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ORIGINAL ARTICLE

Reliability of the axial vertebral rotation measurements of adolescent idiopathic scoliosis using the center of lamina method on ultrasound images: in vitro and in vivo study

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Abstract
Purpose This study aimed to investigate the intra- and inter-observer reliability of the axial vertebral rotation (AVR) measurements of adolescent idiopathic scoliosis (AIS) using the center of lamina (COL) method on ultrasound transverse images.
Methods Three cadaver vertebrae were scanned with 42 AVR configurations by both ultrasound and radiograph. In this in vitro study, four observers measured the AVR using the COL method on ultrasound transverse images and three observers measured the AVR using the Stokes' method on radiographs. In the in vivo study, 13 AIS subjects were recruited. Eighteen spinal curvatures were identified and 48 vertebrae were selected for the AVR measurements. Two observers performed the AVR measurements on both the ultrasound images and radiographs. All measurements were performed twice with 1 week interval apart to reduce memory bias. The intraclass correlation coefficient (ICC), mean absolute differences (MAD), and standard deviation (SD) were used to analyze the intra- and inter-observer reliability of the AVR measurements. The Bland–Altman plot was used to analyze the 95 % limit of the differences between the two methods.
Results The proposed COL method had high intra- and inter-observer reliability on both the in vitro and in vivo studies (ICCs > 0.91, MADs $< 1.4°$) and agreed well with the experimental setup (ICCs > 0.96, MADs $< 2.3°$). The COL method showed good agreement with the Stokes' method for the in vitro study (ICC 0.84–0.85, MAD 4.5°–5.0°), while poor agreement for the in vivo study (ICC 0.49–0.54, MAD 2.7°–3.5°).
Conclusions The pilot study indicated the proposed COL method was a simple and reliable method to evaluate the AVR on ultrasound images. Standardization of the posture during ultrasound scan and taking radiograph is important.

Keywords Adolescent idiopathic scoliosis · Axial vertebral rotation · Ultrasound transverse image · Reliability · Center of lamina method

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Introduction

Scoliosis is a three-dimensional (3D) curvature of spine. The Cobb angle method [1] is the gold standard to measure the severity of scoliosis on the posteroanterior (PA) radiographs. However, the PA measurement of the Cobb angle is limited to 2D, which cannot reveal the full extent of the 3D spinal deformity. The axial vertebral rotation (AVR) is another important parameter that can be used to assess the severity of scoliosis, to predict the risk of curve progression, and to evaluate the treatment outcome [2, 3]. Therefore, AVR becomes increasingly prominent in the study of scoliosis.

Few methods have been developed to measure the AVR on 2D radiographic images using the projected landmarks such as spinous process (SP) and pedicles [1, 4–6]. However, these measurements on the radiographs are not directly performed on the transverse plane and the spinal deformity especially the axial rotation could change the size and shape of the projected landmarks, which limits the accuracy of the 2D measurements in the coronal plane. A new 2D radiographic method based on the properties of the geometric shape of vertebrae was reported and precise measurements could be obtained when the AVR was less than 30° [7]. However, the intra- and inter-observer reliability of this method on the in vivo measurements was not evaluated yet. Recently, a new low dose radiation dual X-ray system, the EOS (EOS imaging, France) system, becomes more popular and is able to reconstruct 3D spine images from standing radiographic images. A comparative study was performed to test the precision of the EOS system and no significant difference was found on the AVR measurements when comparing to CT [8]. However, only seven patients were involved and the intra- and inter-observer reliability of the apical vertebral orientation (AVO) measurements need further validation.

Other 3D methods were proposed to measure the AVR on the transverse images such as computed tomography (CT) [9, 10] and magnetic resonance imaging (MRI) [11]. The CT-based measurement methods, which provide more details on the vertebral structures, are able to display the transverse images and more precisely to assess the axial rotation. However, CT requires more processing time, is relatively more expensive, and exposes patients to more radiation than the standard radiography. Not many clinics use the CT method to diagnose scoliosis regularly. MRI can also be used to measure the AVR on the transverse images and does not introduce ionizing radiations. However, MRI is also very costly and time consuming; it is not common to use MRI to diagnose scoliosis either. Also, the supine position required for the CT and MRI methods affects the lateral curvature and AVR measurements [12].

Compared to other methods, ultrasound is a radiation-free and cost-effective imaging method. Suzuki et al. [13] combined the ultrasound system with an inclinometer to measure the AVR in a prone posture. Burwell et al. [14, 15] applied ultrasound to measure rib rotation and laminal rotation. However, both teams acquired data while subjects were in the prone position, which affected the spinal deformity assessment. Recently, Chen et al. [16, 17] validated that upright ultrasound spine images could be obtained and the center of lamina (COL) method using the ultrasound images provided both Cobb angle and AVR measurements. The Cobb angle validation studies were reported [18, 19]. The purpose of this study was to determine the intra- and inter-observer reliability of the AVR measurements on both in vitro and in vivo studies. The ultrasound in vitro and in vivo AVR measurements were compared to the Stokes measurements.

Materials and methods

In vitro experiments

Experimental setup

Three cadaver vertebrae T7, L1, and L3 were mounted onto custom rotation blocks to allow free turning for different axial rotation setup during experiments. Figure 1a shows the T7 vertebra mounted on top of a plastic bar linked with a sharp pointer, which is screwed onto a plastic platform. A transparent protractor was printed and attached on the surface of the platform for angle indication. This entire set up was considered a phantom for this study. The rotation angle of the vertebra was measured using the pointer with respect to the protractor. Each vertebra was turned from −30° to 30° with 5° increment. To investigate the limitation of the ultrasound measurement on the AVR, three

(a)

(b)

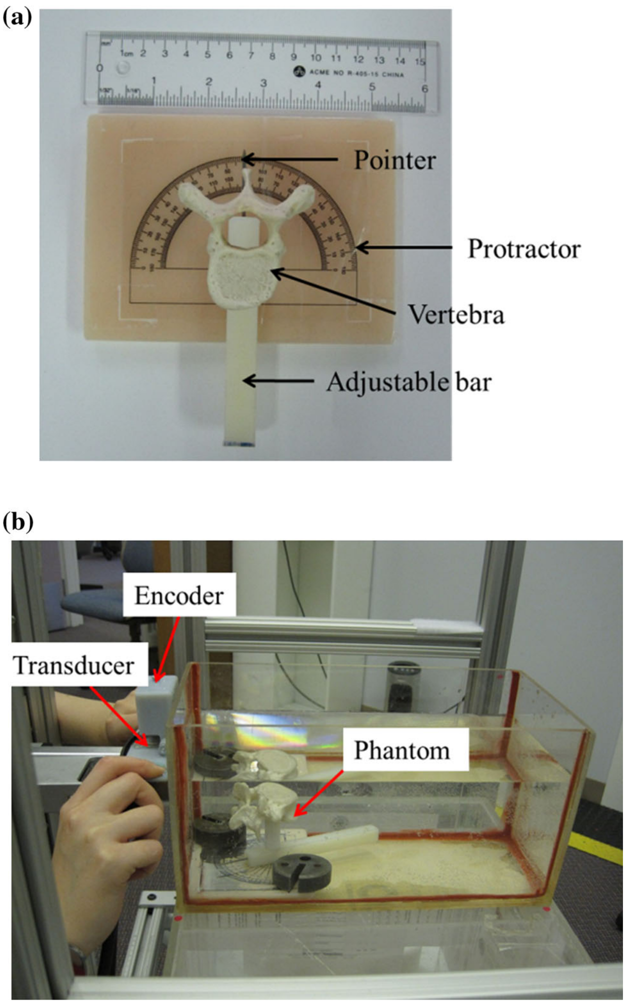


Fig. 1 **a** The T7 Vertebra phantom on the rotation platform. **b** Experimental setup for the vertebra phantom scan

extra rotations 40°, 50°, and 60° were tested on T7. Including the three extra rotations, a total of 42 configurations were set for the three vertebrae.

Ultrasound images of vertebrae

The TomoScan Focus LT™ Phased Array US scanner (Olympus NDT Inc., Canada) equipped with a 5-MHz 128-element transducer and a mini-wheel encoder was used in this study. The wheel encoder is a linear position indicator that can record the position of the transducer during data acquisition. A custom frame was built to control the movement of the transducer and the encoder for data collection. The TomoView™ software (Version 2.9 R12) is an interface program that controls the acquisition parameters and exports the ultrasound images in the coronal, sagittal and transverse planes.

Each vertebra phantom was secured at the bottom of a plexiglass tank filled with water (Fig. 1b). Ultrasound gel was applied between the transducer and the surface of the tank to ensure good coupling. For each rotation setting, one operator controlled the software to record ultrasound data, while the other scanned the vertebra from the top to the bottom along the surface of the container with a scanning speed less than 36 mm/s to obtain good quality ultrasound data.

The transverse ultrasound images were exported in the bitmap image format (BMP) with 1:1 ratio. For each configuration, the transverse image was selected at the position where the 'W' shape of the vertebra was recognized. Figure 2a shows one transverse image of T7 vertebra phantom with rotation of 15°. A total of 42 ultrasound images were prepared for the measurements.

Radiographs of vertebrae

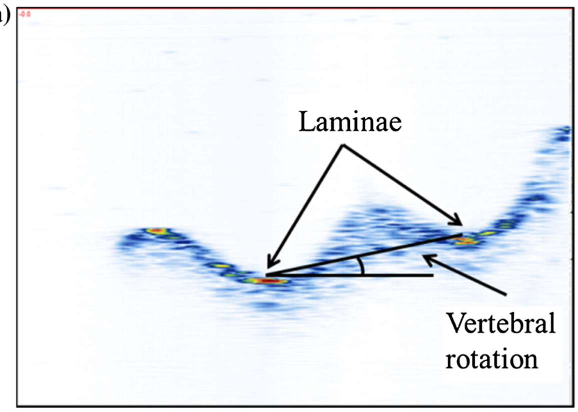
The posteroanterior (PA) radiographs were taken for the three vertebrae with the same 42 configurations. Different configurations were manipulated on the vertebra phantom without physically moving the platform's position while taking the radiographs. One PA image of the T7 vertebra phantom with rotation of 15° is shown in Fig. 2b. After observer 1 reviewing the 42 radiographs, the pedicles could be identified on all images except the two images with rotations of 50° and 60°. Therefore, a total of 40 radiographs were used for this study.

In vivo trials

Study populations

Thirteen participants (13 Females, age 13.7 ± 1.8, Cobb angle 22° ± 8°) who signed the written consent were recruited from our local scoliosis clinic. The inclusion criteria were (1) diagnosed with AIS, (2) the major Cobb angle less than 40°, (3) no in-brace radiograph taken during the study day, and (4) no surgery prior to the study.

(a)



(b)

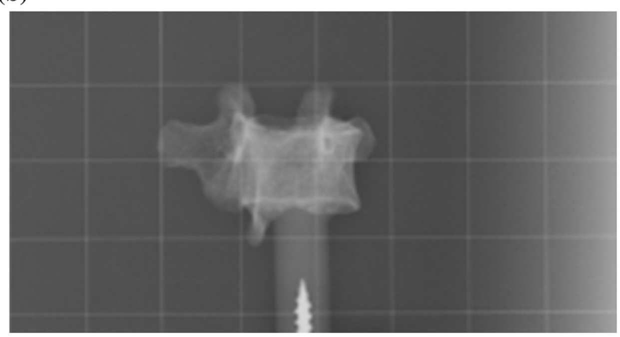


Fig. 2 **a** Ultrasound transverse image from the T7 phantom with rotation of 15°. **b** PA radiograph from the T7 phantom with rotation of 15°

Data acquisition

Each participant wore a gown with the back opened during the scanning process. The participants sat straight inside the frame and looked forward with their arms crossed resting on a metal bar in front of their chest to avoid the shoulder blades protruded out (Fig. 3a). An operator identified C7 by feeling its protruded spinous process at the back of neck and a red sticker was placed at that position. Ultrasound gel was applied on the back of participant to ensure good coupling between the transducer and the skin. Similar to the in vitro experiment, one operator performed the scan from the C7 to L4, while the other controlled the TomoView™ software for data collection. It took approximately 30 s to perform one vertical scan on each participant.

A total of 18 curvatures were recognized from the 13 participants. For each curvature, the apical vertebra as well as the superior and inferior vertebrae of the apical vertebra

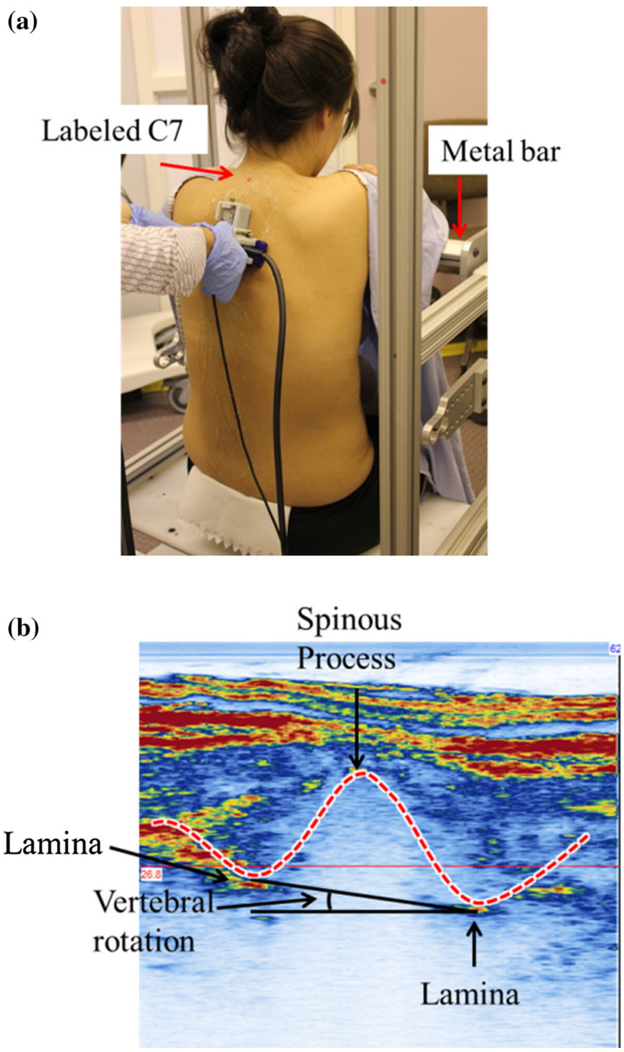


Fig. 3 **a** The set up to scan a subject's back. **b** An ultrasound transverse image from one of the vertebrae

were selected for AVR measurements. Ultrasound transverse images were exported through Tomoview software in bitmap format (BMP) by 1:1 ratio. Fifty-four vertebrae images were exported. However, six vertebrae were then excluded from this study due to poor image qualities in which some of the laminae could not be identified. Thus, 48 AVR measurements were reported. Figure 3b shows an example of an US transverse image.

Observers

Five observers participated in this study. Observers 1 (O1) and 2 had approximately 2-year experience on measuring US images. Observers 3 and 4 were novice researchers and had no experience on ultrasound measurements. Observer 5 had 20-year experience in measuring Cobb angle and 15-year experience in measuring AVR on radiographs. Each observer followed the same measurement instructions to complete the ultrasound and radiograph measurements. Four observers (O1, O2, O3 and O5) measured the in vitro US images. The in vitro radiographs were measured by three observers (O1, O4 and O5). Two observers (O1 and O5) measured the in vivo US images. All measurements were performed twice by each observer with 1 week apart to reduce the recall bias.

Measurement methods

The ImageJ software (v1.45, NIH) was used to measure the AVR on ultrasound images. As shown in Fig. 2a, the laminae, which were strong reflection points (around the two lowest points of the "W-shape") due to a strong reflection signal from the lamina area [17], were used to assess the AVR. A line was drawn through the centers of the left and right laminae and the angle formed between this line and the reference horizontal level indicated the AVR angle. In the in vitro experiment, the reference line was parallel to the surface of the water tank as shown in Fig. 2a.

In the in vivo data (Fig. 3b), the "W-shape" vertebra image was not as sharp as the in vitro data. However, the spinous process (SP) still could be recognized as the top points above the shadow area in the middle of the "W-shape". Similar to the in vitro images, the AVR angle was formed between the line drawing through the center of the laminae (identified as the lowest points of the "W-shape" and adjacent to the SP) and the horizontal line, which was assumed parallel to the transducer.

To measure the AVR on radiographs, the program developed by Zhang et al. [20] using Stokes method was used. The level of measured vertebra needed to be identified and input to the program so that the width-to-depth ratio of the vertebra was determined. Then, the observer drew the rectangular boxes to cover the pedicle areas of the vertebra (Fig. 4a). The program would then use the gradient vector flow (GVF) snake model to determine the centers of pedicles. A line was automatically drawn through the two center points. The observer marked the intersection points formed by the line and vertebra edges manually (Fig. 4b). Based on the four points, the rotation angle was calculated by the Stokes' method, using the pedicle offset from the vertebral body center and width-depth ratio estimation [6].

Randomization of images

The 42 in vitro and 48 in vivo US images were randomly assigned numbers using the free web application (www.random.org) one week prior the measurements.

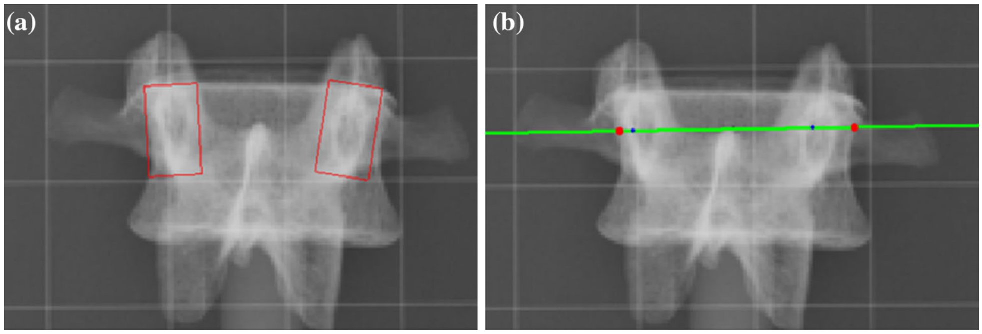


Fig. 4 Axial vertebral rotation measurement on radiograph using Stokes' method. **a** Select the pedicle areas; **b** pick the intersection points by the *line* and the edge of vertebral body (*red dots*)

The in vitro radiographs were classified into three groups according to the vertebral level (14 in T7, 13 in L1, and 13 in L3). In each group, the radiographs were assigned random numbers using the free web application (www.random.org) 1 week prior the measurements. The in vivo radiographs were not randomly assigned since the vertebral levels were needed for the measurements.

Statistical analysis

The intraclass correlation coefficient (ICC; 2-way random and absolute agreement) [21, 22] and the mean absolute difference (MAD) with standard deviations (SD) were used to analyze the intra- and inter-observer reliability of the AVR measurements on both methods. The Currier criteria for ICC values were adopted: high reliability (0.90–1.0), good reliability (0.80–0.89), fair reliability (0.70–0.79), and poor reliability (0.69 and below) [23]. Also, the Bland–Altman plot [24] was used to show the 95 % limit of the differences between two methods.

Results

In vitro study

Among the 42 radiography data sets, pedicles could not be recognized on two radiographs when the AVR were 50° and 60°. For the ultrasound images, the strong reflection signals were not from the laminae when the vertebra rotated to 50° and 60°. Therefore, these two configurations were excluded from this study. Only 40 configurations were used in this study.

Table 1 shows the results of the intra-observer reliability and the discrepancy of the AVR measurements on ultrasound images from the observers O1, O2, O3 and O5. The high ICC values (>0.98) and the small MAD ± SD (in the range of <1.4°) of the AVR measurements between two sessions indicated the US method provided high intra-observer reliabilities and small variability on the measurements. Table 2 shows the intra-observer reliability of the Stokes' method. The ICC values indicate high reliabilities for all three observers (>0.90). The MAD ± SD were 2.3° ± 2.2°, 3.2° ± 3.8° and 2.0° ± 1.7° for O1, O4, and O5, respectively, which were slightly larger than the MAD ± SD values of the ultrasound measurements.

Tables 3 and 4 summarize the inter-observer reliability of both the COL and Stokes' methods. The average values of the two sessions' measurements were used. The ICC values of all comparisons are above 0.99 for the COL method, and above 0.93 for the Stokes' method. The high ICC values indicated both methods were highly reliable. The MAD ± SD values from six pairs observers of the COL method were small around (0.7° ± 1.1°). The MAD ± SD for comparison of Stokes' method for O1 O2 and O5 were slightly larger with maximum 3.0° ± 2.7°.

Table 1 The intra-observer reliability of the COL method for AVR on in vitro ultrasound images

	O1	O2	O3	O5
ICC (95 % CI)	>0.99 (>0.99)	>0.99 (>0.99)	>0.99 (>0.99)	0.98 (0.97–0.99)
MAD ± SD (°)	0.4 ± 0.4	0.5 ± 0.5	0.5 ± 0.6	1.3 ± 1.4

Table 2 The intra-observer reliability of the Stokes' method for AVR on in vitro radiographs

	O1	O4	O5
ICC (95 % CI)	0.96 (0.93–0.98)	0.90 (0.82–0.95)	0.97(0.95–0.98)
MAD ± SD (°)	2.3 ± 2.2	3.2 ± 3.8	2.0 ± 1.7

Table 3 The inter-observer reliability of the COL method for AVR on in vitro data

	O1 vs. O2	O2 vs. O3	O1 vs. O3	O1 vs. O5	O2 vs. O5	O3 vs. O5
ICC (95 % CI)	>0.99 (>0.99)	>0.99 (>0.99)	>0.99 (>0.99)	>0.99 (0.98–0.99)	>0.99 (0.98–0.99)	0.99 (0.96–0.99)
MAD ± SD (°)	0.7 ± 0.8	0.8 ± 0.8	0.7 ± 1.1	0.7 ± 0.8	0.8 ± 0.8	0.7 ± 1.1

Table 4 The inter-observer reliability of stokes methods for AVR on in vitro data

	O1 vs. O4	O1 vs. O5	O4 vs. O5
ICC (95 % CI)	0.93 (0.88–0.96)	0.98 (0.96–0.99)	0.95 (0.91–0.97)
MAD ± SD (°)	3.0 ± 2.7	1.9 ± 1.1	2.3 ± 2.5

Table 5 The agreement between the COL and Stokes' method for AVR on in vitro data

	O1	O5
ICC (95 % CI)	0.85 (0.73–0.92)	0.84 (0.76–0.90)
MAD ± SD (°)	4.5 ± 3.6	5.0 ± 3.8

The agreement between the COL and Stokes' methods for observers O1 and O5 are shown in Table 5. The ICC values indicated there was a good agreement between the two methods; however, the variation was quite large (maximum 5.0° ± 3.8°) indicated there was deviations between the measurements from the two methods. Figure 5a shows the Bland–Altman plot of the differences between the two methods from O1 on the in vitro data.

The validity analysis of the COL and protractor measurements is shown in Table 6. The ICC values showed that the measurements using the COL method highly agreed with the experimental setup (0.96–0.97). The MAD ± SD between the COL and protractor method was small (<2.3°).

In vivo study

The intra-observer reliability results of the AVR measurements using the COL and Stokes' methods are shown in Table 7. The measurements had high ICC values (ICCs > 0.95) and small variations for both the COL (ICCs > 0.95, MAD ± SD < 0.7°) and the Stokes' method (ICC > 0.94, MAD ± SD < 1.5), which indicated high intra-observer reliability. Table 8 shows the inter-observer reliability results for both COL and Stokes' method. The high ICC value (0.91) indicated high inter-observer reliability for the AVR measurements using the COL method with small MAD ± SD (0.9° ± 1.1°), while poor inter-observer reliability (ICC = 0.64, MAD ± SD 2.5° ± 3.1°) for the Stokes' method between O1 and O5.

The agreement of the AVR measurements between the COL and Stokes' method from (O1 and O5) are shown in Table 9. Only poor agreement was obtained with ICC values (0.54 and 0.49) and MAD ± SD value of (3.5° ± 2.3° and 2.7° ± 1.7°), respectively. Also, the Bland–Altman plot was performed and the 95 % of the differences fell in the range of −0.3° ± 8.4° and −0.6° ± 6.3° (mean ± 2SD) for O1 and O5, respectively. Figure 5b shows the Bland–Altman plot of the differences between the two methods from O1 on the in vivo data.

Discussions

The axial vertebral rotation is an important parameter in the study of scoliosis. A simple and precise method can increase the use of the measurement in a scoliosis clinic. The proposed COL method measures the AVR on ultrasound transverse images with simple procedures. Ho's method measured from the CT transverse images was reported as the most reliable method [25] and had small standard deviations (1.2°–3.3°) for both the intra- and inter-observer reliability [26]. The in vitro and in vivo studies showed high intra- and inter-observer reliability for the AVR measurements using the COL method (ICC > 0.90). The proposed COL method had small range of standard deviation (SD < 1.4°). The AVR measurements by the COL method were compared with the measurements by the Stokes' method on radiographs. Although the in vitro comparison had larger MAD value compared to the in vivo comparison between the two methods, the in vivo measurements had a small range of the AVR values. Furthermore, the in vivo "W-shape" image was not as sharp as the in vitro data. This was because the soft tissue is an inhomogeneous medium. When ultrasound signals transmitted through the body, the ultrasound energy was scattered, degrading the contrast of the images. This affected the reliability result of the in vivo measurements. To further verify the accuracy of the COL method to evaluate the AVR measurements, more studies such as comparing with the EOS measurements in a standing position or comparing with the MRI/CT method in a supine position are necessary.

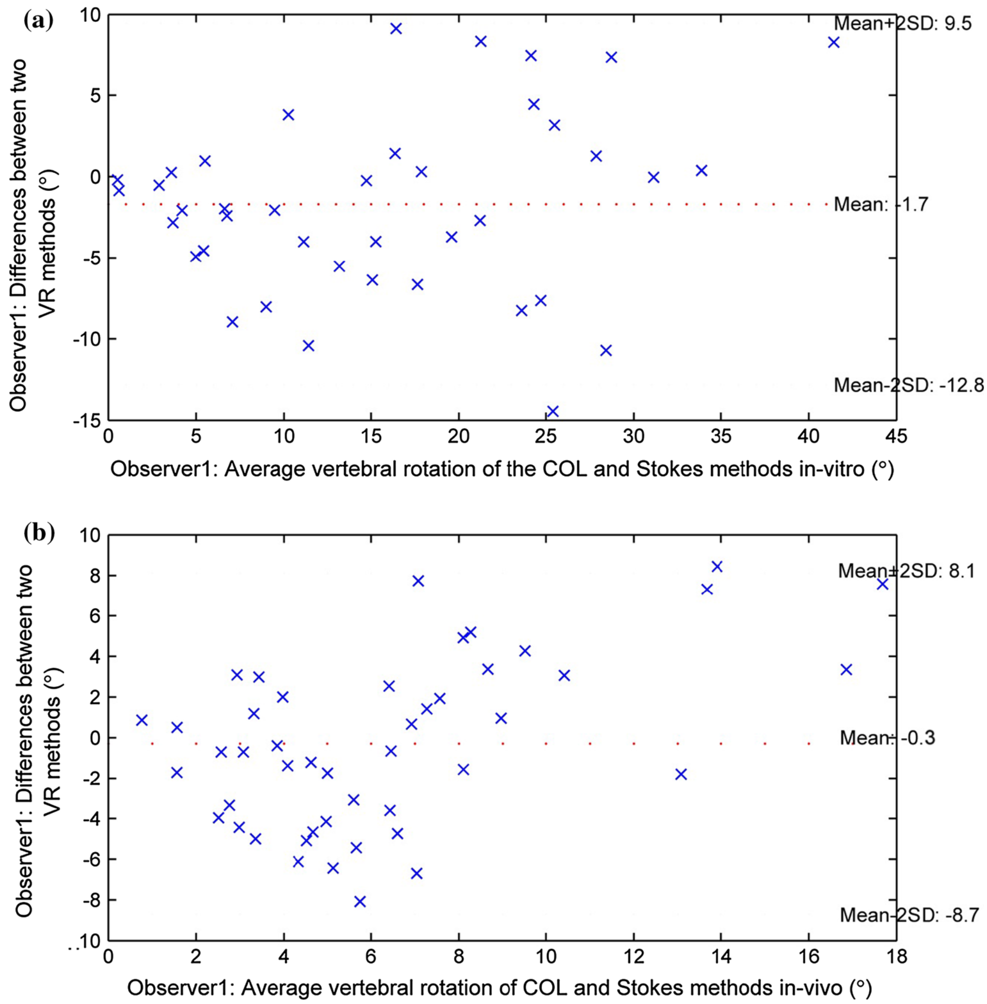


Fig. 5 **a** The Bland–Altman in vitro plot from observer 1: comparison the vertebral rotation comparison between COL and Stokes methods. **b** The Bland–Altman in vivo plot from observer 1: comparison the vertebral rotation comparison between COL and Stokes methods

Table 6 The validity between the COL and protractor measurement for AVR on in vitro data

	O1	O2	O3	O5
ICC (95 % CI)	0.97 (0.94–0.98)	0.97 (0.94–0.98)	0.96 (0.93–0.98)	0.97 (0.94–0.98)
MAD ± SD (°)	2.2 ± 1.3	2.2 ± 1.1	2.3 ± 1.4	2.2 ± 1.3

Table 7 The intra-observer reliability of the COL and Stokes' methods for AVR on in vivo data

	O1		O5	
	COL	Stokes'	COL	Stokes'
ICC (95 % CI)	>0.99 (>0.99)	0.94 (0.89–0.96)	0.95 (0.91–0.98)	0.98(0.98–0.99)
Mean ± SD (°)	6.3 ± 3.3	6.6 ± 5.6	5.7 ± 3.3	5.1 ± 3.3
MAD ± SD (°)	0.3 ± 0.2	1.5 ± 1.4	0.7 ± 0.7	0.4 ± 0.3

According to the in vitro study, the strong reflection ultrasound signals moved from the center of laminae towards the side of the laminae. Therefore, the proposed COL method was not suitable for the assessment of large AVR (50° and 60°) in this ultrasound setting since the proposed COL method used the ultrasound signals from the center of laminae.

For the in vivo study, six ultrasound images were excluded. Since only one vertical scan was performed for each participant, the spine range may be beyond the scan area especially when there were double or triple curves. Two of the six excluded US images missed one side lamina. The other four images were excluded because of the poor image qualities which might be caused by contact

Table 8 The inter-observer (O_1 and O_5) reliability of the COL and Stokes' methods for AVR on in vivo data

	COL	Stokes'
ICC (95 % CI)	0.91 (0.82–0.96)	0.64 (0.42–0.79)
MAD ± SD (°)	0.9 ± 1.1	2.5 ± 3.1

Table 9 The agreement between the COL and Stokes' methods for AVR on in vivo data

	O1	O5
ICC (95 % CI)	0.54 (0.30–0.72)	0.49 (0.24–0.68)
MAD ± SD (°)	3.5 ± 2.3	2.7 ± 1.7
Mean ± 2SD (°)	−0.3 ± 8.4	−0.6 ± 6.3

issue. Although a blue phantom gel pad was already applied between the transducer and the skin surface to improve the contact issue, there were still occasions where the transducer would lose contact when the severe back hump exceeded the flexibility of the blue phantom. Therefore, this ultrasound method may only be applicable to patients who have moderate scoliosis such as the Cobb angle was less than 40° as well as moderate vertebral rotation. The higher the AVR value, the more discrepancy measured between the COL and Stokes method. To solve the contact problems, a freehand 3D ultrasound system with a built-in GPS on a convex transducer is recommended.

Conclusions

This pilot in vitro and in vivo studies demonstrated the axial vertebral rotation can be measured reliably and repeatable using the COL method. The high intra- and inter- observer reliability demonstrated a radiation-free promising method. To apply this method clinically, a larger clinical study is recommended.

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Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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