed a 3D vertebral model based on bilateral calibrated radiographs. Six corresponding anatomic landmarks were identified on both coronal and sagittal radiographs (superior and inferior tips of the pedicles and the center of endplates). Four additional non-corresponding landmarks were placed on each radiograph to define the corners of the vertebral body. Based on the 3D coordinates of these landmarks, two methods were defined to automatically compute axial rotation with MATLAB R2012a software.
  - *3D-Pedicles (5)* method: axial rotation was defined as the angle between the vector joining the reconstructed center of the pedicles and the frontal plane when projected onto the transverse plane.

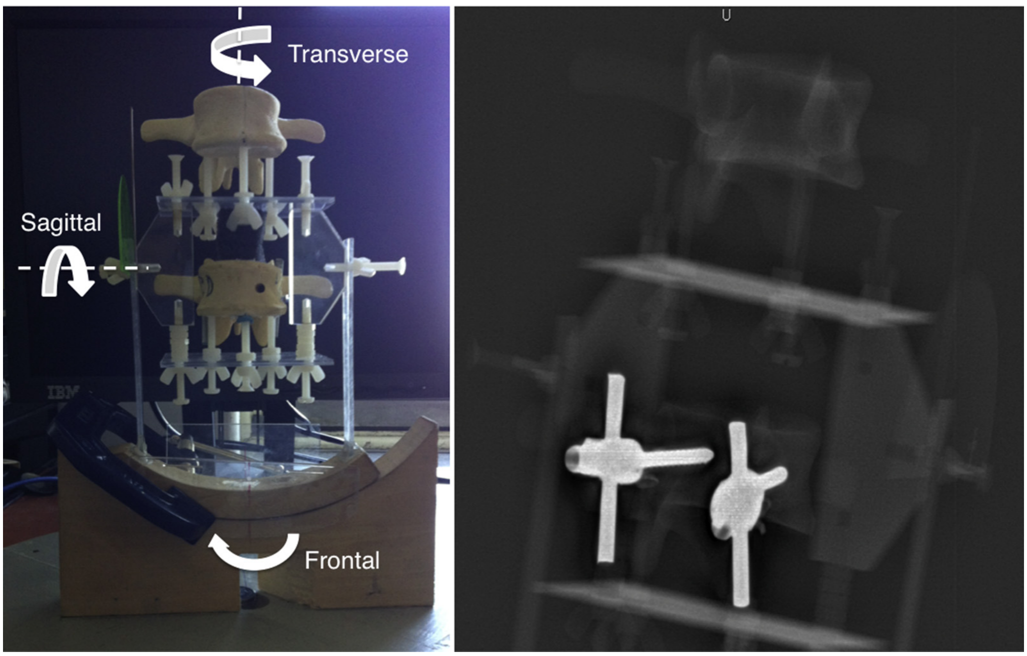

Fig. 2. Vertebrae on the 3D rotation manipulation device (top: non instrumented, bottom: instrumented).

   ◦ *3D-Barycentre (6)* method: a plane of symmetry of the vertebra was defined using the principal components analysis (PCA) of eight 3D-reconstructed landmarks. The axial rotation was computed as the angle between the vertebral axis of symmetry and the sagittal plane, when projected onto the transverse plane.
- Surface-based reconstruction software method: Measurer reconstructed a 3D vertebral model with *SterEOS (7)* software [23]. After the measurer identified the superior and inferior endplates, the shape of the vertebra was automatically reconstructed with an algorithm based on statistical modeling and bone shape recognition. The measurer could adjust the shape and the rotation of the vertebra. SterEOS automatically computed axial rotation.

Two measurers were trained with the appropriate tools (digital ruler, Perdriolle torsiometer, 3D reconstruction software). If the vertebral anatomical structures were obstructed by instrumentation, the observer had to estimate their position on the radiograph to perform the measurement. The measurers followed the protocol described above to measure all the 53 axial rotations on the randomly distributed pairs of biplanar radiographs, with each one of the seven measurement methods consecutively. The measurements were repeated one week later in a different random order to assess the repeatability. The data were analyzed using SPSS statistical software program (version 21.0; IBM Corp., Armonk, NY). This project has been approved by the Research Ethics Committee (#2668) of Sainte-Justine University Hospital Center and Polytechnique Montreal.

Intra-observer precision (repeatability), which quantifies the ability of an observer to repeat the measure (test-retest reliability) was reported as the mean absolute difference (MAD) between the first and second measurement performed by the same observer. To assess interobserver precision (reproducibility), which refers to the ability of different observers to perform the same measurement, the mean absolute difference between the observers' measurements was calculated.

The "measurement error," defined as the difference between the calculated axial rotation and the true axial rotation given to the vertebra, was computed for each of the measurement. Accuracy, which refers to the proximity of the measurement to the true axial rotation, was reported as the mean absolute measurement error.

The presence of a significant relation ($p > .05$) between the measurement error and the axial rotation severity was assessed using Pearson correlation coefficient r. Absolute value of Pearson coefficient between 1 and 0.70 reflected strong correlation, 0.70 to 0.50 moderate, and below 0.50 low correlation [24].

Results

The measurements obtained with each of the seven methods were analyzed to report their precision (intra- and intermeasurer), their accuracy, and the impact of axial rotation severity on measurement error.

Intra- and intermeasurer precision

The intra- and interobserver precision is reported in Table 1. The mean variability due to the same measurer performing multiple measurements for the noninstrumented vertebra ranged from 2.0° with Perdriolle and SterEOS to 3.6° with Visual Estimation. For the instrumented vertebra, intraobserver variability ranged from 2.2° with SterEOS to 9.7° with the Nash-Moe method. The change in intraobserver variability from "noninstrumented" to "instrumented vertebra" was between −0.4° with Visual Estimation (increase in precision) and +7.3° with Nash-Moe (decrease in precision).

For the interobserver precision, the difference between the two measurements of the noninstrumented vertebra ranged from 1.2° with SterEOS to 9.3° with Nash-Moe. For the instrumented vertebra, it ranged from 1.7° with SterEOS to 6.2° with Visual Estimation.

Accuracy

The accuracy of axial rotation measurement (absolute difference between the measurement and the actual rotation) of noninstrumented and instrumented vertebrae is presented in Figure 3. For the noninstrumented vertebra, the accuracy ranged from 2.6° with Perdriolle torsiometer to 7.6° with the Nash-Moe method. For the instrumented vertebra, the accuracy of the method changed by less than

Table 1
Intra- and interobserver precision of the seven axial rotation measurement techniques for the vertebrae with and without instrumentation.

	Intraobserver precision		Interobserver precision	
	Noninstrumented	Instrumented	Noninstrumented	Instrumented
Visual estimation	3.6°	3.2°	5.3°	6.2°
Nash-Moe	2.4°	9.7°	9.3°	5.3°
Perdriolle	2.0°	3.4°	3.5°	3.6°
Stokes	3.1°	4.6°	3.6°	3.7°
3D-Pedicles	3.2°	3.7°	2.6°	4.1°
3D-Barycentre	3.4°	4.6°	3.1°	3.4°
SterEOS	2.0°	2.2°	1.2°	1.7°

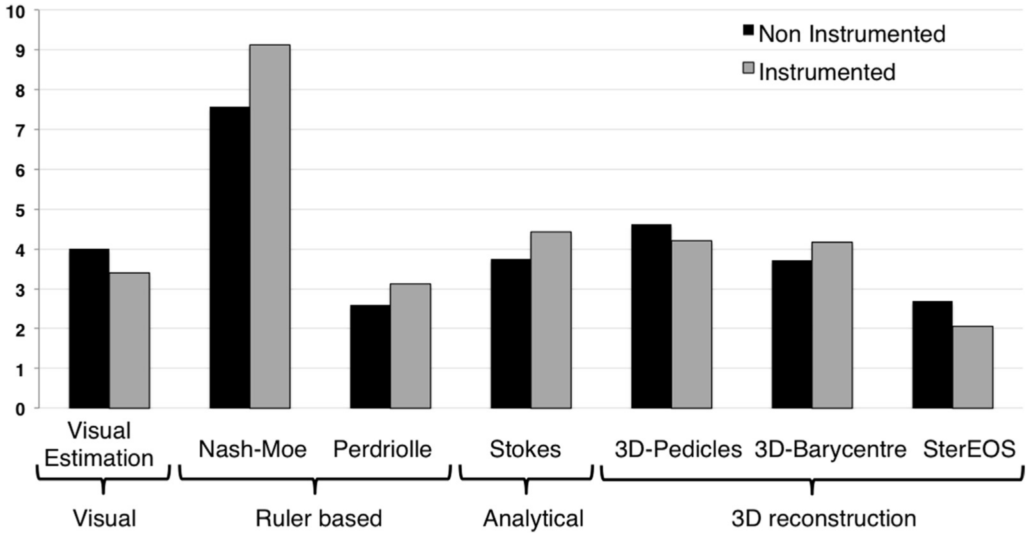

Fig. 3. Accuracy of the seven axial rotation measurement methods for the vertebrae with and without instrumentation (mean absolute measurement error in degrees).

1.5°, resulting in an accuracy ranging from 2.1° with SterEOS to 9.1° with the Nash-Moe method.

Impact of axial rotation severity on measurement error

The statistical association between the severity of axial rotation and the measurement error is reported in Table 2. The measurement error was significantly associated with axial rotation severity for Nash-Moe and 3D reconstruction techniques with low to moderate correlation. An increase of axial rotation from 0° to −20° resulted in an average increase of measurement error of 4.6°, 2.9°, 2.2°, and 2.0° for Nash-Moe, 3D-Pedicles, 3D-Barycentre, and SterEOS methods, respectively. With the Nash-Moe method, there was a tendency to overestimate the severity of the axial rotation when increasing the axial rotation (positive correlation), whereas with 3D reconstruction methods the severity of axial rotation was underestimated (negative correlation).

Table 2
Impact of axial rotation severity on measurement error (*p < .05).

	Pearson correlation (*r*)	Average measurement error	
		Rotation applied to the noninstrumented vertebra	
		0°	−20°
Visual estimation	−0.29*	0°	2.7°
Nash-Moe	0.41*	−1.4°	−5.9°
Perdriolle	0.14*	−0.3°	−1.0°
Stokes	−0.58	−0.1°	0.9°
3D-Pedicles	−0.54*	1.1°	4.0°
3D-Barycentre	−0.46*	0.5°	2.6°
SterEOS	−0.46*	0.4°	2.4°

The asterisk (*) indicates statistical significance.

Discussion

An average error of 2° to 5° should be expected when measuring axial rotation with most of currently available radiography-based methods. Being aware of such measurement error is essential to compare correction treatment efficiency (power analysis calculation), or to monitor or assess deformity progression.

The measurement method using SterEOS 3D reconstruction software based on biplanar calibrated radiographs was the most precise and accurate, with an error of 2.4° on average. The Perdriolle torsiometer method is similarly accurate (2.9° average error), while only requiring the use of a physical measuring ruler on a posteroanterior radiograph, making this method an interesting alternative for axial vertebral rotation assessment. We found that the Nash-Moe method resulted in a much higher measurement error (8.4° average error) compared with the other methods. This is in agreement with the findings from Drerup et al., who previously reported an average error of 12° in thoracic and lumbar vertebrae rotation measurement with the Nash-Moe technique [25]. Although Drerup et al. tried to introduce an empirical method called “Nash-Moe − 10°” to overcome this inaccuracy, the Nash-Moe method was neither accurate nor precise, making this mathematical adjustment limited for improving measurement error. The Nash-Moe method is therefore not suitable for axial vertebral rotation measurement.

The presence of screws and rods on postoperative radiographs did not compromise the accuracy (<0.6° increase) and precision (<1.5° increase) in determining axial rotation, except for the Nash-Moe method (7.3° increase). A previous study also reported excellent measurement precision when evaluating axial vertebral rotation of instrumented scoliotic spine with the SterEOS software (ICC of 0.97 before instrumentation and 0.94 after instrumentation) [26]. The anatomical landmarks necessary to compute the rotation could be fairly estimated despite their obstruction by the hardware. Several authors demonstrated that pedicle screw orientation on posteroanterior radiograph and concave and convex rods' relative position on the sagittal radiograph can give a good estimation of vertebral axial rotation [27,28].

The more the vertebrae were rotated, the less accurate were the 3D reconstruction−based measurement methods, which should be taken into consideration when evaluating severe spinal 3D deformity. The increase of measurement error can be attributed to the projection of 3D anatomical structures of highly rotated vertebrae on planar radiographs. Gunzburg et al. demonstrated that when axial vertebral rotation was increased, the center of the pedicle observed on the radiograph was offset from its actual 3D position [18]. We compared three different measurement methods based on 3D reconstruction techniques (3D-Pedicles, 3D-Barycentre, SterEOS) and found that using an increased number of landmarks for defining vertebral shape reduced the error resulting from vertebral rotation severity.

Our study has some limitations owing to the use of a synthetic asymptomatic lumbar vertebra. Only two observers performed the measurements, and adding an observer trained as orthopaedic surgeon would be valuable to determine if a higher skill level would yield better intraobserver agreement. The precision and accuracy of the different methods may depend on the vertebral shape and age of the patient, which may modify the ability to identify vertebral structures on the radiographs, and which impact on the resulting error remains to be investigated. On the patient's radiograph, soft tissue shadow may complicate the identification of vertebral structures and increase the measurement error. The study radiographic acquisitions may not be fully representative of patient spine radiographs, but we considered the radiographs provided equivalent image quality and details required to make such measurements, as seen on Figure 1. The manipulation device implied different spatial positions for the noninstrumented and instrumented vertebrae in the x-ray setup, resulting in differing projections on the two vertebrae, but the estimated difference of axial rotation measurement was around 0.8° for the most severe rotation sequence. The accuracy of methods remains to be further investigated with other vertebral 3D positions [21]. In addition, the capacity of the methods to quantify the rotation between adjacent vertebrae needs to be further assessed, as the intervertebral rotation along the length of the spine, also called "torsion," is a key index in the 3D evaluation of scoliosis. Despite these limitations, our setup allowed to relatively compare the accuracy and precision of the different methods in a controlled environment, on identical noninstrumented and instrumented vertebrae, with a clinically relevant variety of vertebral orientations, which would not have been possible with patients' radiographs or cadaveric vertebrae.

In summary, current radiography-based methods measured vertebral axial rotation with an average error of 2° to 5° when evaluating pre- and postoperative transverse plane scoliotic deformity. The Nash-Moe method should be avoided considering its poor accuracy compared with other measurement methods. The methods were as well suited for the assessment of pre- or postoperative vertebral axial rotation, as instrumentation inserted in vertebrae during surgical correction did not compromise precision and accuracy of measurement. The increase of measurement error should be taken into account when evaluating severe spinal 3D deformity. In addition to precision and accuracy, clinical applicability must be appraised for measurement methods selection, and further studies are required to assess their respective ease of use or time and cost effectiveness in a clinical environment.

Key points

- Accuracy, and intra- and inter-observer precision of 7 vertebral axial rotation measurement methods were assessed.
- 2° to 5° inaccuracy should be considered when assessing axial vertebral rotation except for the Nash-Moe method (>9°) which should be avoided.
- Instrumentation did not significantly affect the precision and accuracy for the measurement of axial rotation.
- Measurement accuracy of 3D reconstruction methods was impaired by the severity of the axial vertebral rotation.

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