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CASE SERIES

A comparison of the reliability and vulnerability of 3D sterEOS and 2D EOS when measuring the sagittal spinal alignment of patients with adolescent idiopathic scoliosis

Masayoshi Machida[1] · Brett Rocos[1] · Karl Zabjek[1] · David E. Lebel[1]

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Abstract

Purpose An essential component of making the diagnosis of adolescent idiopathic scoliosis (AIS) is standing anteroposterior and lateral radiographs. Two-dimensional (2D) radiographs inevitably fail to reflect every plane of the three-dimensional (3D) deformity in scoliosis. We have tested the hypothesis that there is no difference in the assessment of the sagittal plane deformity when measured with either 2D or 3D EOS radiography.

Methods A retrospective radiographic analysis was performed on patients diagnosed with AIS, with subdivided into three groups according to the coronal angular deformity (mild group: 45°–69°, moderate group: 70°–89°, and severe group: 90° +). The sagittal parameters were compared between manual measurement with 2D sterEOS and those made using computer-aided 3D reconstruction.

Results Fifty-two patients were included in each group. The inter-study reliability when measuring the thoracic Kyphosis (TK) and lumbar lordosis (LL) between the two study modalities was excellent in mild group (ICC: 0.90, 95% CI 0.82 ~ 0.94 and ICC: 0.84, 95% CI 0.74 ~ 0.91), excellent in TK and fair in LL in moderate group (ICC: 0.76, 95% CI 0.61 ~ 0.85 and ICC: 0.70, 95% CI 0.53 ~ 0.81), and fair in TK and LL in severe group, respectively (ICC: 0.74, 95% CI 0.57 ~ 0.84 and ICC: 0.65, 95% CI 0.46 ~ 0.84). A Bland–Altman plot showed proportional bias in TK measurements in each group and LL in moderate group, which means the measured value is underestimated in 2D method when the angle is small.

Conclusion 3D sterEOS is less vulnerable to the influence of coronal plane than 2D EOS in evaluating the sagittal spinal parameters of patients with a coronal deformity exceeding 70°.

Level of evidence 4.

Keywords Scoliosis · EOS · Pediatric scoliosis · Radiography · Deformity

Introduction

Adolescent idiopathic scoliosis (AIS) is common, with a prevalence approaching 3% [1]. Key to making the diagnosis and planning treatment are standing anteroposterior (AP) and lateral radiographs [2]. An important limitation of two-dimensional (2D) radiography is its inability to reflect every anatomic plane, and as a result this technique misrepresents the precise nature of the deformity [3]. The situation is further complicated by the interaction between the coronal and sagittal deformities which has been shown to accentuate the sagittal deformity on AP and lateral radiographs [4–6].

With the advent of computer-aided 3D imaging, surgeons have been able to construct an accurate and precise model of a patient's deformity prior to treatment using the EOS 2D/3D imaging system (EOS Imaging, Paris, France) [3]. This device is able to simultaneously capture full-body standing orthogonal digital biplanar images in a weight-bearing upright position at a fraction of the radiation dose used for conventional radiography [3]. The models that this system create permit measurement of the deformity in three planes at each motion segment, and recent evidence has suggested that the magnitude of deformity as measured by this technique differ to that made with plain radiography [7].

Masayoshi Machida and Brett Rocos had equal contribution and, therefore, considered as primary authors.

✉ Masayoshi Machida
masayoshimachida1985@yahoo.co.jp

[1] Department of Orthopaedic Surgery, The Hospital for Sick Children, 555 University Ave., Toronto M5G 1X8, Canada

Hayashi et al. assessed the magnitude of the differences between 2 and 3D radiographic techniques in sagittal plane and Somoskeoy et al. in coronal plane [3, 7]. As the sagittal correction is key to a successful outcome, it is important to have a complete understanding of the differences in 3D and 2D radiographic assessment of the deformity in this plane as the first step in determining which technique is superior for use in surgical planning. In this retrospective cohort study, we have tested the hypothesis that there is no difference in the assessment of the sagittal plane deformity in patients being treated for AIS when measured with either 2D or 3D EOS radiography.

Methods

Local research ethics board approval was granted for the study. A retrospective analysis of radiographic investigations was carried out for all patients treated for AIS by a single surgeon in a quaternary referral center for AIS between 2009 and 2017. Patients were included if diagnosed with AIS aged less than 18 years and excluded if they had undergone previous spinal surgery for any reason. The included patients were then categorized into three groups according to the magnitude of the coronal angular deformity of the major curve (mild group: 45°–69°, moderate group 70°–89°, and severe group 90° +). From each of these groups, a random number of cases were selected by computer to create groups of equal sizes.

Each patient underwent EOS imaging with low dose during the investigation of their deformity. A standardized radiographic protocol was employed to acquire an AP and lateral EOS radiograph with the arms in a prescribed position [3]. The radiographs, which included 2D and 3D measurements with a new reconstruction, were then assessed by a board-certified spine surgeon independent of the treating surgical team on two occasions separated by 3 months using the sterEOS software (EOS, Paris, France), and the measurements were averaged. Using the Cobb method on the 2D EOS images, an average value of thoracic kyphosis (TK) measured from the superior endplate of T4 to the inferior endplate of T12 and lumbar lordosis (LL) from the superior endplate of L1 to the inferior endplate of L5 as described by Somoskeoy et al. was calculated [3].

The 3D reconstruction was carried out using the method described by Humbert et al. [8]. After standardizing the radiograph through ensuring perfect overlap of the femoral heads in the lateral view, the positions of the T1 superior endplate and L5 inferior endplate are identified. The software then generates a line that is adjusted manually for both the spinal contour and the width of the vertebral column. The morphology of each vertebra is then described through identifying 28 points on each. Finally, a 3D model of the spine is generated using a database of vertebral 3D morphology included within the SterEOS software. This model is then used to calculate TK, LL and apical vertebrae rotation.

The data were analyzed using R (version 3.6.1, The R Foundation for Statistical Computing, Vienna, Austria). Summary statistics were used to describe the distribution of continuous variables. Inter-study reliability was assessed using Bland–Altman plots and the single measure two-way mixed intra-class correlation coefficient (ICC) was employed to assess the agreement and reliability between 2 and 3D measurement. ICC is an indicator of the similarity of a group and shows the degree to which the independence of the observed values is not guaranteed. If ICC is high, the independence of the observed values is not considered to be maintained. The presence of proportional bias which is present when the difference in values resulting from two methods increases or decreases in proportion to the average values [9], was tested by assessing the slope of regression line fitted to the Bland–Altman plot (t-value). If the obtained t-value was larger than the t-value with n–2 degrees of freedom and 5% level of significance it was considered that there was a proportional bias. P values < 0.05 were considered statistically significant. Required sample was 20 calculated with formula reported by Doros et al. ($k = 2$, $\alpha = 0.05$, $\rho = 0.8$, $\Delta = 0.4$) [10].

Results

Fifty-two patients met the inclusion criteria for a severe deformity. To match this number, 52 cases were randomly selected from each of the mild and moderate groups to give a total cohort of 156 patients. Table 1 shows the demographics of each group.

Table 1 The demographics of each group of patients

	Mild deformity (45°–69°)	Moderate deformity (70°–89°)	Severe deformity (90°+)
Number	52	52	52
Age (years)	15.6±1.6	14.7±1.5	13.7±1.5
Male: female	4:48	3:49	12:40
Lenke classification			
1	35	33	38
2	1	8	6
3	10	9	15
4	0	0	1
5	4	2	2
6	2	0	0

Table 2 Comparison of the thoracic kyphosis (TK) and lumbar lordosis (LL) measurements taken from two-dimensional (2D) EOS and three-dimensional (3D) sterEOS images

Severity of deformity	Sagittal measurement	Manual 2D (°) (Mean±SD)	sterEOS 3D (°) (Mean±SD)	95% CI difference	*p* value
Mild	TK (°)	18.5±16.2	16.2±16.3	−8.25~3.71	0.45
	LL (°)	48.3±11.7	50.0±10.2	−2.54~6.08	0.42
Moderate	TK (°)	22.0±13.1	20.3±16.9	−7.69~4.18	0.56
	LL (°)	46.6±8.8	48.5±11.3	−2.01~5.94	0.33
Severe	TK (°)	30.4±15.2	25.4±23.6	−12.75~2.84	0.21
	LL (°)	45.2±11.2	47.9±13.4	−2.18~7.55	0.27

SD standard deviation

Table 3 Inter-rater reliability of curve measurements for all patients

Severity of deformity	Sagittal measurement	ICC	*p* value	95% CI	
				Lower	Upper
Mild group	TK	0.90	<0.001	0.82	0.94
	LL	0.84	<0.001	0.74	0.91
Moderate group	TK	0.76	<0.001	0.61	0.85
	LL	0.70	<0.001	0.53	0.81
Severe group	TK	0.74	<0.001	0.57	0.84
	LL	0.65	<0.001	0.46	0.78

TK thoracic kyphosis, *LL* lumber lordosis, *ICC* intraclass correlation coefficient, *CI* confidence interval

Comparison of both TK and LL measurements taken from 2D EOS and 3D sterEOS images using a paired t-test showed no significant differences in any group (Table 2).

Using single measure two-way mixed intra-class correlation coefficient (ICC), the inter-study reliability when measuring the TK and LL between the two study modalities was excellent in mild group (ICC 0.90, 95% CI 0.82 ~ 0.94 and ICC 0.84, 95% CI 0.74 ~ 0.91), excellent in TK and fair in LL in moderate group (ICC 0.76, 95% CI 0.61 ~ 0.85 and ICC 0.70, 95% CI 0.53 ~ 0.81), and fair in TK and LL in severe group, respectively (ICC 0.74, 95% CI 0.57 ~ 0.84 and ICC 0.65, 95% CI 0.46 ~ 0.84) (Table 3). The intra-study reliability was poor in TK in severe group and LL in moderate and severe group (Table 3). This result shows that measuring sagittal alignment in 2D images is more vulnerable to the effects of coronal deformity than 3D images. Furthermore, the data show that this effect is most evident when coronal deformity exceeds 70°.

A Bland–Altman plot showed proportional bias in the TK measurements in each group and LL in the moderate group (Figs. 1, 2, 3). This shows that the measured value is underestimated in 2D method when the angle is small. In contrast, the measured value in 2D method is overestimated when the angle is large. The difference between 95% upper and lower limits were 9.94 and − 13.48 in mild group, 13.23 and − 17.17 in moderate group, and 17.37 and − 22.74 in severe group. The difference between 95% upper and lower limits increased as the Cobb angle increased. This result represents

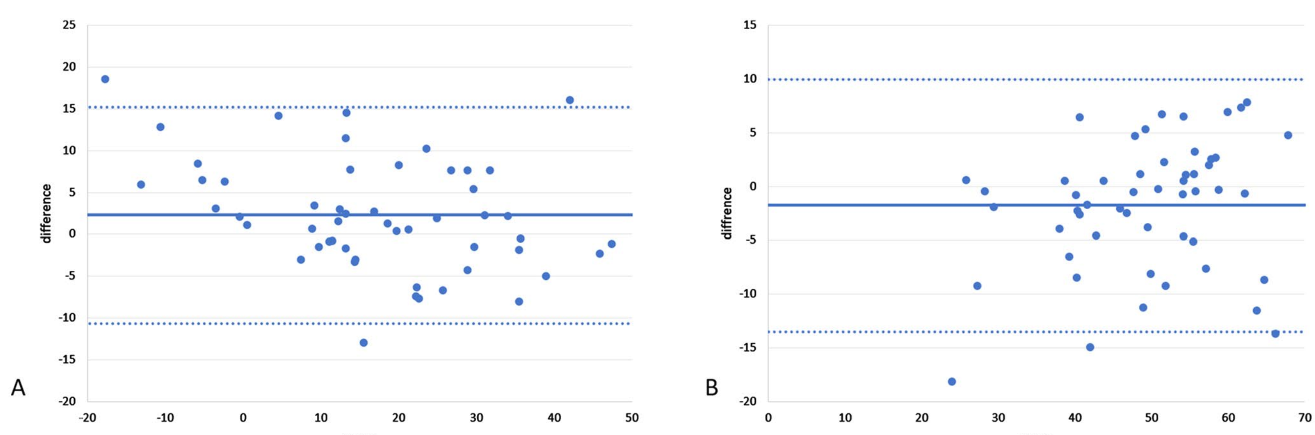

Fig. 1 Bland–Altman plots for the mild group (45° < Cobb angle < 70°). **A** Thoracic kyphosis (TK) ($n = 52$, $t = -2.63$). There are no additive bias but there is proportional bias. Mean difference is 2.27, 95% upper limit is 15.19, and 95% lower limit is − 10.64. **B** Lumber lordosis (LL) ($n = 52$, $t = 1.85$). There is no additive bias, but there is proportional bias. Mean difference is − 1.77, 95% upper limit is 9.94, and 95% lower limit is − 13.48

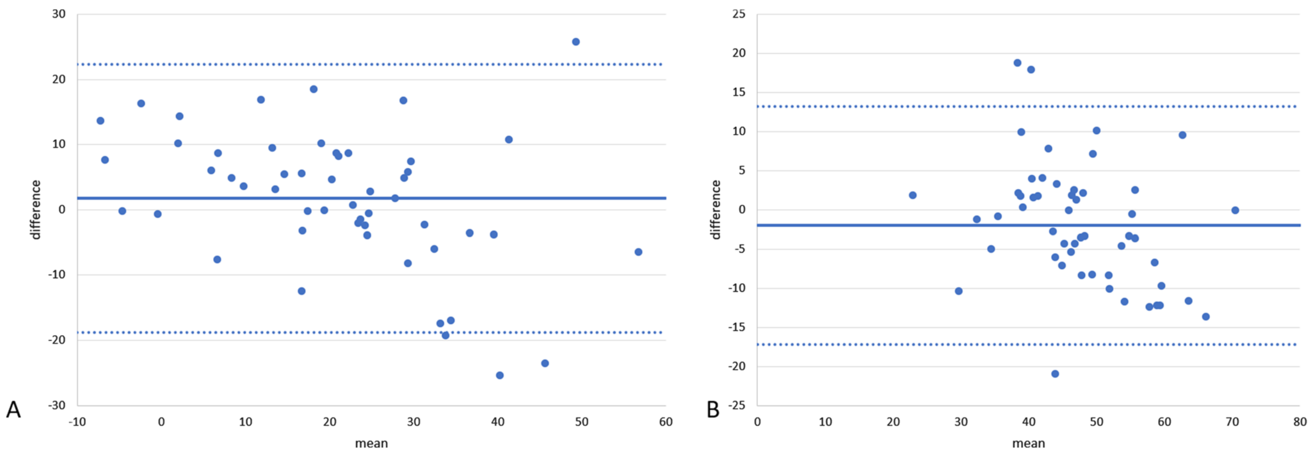

Fig. 2 Bland–Altman plots for the moderate group (70° < Cobb angle < 90°). **A** TK ($n = 52$, $t = -2.99$). There are no additive bias but there is proportional bias. Mean difference is 1.76, 95% upper limit is 22.29, and 95% lower limit is -18.78. B) LL ($n = 52$, $t = -2.51$). There is no additive bias, but there is proportional bias. Mean difference is −1.97, 95% upper limit is 13.23, and 95% lower limit is −17.17

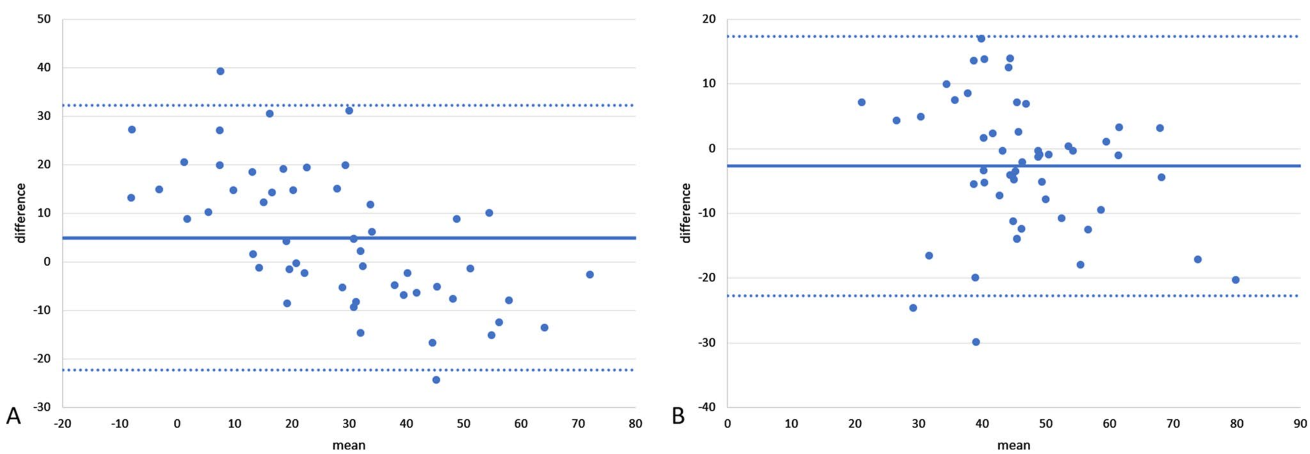

Fig. 3 Bland–Altman plots for the severe group (90° < Cobb angle). **A** TK ($n = 52$, $t = -5.74$). There are no additive bias but there is proportional bias. Mean difference is 4.96, 95% upper limit is 32.27, and 95% lower limit is −22.35. **B** LL ($n = 52$, $t = -1.73$). There is no additive bias and no proportional bias. Mean difference is −2.69, 95% upper limit is 17.37, and 95% lower limit is −22.74

a measurement unreliability with 2D EOS which increases in proportion to the Cobb angle. Individual Bland–Altman plots are available in the additional material.

Discussion

The analysis of these data shows that at small coronal angular deformities, there are no significant differences observed in the magnitude of sagittal spinal parameters when measured using 2D EOS or 3D sterEOS techniques. However, as coronal deformity increases beyond 70°, ICC shows that 2D EOS is unreliable when used to evaluate sagittal parameters when compared to 3D images. Furthermore, A Bland–Altman plot shows that the 2D measurements become increasingly unreliable as the coronal angular deformity increases.

It is usually considered that the value of 3D imaging is limited to an assessment of axial rotation of the vertebrae and surgical planning. However, these data show that 3D EOS imaging has added value in its ability to avoid misrepresentation of sagittal alignment at more severe coronal deformity, presumably through its ability to account for every plane of the deformity. One would expect that because of this, there may be significant differences in the measurements of sagittal values between the two techniques at all magnitudes of coronal curves; however, this analysis shows that this is the case only in severe deformity and suggests that 3D imaging brings little additional value to the assessment of lesser deformities [3].

This potential advantage was suggested by Sullivan et al., who explained that 3D imaging should be considered important in understanding sagittal alignment in AIS by finding that 2D radiography misrepresents thoracic hypokyphosis in severe coronal deformity [11]. Adding this to the knowledge that the measurement of TK in 2D radiographs is unreliable and underestimated by as much as 10° because of axial rotation of the apical vertebra when compared to 3D assessment of sagittal alignment, the potential advantages of 3D imaging becomes clear [3, 7, 12].

Our analysis shows that there was consistency between the measurements of TK and LL regardless of the severity of coronal deformity when compared using a t-test, but that ICC reduced as the coronal deformity increased despite no significant difference between 2 and 3D measurements. This may be because the t-test uses the mean to assess consistency, while the ICC uses the variance to assess reliability. Once the coronal deformity reached 70°, the consistency becomes untenable, suggesting that 3D sterEOS should be used to guide surgical planning. These findings are further confirmed by Bland–Altman plots which show that proportional bias exists dependent on the coronal deformity [13]. Furthermore, proportional bias shows that the measurements of TK and LL in 2D EOS are underestimated as the sagittal angle decreases, and overestimated as these values increase. This result shows that 3D measurement is valuable in accurate preoperative planning for correction of severe scoliosis. Furthermore, the concordance we have observed agrees with that described by Pasha et al. [14]. These authors concluded that the differences in the 2D and 3D assessment of sagittal alignment increase as apical vertebral and pelvic rotation increases and that out of plane tilt (i.e., lateral tilt) of the vertebrae can compromise measurements. This stands to reason, as in 2D radiography the identification of the endplate of a tilted (when the endplate presents as an ovoid shape) or wedged vertebra is prone to error [15, 16]. We speculate that this oval shape is the cause of error. When TK is increased, the measurement is taken at the anterior part of the oval leading to overestimation, and TK is decreased, the measurement at the posterior leading underestimation. In contrast, when LL is increased, the measurement is done at the centered on the posterior part of the oval leading to overestimation, and LL is decreased, whereas measuring at the anterior leading underestimation.

Scoliosis is a 3D deformity consisting of coronal, sagittal, and axial rotation of the spinal column; however, the 2D based on X-ray images are used for planning for surgery and follow-up. It is impossible to assess accurately complex 3D deformity with current 2D evaluation. It will be important in the future to conduct preoperative planning and postoperative follow-up not only in the coronal plane but also in the sagittal and horizontal planes for 3D deformities.

This study is the first step in the investigation of the utility of 3D imaging in the management of AIS. Recent work has shown that using EOS with 3D reconstructions shows consistently good inter-observer reliability, which alongside an increased radiation safety suggests that it may be a useful evolution in planning the treatment of these complex patients [3, 17]. Nonetheless, an important limitation to this study is that the matching of patients by age and deformity classification is impossible due to the rarity of severe deformities, which may have introduced bias. Furthermore, we recognize that EOS is not universally available, which may limit the external generalizability of these conclusions.

Conclusion

In this study, we have shown that 3D sterEOS images are less susceptible to the effects of coronal deformity exceeding 70° than 2D images when evaluating sagittal alignment. However, the two methods are equivalent when evaluating sagittal parameters in coronal deformity less than 70°. Where available, 3D sterEOS may be a more representative mode of radiographic investigation for patients with severe AIS prior to planning and delivering treatment.

Author contributions MM: acquisition, analysis and interpretation of data, drafted the work, approved the version to be published and agrees to be accountable for all aspects of the work. BR: analysis and interpretation of data, drafted the work, approved the version to be published and agrees to be accountable for all aspects of the work. KZ: made substantial contributions to the conception and design of the work, critically revised the manuscript, approved the version to be published and agrees to be accountable for all aspects of the work. DEL: made substantial contributions to the conception and design of the work, critically revised the manuscript, approved the version to be published and agrees to be accountable for all aspects of the work.

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Availability of data and material Data are available on request to the corresponding author.

Code availability Not applicable.

Declarations

Conflict of interest Masayoshi Machida, Brett Rocos, and Karl Zabjek declare that they have no conflict of interest. David E. Lebel declares fellowship support from Stryker and SpineVision.

Ethics approval Institutional research ethics board approval was granted for this study.

Consent to participate No applicable.

Consent for publication Not applicable.

References

1. Tsirikos AI, Roberts SB, Bhatti E (2020) Incidence of spinal deformity surgery in a national health service from 2005 to 2018: an analysis of 2205 children and adolescents. Bone Jt Open 1:19–28. https://doi.org/10.1302/2633-1462.13.BJO-2020-0001.R1
2. Vrtovec T, Pernus F, Likar B (2009) A review of methods for quantitative evaluation of spinal curvature. Eur Spine J 18:593–607. https://doi.org/10.1007/s00586-009-0913-0
3. Somoskeoy S, Tunyogi-Csapo M, Bogyo C et al (2012) Accuracy and reliability of coronal and sagittal spinal curvature data based on patient-specific three-dimensional models created by the EOS 2D/3D imaging system. Spine J 12:1052–1059. https://doi.org/10.1016/j.spinee.2012.10.002
4. Stagnara P, Fleury D, Fauchet R et al (1975) Major scoliosis, over 100 degrees, in adults. 183 surgically treated cases. Rev Chir Orthop Reparatrice Appar Mot 61:101–122
5. Papin P, Labelle H, Delorme S et al (1999) Long-term three-dimensional changes of the spine after posterior spinal instrumentation and fusion in adolescent idiopathic scoliosis. Eur Spine J 8:16–21. https://doi.org/10.1007/s005860050121
6. Guo X, Chau WW, Chan YL et al (2003) Relative anterior spinal overgrowth in adolescent idiopathic scoliosis. Results of disproportionate endochondral-membranous bone growth. J Bone Joint Surg Br 85:1026–1031. https://doi.org/10.1302/0301-620x.85b7.14046
7. Hayashi K, Upasani VV, Pawelek JB et al (2009) Three-dimensional analysis of thoracic apical sagittal alignment in adolescent idiopathic scoliosis. Spine (Phila Pa 1976) 34:792–797. https://doi.org/10.1097/BRS.0b013e31818e2c36
8. Humbert L, De Guise JA, Aubert B et al (2009) 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences. Med Eng Phys 31:681–687. https://doi.org/10.1016/j.medengphy.2009.01.003
9. Doğan NÖ (2018) Bland-Altman analysis: a paradigm to understand correlation and agreement. Turk J Emerg Med 18(4):139–141. https://doi.org/10.1016/j.tjem.2018.09.001 (**eCollection 2018 Dec**)
10. Doros G, Lew R (2010) Design based on intra class correlation coefficients. Am J Biostatistics 1(1):1–8
11. Sullivan TB, Bastrom TP, Bartley CE et al (2020) More severe thoracic idiopathic scoliosis is associated with a greater three-dimensional loss of thoracic kyphosis. Spine Deform 8:1205–1211. https://doi.org/10.1007/s43390-020-00149-7
12. Newton PO, Fujimori T, Doan J et al (2015) Defining the "Three-Dimensional Sagittal Plane" in thoracic adolescent idiopathic scoliosis. J Bone Joint Surg Am 97:1694–1701. https://doi.org/10.2106/JBJS.O.00148
13. Giavarina D (2015) Understanding Bland Altman analysis. Biochem Med (Zagreb) 25:141–151. https://doi.org/10.11613/BM.2015.015
14. Pasha S, Cahill PJ, Dormans JP et al (2016) Characterizing the differences between the 2D and 3D measurements of spine in adolescent idiopathic scoliosis. Eur Spine J 25:3137–3145. https://doi.org/10.1007/s00586-016-4582-5
15. Schmid SL, Buck FM, Boni T et al (2016) Radiographic measurement error of the scoliotic curve angle depending on positioning of the patient and the side of scoliotic curve. Eur Spine J 25:379–384. https://doi.org/10.1007/s00586-015-4259-5
16. Villemure I, Aubin CE, Grimard G et al (2001) Progression of vertebral and spinal three-dimensional deformities in adolescent idiopathic scoliosis: a longitudinal study. Spine (Phila Pa 1976) 26:2244–2250. https://doi.org/10.1097/00007632-200110150-00016
17. Dubousset J, Charpak G, Skalli W et al (2007) EOS stereo-radiography system: whole-body simultaneous anteroposterior and lateral radiographs with very low radiation dose. Rev Chir Orthop Reparatrice Appar Mot 93:141–143. https://doi.org/10.1016/s0035-1040(07)92729-4