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Basic Science

Development and assessment of a digital X-ray software tool to determine vertebral rotation in adolescent idiopathic scoliosis

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Abstract

BACKGROUND CONTEXT: The amount of vertebral rotation in the axial plane is of key importance in the prognosis and treatment of adolescent idiopathic scoliosis (AIS). Current methods to determine vertebral rotation are either designed for use in analogue plain radiographs and not useful in digital images, or lack measurement precision and are therefore less suitable for the follow-up of rotation in AIS patients.

PURPOSE: This study aimed to develop a digital X-ray software tool with high measurement precision to determine vertebral rotation in AIS, and to assess its (concurrent) validity and reliability.

STUDY DESIGN/SETTING: In this study a combination of basic science and reliability methodology applied in both laboratory and clinical settings was used.

METHODS: Software was developed using the algorithm of the Perdriolle torsion meter for analogue AP plain radiographs of the spine. Software was then assessed for (1) concurrent validity and (2) intra- and interobserver reliability. Plain radiographs of both human cadaver vertebrae and outpatient AIS patients were used. Concurrent validity was measured by two independent observers, both experienced in the assessment of plain radiographs. Reliability-measurements were performed by three independent spine surgeons.

RESULTS: Pearson correlation of the software compared with the analogue Perdriolle torsion meter for mid-thoracic vertebrae was 0.98, for low-thoracic vertebrae 0.97 and for lumbar vertebrae 0.97. Measurement exactness of the software was within 5° in 62% of cases and within 10° in 97% of cases. Intraclass correlation coefficient (ICC) for inter-observer reliability was 0.92 (0.91–0.95), ICC for intra-observer reliability was 0.96 (0.94–0.97).

CONCLUSIONS: We developed a digital X-ray software tool to determine vertebral rotation in AIS with a substantial concurrent validity and reliability, which may be useful for the follow-up of vertebral rotation in AIS patients.

Keywords: Prognosis; Radiology; Reliability; Scoliosis; Software; Vertebral rotation

FDA device/drug status: Not applicable.

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Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the spine, predominantly affecting patients in the age of 10–18 [1]. Adolescent idiopathic scoliosis may progress over the years, especially during growth, and can cause significant pain, as well as musculoskeletal, pulmonary, and psychological problems [2]. The pathogenesis is complex and multifactorial. For both prognostic and therapeutic purposes, the rotational component of the deformity in AIS is an important parameter [3–5]. A higher value of rotation is reported in progressive curves compared with non-progressive curves, even at first presentation [6,7]. Currently, a broad variety of methods is used to measure vertebral rotation [8]. The Perdriolle torsion meter is a frequently used tool for analogue X-rays [9]. This tool determines the amount of vertebral rotation using the radiographic relationship between a vertebral body and its pedicles. In literature, there is consensus about its measurement precision and simplicity of use [7]. Intra- and interobserver variability analysis of the Perdriolle torsion meter shows a moderate precision: 53% of measurements were exact within 5° of the real angle of rotation and overall error from the actual torsion averaged 6° [9]. The torsion meter is designed for analogue X-rays and is therefore less compatible with computer displays. Since digital imaging has made its entrance in clinical practice, the Nash Moe method is commonly used for the assessment of vertebral rotation in scoliosis [8]. This method uses the percentage displacement of the pedicle on the convex side of the vertebra with respect to the vertebral width to estimate the angle of vertebral rotation. The latter method divides the amount of rotation in multiple categories and uses an ordinal scale, providing only a rough approximation of vertebral rotation. Compared to a continuous scale, the measurement precision of an ordinal scale is lower. A digital version of the Perdriolle torsion meter could therefore be useful for clinical practice.

The aim of the present study is to develop a digital X-ray software tool to determine vertebral rotation with high measurement precision and to test its concurrent validity compared with the analogue Perdriolle torsion meter. The secondary objective is to measure the intra- and interobserver reliability of the abovementioned software tool.

Materials and methods

Overall study design

A digital X-ray software tool for the measurement of vertebral rotation was developed, which was subsequently assessed for concurrent validity in an experimental setting, using a cadaver vertebral model. After that, intra- and interobserver reliability was assessed in a clinical setting, using plain radiographs of AIS patients.

Ethical approval

The Institutional Medical Ethics Review Committee has reviewed the protocol. It stated that, according to the Medical Research Involving Human Subjects Act, the Institutional Medical Ethics Review Committee's approval is not needed for this study. The X-ray images used in this study were collected within the context of regular medical care and were anonymized before use. In this study, vertebrae of one human cadaver specimen were used. A handwritten and signed codicil is kept at the department of Anatomy and Embryology of Maastricht University, the Netherlands. This is required by law for the use of cadavers for scientific research and education.

Software development

Using Wolfram Mathematica 8.0 (Wolfram Research, Inc, Champaign, IL, USA) software for the measurement of vertebral rotation on digital radiographs based on the analogue graphic, of the Perdriolle torsion meter was developed. Instead of using an overlay with vertical lines, markers positioned on vertebral landmarks in digital images are used to evaluate rotation. These markers are placed on their correct location by the observer. Landmarks include the convex and concave lateral side of the vertebra located on the most convex side of the curve (the apical vertebra) and the center of the pedicle at the convex site, comparable with the analogue Perdriolle torsion meter, on a digital AP full spine radiograph (Fig. 1). The software uses vector angles based on the observer's input to calculate distance ratios. These ratios are used to determine the angle of vertebral rotation by comparing the calculated ratios to the ratios that were extracted from the original Perdriolle torsion meter. The latter were extracted from the graphical tool by measuring several points for each known value and running these coordinates through a linear curve fitting algorithm. The Wolfram Mathematica file and source code are available as online supplementary content with this paper (file names: "startscreen v4.0.nb" and "startscreen v4.0.pdf").

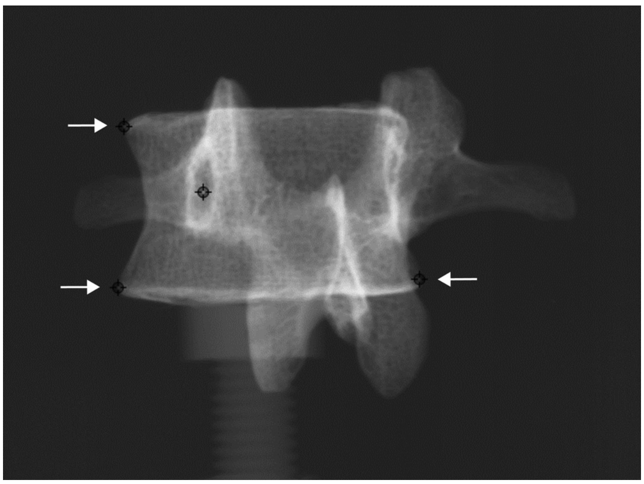

Fig. 1. Screenshot of digital X-ray software tool.
Markers are placed on anatomical landmarks of vertebrae. (Arrows are added to highlight three of the markers for reasons of clarity.)

Assessment of concurrent validity in human vertebral cadaver model

Concurrent validity is a measure of agreement between the results obtained by a given instrument and the results obtained for the same population by a (frequently used) other instrument. To investigate the concurrent validity of the digital X-ray software tool, an anatomical model was designed using human cadaver vertebrae. Single vertebrae of levels Th8, Th12, and L1 were respectively attached to a rotating frame with a goniometer (Fig. 2). The base of the frame was outlined perpendicular to the X-ray device. The frame was rotated to 1 of 10 different angles (0°, 3°, 9°, 15°, 18°, 22°, 26°, 32°, 38°, 43°) and an X-ray was taken. This procedure was repeated for all 10 angles, for each of the three vertebrae, resulting in a total of 30 X-rays.

Two observers independently measured vertebral rotation twice on the acquired AP radiographs of the anatomical model using both the digital X-ray software tool and the analogue Perdriolle torsion meter. Between the two test sessions was a 1 week-interval. Measurements were performed in standardized conditions (ie, the same computer and monitor were used). To prevent bias, observers where blinded for the real angle and the sequence in which the X-rays were presented to the observers was randomly allocated for both sessions for both observers by a third person who kept the randomization key confidential until data collection was complete.

Before the analysis of concurrent validity of the digital X-ray software tool, the intra- and interobserver variability of the observers were quantified to estimate the amount of agreement c.q. error between the observers. Intraclass correlation coefficient (ICC), measuring absolute agreement, Bland-Altman plots, and Standard Error of the Measurement (SEM) were calculated. An ICC of more than 0.8 was considered to be acceptable to warrant a meaningful assessment of validity. For the quantification of concurrent validity of the digital X-ray software tool, Pearson correlations were calculated.

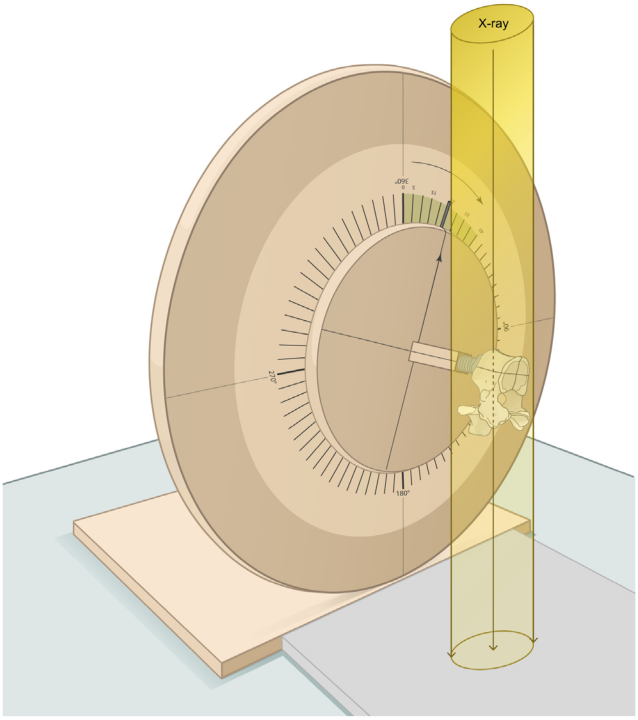

Fig. 2. Human cadaver vertebra placed on rotating goniometer. This model was placed in an X-ray setup to obtain radiographs of the vertebra in different rotation angles. Arrows indicate direction of radiation.

Table 1
Patient demographic data and curve characteristics

Patient parameters	
Female/male	11/4
Mean age	14.22 (10–22)
Mean Cobb angle	34.3° (18–58°)
Type of curve	Lenke 2A, 3A, 4C
Level of apex-vertebra	Th8 (2), Th9 (3), Th10 (4), Th11 (2), Th12 (1), L1 (2), L2 (1)

Assessment of intra- and interobserver reliability in clinical setting

AP full spine radiographs of 15 AIS patients from our outpatient clinic were selected for reliability tests of the digital X-ray software tool. Radiographs were anonymized before use in this study. For patient characteristics, see Table 1. Three spine surgeons (two orthopedic surgeons, one neurosurgeon) individually evaluated vertebral rotation on each of the 15 radiographs using the digital X-ray software tool and the analogue Perdriolle torsion meter. Radiographs were zoomed in at the level of the apex of the curvature. The outcome of the software-measurement was blinded to the surgeons in all cases. After 2 weeks, a re-test was performed. For all sessions, the sequence of radiographs was randomly allocated. A total of 90 measurements were obtained.

To quantify reproducibility of the X-ray software tool, measures of agreement and measures of reliability were calculated. The inter-observer agreement was analyzed by calculating the mean difference between observers, standard deviation of the mean, and 95% confidence intervals. Bland-Altman plots were created using the mean of two observers and the difference between two observers. ICCs were calculated using a random-effects two-way analysis of variance, measuring for absolute agreement. We consider an ICC of at least 0.90 and a SEM of maximal 1.0 to be acceptable.

All statistical analyses were performed using IBM SPSS 22.0 (IBM SPSS Statistics for Windows, Version 22.0, IBM Corp., Armonk, NY, USA).

Results

Intra- and interobserver reliability analysis of the observations in the anatomical model, performed before the assessment of concurrent validity, showed high ICCs (>0.9, Table 2). Bland-Altman plots of these measurements showed narrow confidence intervals and no systematic error (Figs. 3 and 4). Concurrent validity of the software tool compared with

Table 2
Intra and inter-observer reliability measured before the analysis of concurrent validity

	$ICC_{agreement}$	SEM
Observer 1	0.94	0.37
Observer 2	0.96	0.61
Observers 1–2	0.97	0.74

$ICC_{agreement}$, intraclass correlation coefficient of agreement; SEM, standard error of measurement.

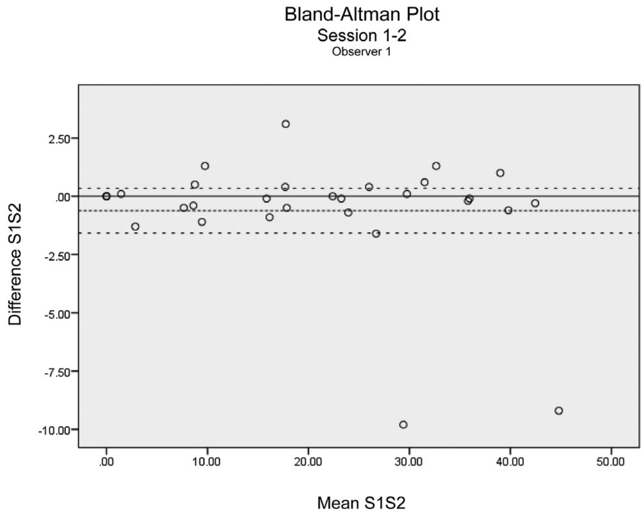

Fig. 3. Bland-Altman plot of intra-observer variability, using X-rays of human cadaver vertebrae (anatomical model).
On the x-axis, the mean of measurements is shown. On the y-axis, the differences between repeated measurements performed by the same observer are shown. The bold line represents the mean difference, the dotted line represents the 95% confidence interval.

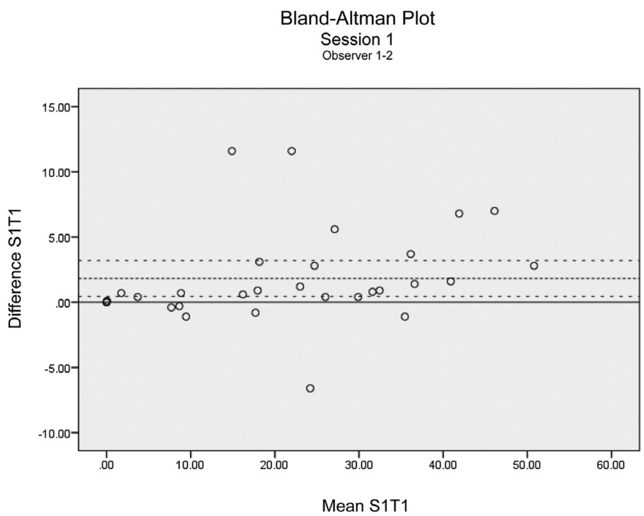

Fig. 4. Bland-Altman plot of inter-observer variability, using X-rays of human cadaver vertebrae (anatomical model).
On the x-axis, the mean of measurements is shown. On the y-axis, the differences between measurements performed by different observers are shown. The bold line represents the mean difference, the dotted line represents the 95% confidence interval.

Table 3
Analysis of concurrent validity of the digital X-ray software tool compared to (A) the analogue Perdriolle torsion tool and (B) the assumed real angle

A. Compared to Perdriolle torsion tool	Pearson correlation
Th8	0.98
Th12	0.97
L2	0.97
B. Compared to assumed real angle	
Th8	0.97
Th12	0.98
L2	0.99
Exactness	
Within 5° of assumed real angle	62%
Within 10° of assumed real angle	97%
Mean of individual measurement error	4.7°

the analogue Perdriolle torsion meter was high; we found Pearson correlations of at least 0.97. Pearson correlations of the software tool compared with the assumed real angle (ie, the angle as set up on the rotating frame) showed similar values (Table 3). No significant differences were found between levels of vertebrae, or between different rotation angles. Sixty-two percent of the measurements were within 5° of the assumed real angle and 97% within 10° of the assumed real angle. The measurement error overall averaged 4.7°. Reliability analysis, performed in clinical setting, showed high ICCs (>0.9, Table 4). SEMs were moderate to good (0.41–1.14), indicating a relatively low dispersion of reliability measurements. Bland-Altman plots of intra- and interobserver reliability showed no systematic error (plots available from the corresponding author upon request).

Discussion

The amount of vertebral rotation is of key importance in the prognosis and treatment of AIS [5,7]. Especially for prognostic purposes, measurement precision is important. Existing radiographic methods for the assessment of spinal rotation in scoliosis provide rough estimates of rotation, since they make use of an ordinal scale [10]. Using computerized tomography (CT), 3-D reconstruction of the spine and, therefore,

Table 4
Analysis of reliability of the digital X-ray software tool

Intra-observer reliability of software	$ICC_{agreement}$	SEM
Spine-oriented surgeon 1	0.94	0.88
Spine-oriented surgeon 2	0.96	0.60
Spine-oriented surgeon 3	0.97	0.41
Inter-observer reliability of software	$ICC_{agreement}$	SEM
Spine-oriented surgeon 1–2	0.91	1.14
Spine-oriented surgeon 1–3	0.95	0.73
Spine-oriented surgeon 2–3	0.91	0.99

$ICC_{agreement}$, intraclass correlation coefficient of agreement; SEM, standard error of measurement.

Intra- and interobserver variability of three spine-oriented surgeons are shown.

vertebral rotation with relatively high measurement precision, can easily be obtained. However, for the follow-up of scoliotic curves, CT is less suitable because patients, mostly juvenile, are repeatedly exposed to high doses of ionizing radiation. Furthermore, the supine position required for this method may influence the spinal deformity [11,12].

The aim of this study was to develop and assess a digital X-ray software tool for the measurement of vertebral rotation in AIS. We developed a tool which combines measurement precision of the analogue Perdriolle torsion meter with compatibility for digital plain radiographs. Main findings of the present study are an excellent concurrent validity (ρ=0.97–0.99) of the digital X-ray software tool with its analogue equivalent, a moderate exactness (62% within 5° of assumed real angle, 97% within 10° of assumed real angle), and a good intra- and interobserver reliability (ICCs 0.91–0.97). In a recently published study of Cerny et al., a method is described to determine vertebral rotation using conventional X-rays as well [13]. This method is based on geometric shape properties of vertebrae and their shared dimensional proportions. Axial rotation is calculated by measuring the angles of manually drawn lines using vertebral landmarks. Unfortunately, data concerning intra- and interobserver variability, such as ICCs and Bland-Altman plots, are completely lacking.

The concurrent validity and reliability of the present digital X-ray software tool is high. The software is therefore particularly suitable for prognostic features; progression or regression in vertebral rotation in AIS patients can be easily monitored this way. The measurement precision of the digital X-ray software tool we developed compares favorably with other methods for the measurement of vertebral rotation. Therefore, adequate follow-up of the rotational component in children suffering AIS is possible. However, current methods for the measurement of vertebral rotation, the digital X-ray software tool included, appear to be less suitable to draw conclusions concerning the real angle of rotation, for example, in decision making (eg, use as a cutoff point for surgical intervention). In clinical practice, this means the tool is especially suitable to monitor an increase or decrease of vertebral rotation over time, rather than measuring the actual, exact amount of rotation. The software's low exactness is not surprising, as it is based on the analogue Perdriolle torsion meter, the exactness of which is known to be relatively low [9]. Possible reasons for this low exactness are the relatively low quality of radiographs, the fact that a 2-D method is used to assess a 3-D parameter, variations in pedicle anatomy, and interobserver variability in locating the landmarks. To obtain a higher exactness of the tool, the algorithm of the Perdriolle torsion meter and the quality of spinal X-rays need to be optimized or other imaging techniques could be used (which probably requires a new format of the assessment tool). Furthermore, placing the dots on the exact right location requires practice, so training of observers might improve measurement quality.

The strengths of the present study are the unique nature of the digital X-ray software tool to combine ease of use of the digital Perdriolle tool with those of digital imaging, and its clinical relevance due to the good prognostic value of vertebral rotation. Furthermore, the study design—a stepwise combination of (1) basic radiographs using human cadaver vertebrae and (2) clinically valid radiographs of outpatient AIS patients—contributes to a high quality.

The limitations of the study are the small groups of X-rays and the small groups of observers, which lead to a relatively low statistical power. Furthermore, the analysis of concurrent validity is based on a single set of non-scoliotic cadaver vertebrae, using artificial ex vivo radiographs without the soft tissue scatter etc., of regular in vivo X-rays. Also, the digital X-ray software tool is written in Mathematica. The Mathematica file and source code are provided to share as online supplementary material with this paper, but still the tool needs to be converted to a format which is compatible to be used in patient-information-systems. Suggestions for further research could be an assessment of validation and reproducibility of the digital X-ray software tool in larger groups of patients by a larger number of observers and in a study design that includes follow-up of AIS over time. Also, the tool needs to be converted to an open-source tool which can then be used in digital plain radiographs in patient-information-systems.

Conclusions

In conclusion, the requirements of measurement instruments generally depend on their purpose: regular monitoring of AIS progression or high-impact decision making demand different clinimetric properties. With the Perdriolle tool, assessment of the exact angle of rotation is not possible, which makes it unsuitable as an instrument to determine, for example, a surgical cutoff score. However, with its high concurrent validity and reliability, the digital Perdriolle tool that we developed may be a valuable clinical tool to monitor AIS and to detect meaningful differences (ie, progression of the curve) over time.

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Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.spinee.2015.09.039.

References

[1] Konieczny MF, Senyurt H, Krauspe R. Epidemiology of adolescent idiopathic scoliosis. J Child Orthop 2013;7:3–9.

[2] Heft F. Pathogenesis and biomechanics of adolescent idiopathic scoliosis (AIS). J Child Orthop 2013;7:17–24.

[3] Dreiman M, Hoffmann M, Kossow K, Hitzl W, Meier O, Koller H. Scoliosis and chest cage deformity measures predicting impairments in pulmonary function: a cross-sectional study of 492 scoliosis patients to improve the early identification of patients at risk. Spine 2014;39:2024–33.

[4] Cholewicki J, Crisco JJ 3rd, Oxland TR, Yamamoto I, Panjabi MM. Effects of posture and structure on three-dimensional coupled rotations in the lumbar spine. Spine 1996;21:2421–8.

[5] Perdriolle R, Vidal J. Thoracic idiopathic scoliosis curve evaluation and prognosis. Spine 1985;10:785–91.

[6] Perdriolle R, Vidal J. Morphology of scoliosis: three-dimensional evaluation. Orthopaedics 1987;10:909–15.

[7] Nault ML, Mac-Thiong JM, Roy-Beaudry M, Turgeon I, Deguise J, Labelle H, et al. Three-dimensional spinal morphology can differentiate between progressive and nonprogressive patients with adolescent idiopathic scoliosis at the initial presentation. Spine 2014;10: E601–6.

[8] Stokes IAF. Axial rotation component of thoracic scoliosis. J Orthop Res 1989;7:702–8.

[9] Richards BS. Measurement error in assessment of vertebral rotation using the Perdriolle torsion meter. Spine 1992;17:513–17.

[10] Lam GC, Hill DL, Le LH, Raso JV, Lou EH. Vertebral rotation measurement: a summery and comparison of common radiographic and CT methods. Scoliosis 2008;3:16.

[11] Ho EKW, Upadhyay SS, Ferris L, Chan FL, Bacon-Shone J, Hsu LC, et al. A comparative study of computed tomographic and plain radiographic methods to measure vertebral rotation in adolescent idiopathic scoliosis. Spine 1992;17:771–4.

[12] Yazici M, Acaroglu ER, Alanay A, Deviren V, Cila A, Surat A. Measurement of vertebral rotation in standing versus supine position in adolescent idiopathic scoliosis. J Pediatr Orthop 2001;21:252–6.

[13] Cerny P, Marik I, Pallova I. The radiographic method for evaluation of axial vertebral rotation—presentation of the new method. Scoliosis 2014;9:11.