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ORIGINAL ARTICLE

New sagittal classification of AIS: validation by 3D characterization

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Abstract

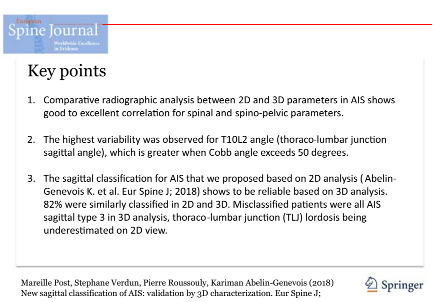
Introduction and aim In order to improve surgical planning of sagittal correction in AIS, we proposed a new sagittal classification—Abelin-Genevois et al. Eur Spine J (27(9):2192–2202, 2018. https://doi.org/10.1007/s00586-018-5613-1). The main criticism is related to the fact that 2D lateral view results from the projection of the 3D deformity. The aim of this study is to show that the new sagittal classification system is a reliable system to describe the different sagittal scenarios that AIS could create both in 2D and 3D.

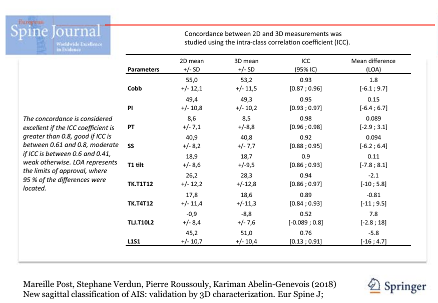
Methods We performed retrospective radiograph analysis of prospectively collected data from 93 consecutive AIS patients who underwent an examination of the whole spine using the EOS® imaging system. 2D (Keops®) and 3D analyses (sterEOS®) provided frontal and sagittal spinal and spinopelvic parameters. In addition, 3D analysis provided apical vertebra rotation (AVR).

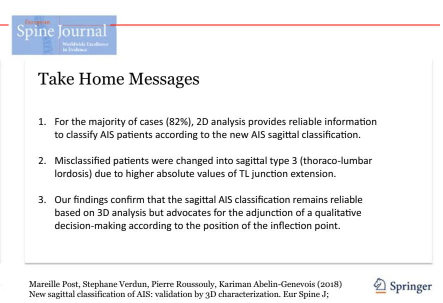
Results Comparing 2D and 3D measurements for the general cohort, excellent correlation can be found for all parameters, but only fairly good for T10L2 and L1S1 angles. The highest variability was observed for T10L2, differences between 2D and 3D measurements being greater when the Cobb angle increased. AVR did not influence concordance between 2D and 3D measurements. Eighty-two percent were similarly classified in 2D and 3D according to the new classification. Misclassified patients were all AIS sagittal type 3 in 3D analysis, thoracolumbar junction (TLJ) lordosis being underestimated on 2D view.

Discussion In conclusion, for the majority of cases (82%), 2D analysis may provide enough information for decision making when using a semi-automated 2D measurement system. However, in severe cases, especially when Cobb angle exceeds 55°, 3D analysis should be used to get a more accurate view on the thoracolumbar junction behavior.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.







Keywords Adolescent idiopathic scoliosis · Classification · 3D modeling · Sagittal alignment · sterEOS

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Introduction

Adolescent idiopathic scoliosis (AIS) is a complex multi-directional spine deformity resulting from axial rotation, intersegmental extension and translation [1, 2]. Faithfull representation of the true shape of the curve is essential to understand and plan surgical strategy [3–7].

Throughout the years, different classifications have been used to describe AIS. Ponseti was the first to describe scoliosis according to the location of the deformity [8]. In 1983, Howard King proposed a more extended classification based on the surgical treatment of AIS patients using Harrington rod instrumentation [9]. During the next years, surgical treatments developed and the King classification failed to give an accurate and reliable guideline to choose the adequate level of fusion [10]. In 2001, Lenke et al. proposed a new classification system in which AIS curve types are defined according to the location and structure of the major and minor curves [11]. The Lenke classification also attempted to address the sagittal component describing sagittal modifiers [12]. This new classification system became a gold standard due to its excellent reliability. However, the sagittal modifiers were not popularized and the sagittal profile still remained the great forgotten of this classification system [7]. Meanwhile, surgical techniques improved in order to address the sagittal correction [4]. In addition, three-dimensional (3D) imaging is becoming routinely available since biplanar stereoradiography has been developed [13]. Hong et al. [14] stated that 3D measurements of the deformity obtained from computerized tomography (CT) provide useful information on planning and outcome assessment of corrective surgery in AIS. Although Lenke approached AIS as a 3D deformity by including the lateral and frontal plane, the third dimension meaning axial rotation of the vertebrae cannot be accurately measured on a 2D X-ray. To provide 3D measurements, the ‘full spine mode’ of EOS imaging® software uses a semi-automated technique that incorporates the user input and a statistical model to generate the 3D model of the spine. An advantage of EOS compared to CT-scan is the lower radiation dose and the weight baring position of the patients during examination [5, 15, 16].

AIS sagittal view is altered by the 3D movements of scoliosis. Even though the global balance is maintained, segmental modifications disrupt the normal sequence of sagittal curves. As for the frontal view, these modifications may result into structural or non-structural pathological curves.

In 2011, Labelle et al. provided the first and only attempted to develop a 3D classification for AIS. In their results, they provide evidence which states that 3D shows more structural differences than shown on a single planar radiographic assessment [17]. Through this effort of classifying AIS patients in both coronal and sagittal plane, the SRS 3D Classification Committee described 11 subtypes, the main conclusion being that thoracic deformities (Lenke 1–4) would produce either kyphotic or hypokyphotic patterns, while thoracolumbar or lumbar curves were more likely to provide hyperlordosis [18].

More recently, Abelin-Genevois et al. [19] described a new AIS sagittal classification system complementary to the Lenke classification. This classification describes three sagittal types based on the location of the sagittal structural curves, independent of the coronal type of curve (Fig. 1). AIS Sagittal Type 1 is characterized by a maintained harmonious sagittal alignment of three alternating sagittal curves—straight or lordotic cervical spine, thoracic kyphosis

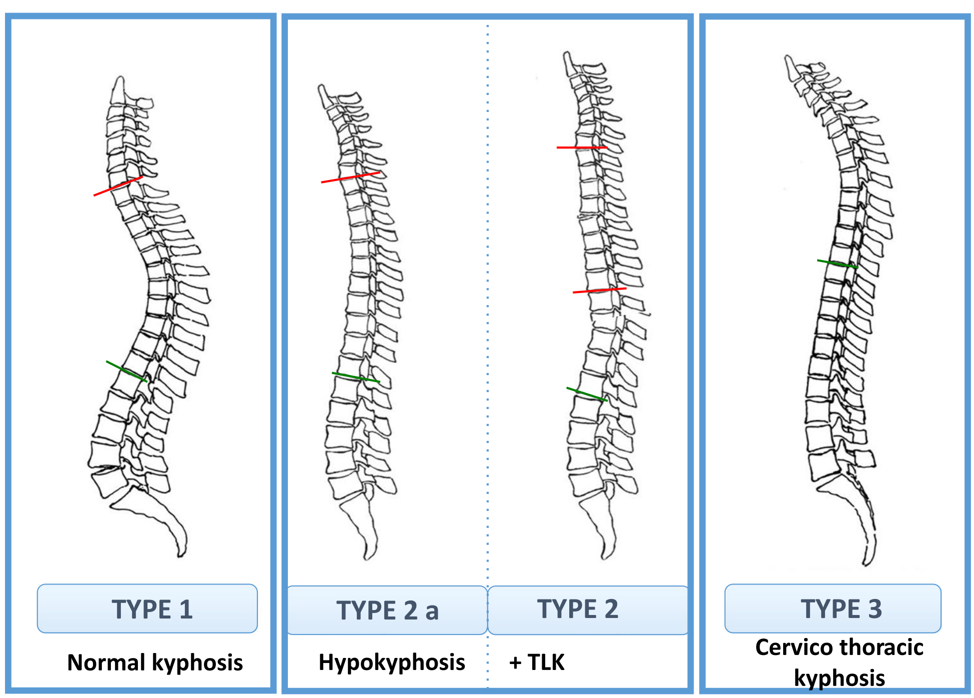

Fig. 1 New AIS Sagittal classification (Abelin-Genevois et al. [19]). Type 1 has a harmonious sagittal alignment which should be preserved. Type 2 is characterized by structural thoracic hypokyphosis related to the scoliotic deformity. Two subtypes are described as structural thoracolumbar kyphosis (T10L2 > 10°) may be concomitant. Type 3 is a two-curve sagittal shape with a long thoracolumbar lordosis (lumbar lordosis is extended by a structural thoracolumbar lordosis (T10L2 < – 10°) usually followed by a unique cervicothoracic kyphosis

with an average of 11 ± 2.2 vertebrae and lumbar lordosis with an average of 5.1 ± 0.87 vertebrae. Mean T1T12 thoracic kyphosis is 34°, which is slightly lower but close to the normal adolescent population TK [20]. Type 2 is characterized by thoracic hypokyphosis—T1T12: 18° ± 9.8° for type 2a (neutral thoracolumbar junction); 11° ± 13° for type 2b (thoracolumbar kyphosis)—inducing reciprocal cervical kyphosis. Sagittal Type 3 is characterized by the prolongation of sagittal lumbar lordosis within the thoracolumbar junction due to thoracolumbar structural lordosis induced by the scoliotic deformity. Sagittal Type 3 is characterized by a sequence of only two alternating sagittal curves. The length of lumbar sagittal curve is significantly modified (8.1 ± 0.93 lordotic vertebrae vs 5.3 ± 1.3 in Type 1 ($p < 0.0001$), due to TL junction hyperextension (T10 L2: − 13° ± 5.6°).

The main critic about specific sagittal classification is due to the fact that 2D lateral view may not show the true sagittal curve. Newton et al. [21] showed that 2D analysis underestimates the loss of kyphosis in AIS. We hypothesize that despite the differences between 2D and 3D analysis of sagittal parameters in AIS patients, the new sagittal classification system is a reliable system to describe the different sagittal scenarios that AIS could create. The present study also aims to define the influence of apical vertebra rotation (AVR) and Cobb angle on the concordance between 2D and 3D.

Method

We performed a retrospective radiograph analysis of prospectively collected data from 93 consecutive AIS patients who underwent an examination of the whole spine using the EOS imaging® system. Exclusion criteria were non-idiopathic scoliosis, associated spinal abnormalities, previous spine surgery and transitional abnormalities.

Radiographic analysis

Simultaneously frontal and lateral X-ray images of the whole spine were obtained in weight-bearing standing position, arms flexed 45° in EOS(EOS imaging, Paris, France) [22].

Both 2D and 3D reconstructions were generated by an independent junior observer, trained previously on two specific semi-automatic software for each of the 2D and 3D radiographic analysis. Reconstructions were randomly verified by a senior experienced spine surgeon. An intra-rater reliability test was randomly performed on 20 cases.

3D analysis

3D measurements were obtained using EOS software ‘full spine’ mode. After the acetabula were positioned and the sacral endplate was located, upper T1 endplate and lower L5 endplate were identified. After adjusting the vertebral bodies line on both sagittal and frontal view, manual adjustment of each automatically detected vertebra from T1 to L5 was done using control points on the vertebral landmarks (endplates, pedicles, process transversi/spinosi and posterior arches) [23].

Once the 3D model of the spine was generated on sterEOS software (EOS imaging, Paris, France), the parameters were extracted in Excel®.

2D analysis

2D measurements were obtained using KEOPS® Analyser separately on frontal and sagittal EOS full spine views. On the lateral view, after the acetabula were positioned and the sacral endplate was located, upper C7 plate was identified, allowing to adjust the line joining the middle of each vertebral body. Each vertebral body was detected semi-automatically in order to measure the radiographic segmental parameters.

Parameters

Both reconstructions provided frontal (Cobb angle, apical vertebra, upper and lower vertebra) and sagittal spinopelvic parameters (T1-T12, T4-T12, T10-L2, L1-S1, PI, SS, PT). In addition, 3D reconstruction provided apical vertebra rotation (AVR).

T10-L2 was not automatically generated by sterEOS® software. We calculated this angle by the sum of intervertebral sagittal inclination from T10-T11 to L1-L2.

Patients were classified according to Lenke based on AP view and flexibility tests. After the parameters were measured, patients were categorized according to the new AIS sagittal classification (Fig. 1).

Statistical analysis

The concordance between 2D and 3D measurements was studied using the intra-class correlation coefficient (ICC). A model with 2 random factors on raw data was used (ICC (2.1)), which allowed to obtain the absolute agreement between the two measurements. The calculations were performed with R software. The confidence intervals of these ICCs were also calculated. The concordance is considered very good if the ICC coefficient is greater than 0.8, good if ICC is between 0.61 and 0.8, moderate if ICC is between 0.6 and 0.41, weak otherwise. The limits of approval, where 95% of the differences were located, were also produced.

For the apical rotation and the curve magnitude given by Cobb angle, Cohen’s Kappa coefficient was calculated, and the contingency table between the 2 variables (2D and 3D) was calculated.

Table 1 Demographic analysis

	All cohort $N=93$	Type 1 $N=44$	Type 2 $N=29$	Type 3 $N=20$	p value
Gender (2)	10 (10.8%)	6 (13.6%)	2 (6.9%)	2 (10%)	0.76
Cobb.1.2D	55 ± 12.1	53.2 ± 11.7	57.9 ± 12.4	54.8 ± 12.4	0.36
Axial.rotation.of.apex.3D	21.1 ± 5.9	21.5 ± 5.7	20.4 ± 5.5	21.5 ± 6.8	0.71
Pelvic.rotation.3D	− 1.9 ± 3.6	− 2.9 ± 3.2	− 0.7 ± 2.8	− 1.4 ± 4.9	**0.014**

Comparison between the three AIS sagittal types. For quantitative variables, comparisons are done with Anova or Kruskal–Wallis if the data are not Gaussian, and the gender is compared with a Fisher exact test

Bold indicates significant difference

Table 2 Intra-rater reliability for each sagittal radiographic parameter measured using sterEOS 3D Software®

Studied parameters	Intra-rater
PI	0.94 [0.86; 0.98]
PT	0.99 [0.98; 1]
SS	0.89 [0.75; 0.96]
Cobb angle	0.97 [0.92; 0.99]
Apical vertebra	1 [1; 1]
Apical vertebral rotation	0.91 [0.79; 0.97]
TK T1T12	0.94 [0.86; 0.98]
TK T4T12	0.94 [0.85; 0.98]
TLJ T10L2	0.97 [0.93; 0.99]
L1S1	0.95 [0.88; 0.98]
Pelvic rotation	0.92 [0.8; 0.97]

Results

Demographic information

Ninety-three patients were included in the study with a mean Cobb angle of 55° ± 12.1° in 2D and 53.2° ± 11.5° in 3D measurements. 3D mean apical rotation was 21.1° ± 5.9° (Table 1). According to the sagittal types, patients were comparable in terms of gender and we found no differences in terms of curve magnitude and apical vertebra rotation.

Intra-observer test

An intra-rater reliability test was randomly performed on 20 cases. Table 2 shows that the intra-rater reliability was high for all the 3D parameters described for the current study.

ICC 2D and 3D measurements in general cohort

Table 3 summarizes the concordance of the main sagittal spinal and spinopelvic parameters between 2D and 3D measurements. ICC values showed to be excellent for curve magnitude and spinopelvic parameters (PT, PI, SS). Thoracic kyphosis was also highly comparable for both T1T12 and T4T12. The mean error was 1° for T4T12 and 2.1° for T1T12. Correlation was good for L1S1 with a systematic error of 5.8°. The most variable parameter between 2D and 3D was T10L2 which is reflecting the TL junction sagittal orientation.

ICC 2D and 3D according to sagittal type

When parameters variability was tested within each sagittal subtype, we found no variation for spinopelvic parameters (Table 4). Considering TK, T4T12 concordance was weaker in type 2. Lumbar lordosis (L1S1) had an excellent concordance for type 1 and again weaker for type 2. TL junction had the highest variability especially for type 3.

Table 3 Concordance between 2D and 3D measured spinal parameters within the global cohort

Parameters	2D mean ± SD	3D mean ± SD	ICC (95% IC)	Mean difference (LOA)
Cobb	55.0 ± 12.1	53.2 ± 11.5	0.93 [0.87; 0.96]	1.8 [− 6.1; 9.7]
PI	49.4 ± 10.8	49.3 ± 10.2	0.95 [0.93; 0.97]	0.15 [− 6.4; 6.7]
PT	8.6 ± 7.1	8.5 ± 8.8	0.98 [0.96; 0.98]	0.089 [− 2.9; 3.1]
SS	40.9 ± 8.2	40.8 ± 7.7	0.92 [0.88; 0.95]	0.094 [− 6.2; 6.4]
T1 tilt	18.9 ± 8.6	18.7 ± 9.5	0.9 [0.86; 0.93]	0.11 [− 7.8; 8.1]
TK.T1T12	26.2 ± 12.2	28.3 ± 12.8	0.94 [0.86; 0.97]	− 2.1 [− 10; 5.8]
TK.T4T12	17.8 ± 11.4	18.6 ± 11.3	0.89 [0.84; 0.93]	− 0.81 [− 11; 9.5]
TLJ.T10L2	− 0.9 ± 8.4	− 8.8 ± 7.6	0.52 [− 0.089; 0.8]	7.8 [− 2.8; 18]
L1S1	45.2 ± 10.7	51.0 ± 10.4	0.76 [0.13; 0.91]	− 5.8 [− 16; 4.7]

Table 4 Concordance between 2D and 3D measured spinal parameters according to AIS sagittal type

	Type 1		Type 2		Type 3	
	ICC	Mean dif.	ICC	Mean dif.	ICC	Mean dif.
Cobb.1	0.95 [0.8; 0.98]	2.3 [− 3.2; 7.7]	0.92 [0.82; 0.96]	2 [− 7.3; 11]	0.9 [0.77; 0.96]	0.58 [− 9.4; 11]
PI	0.97 [0.94; 0.98]	0.59 [− 4.9; 6.1]	0.94 [0.87; 0.97]	− 0.45 [− 6.8; 5.9]	0.93 [0.83; 0.97]	0.052 [− 8.4; 8.5]
PT	0.99 [0.98; 0.99]	0.16 [− 1.7; 2]	0.99 [0.98; 1]	0.3 [− 1.7; 2.3]	0.93 [0.84; 0.97]	− 0.36 [− 5.7; 4.9]
SS	0.92 [0.85; 0.95]	0.51 [− 5.7; 6.7]	0.88 [0.76; 0.94]	− 0.75 [− 7.6; 6.1]	0.95 [0.89; 0.98]	0.41 [− 5; 5.8]
T1.tilt	0.88 [0.78; 0.93]	− 0.79 [− 7.5; 5.9]	0.77 [0.57; 0.89]	1.6 [− 7.1; 10]	0.9 [0.76; 0.96]	− 0.04 [− 8.7; 8.6]
TK.T1T12	0.87 [0.72; 0.94]	− 2.1 [− 10; 6]	0.91 [0.77; 0.96]	− 1.9 [− 9; 5.2]	0.94 [0.82; 0.98]	− 2.4 [− 11; 6.3]
TK.T4T12	0.85 [0.74; 0.91]	− 1.1 [− 10; 7.9]	0.7 [0.45; 0.84]	− 0.82 [− 12; 11]	0.91 [0.79; 0.96]	− 0.068 [− 12; 12]
TLJ.T10L2	0.39 [− 0.1; 0.72]	8.8 [− 1.7; 19]	0.29 [− 0.11; 0.62]	8.2 [− 3.2; 20]	0.093 [− 0.11; 0.38]	5.1 [− 3.1; 13]
L1S1	0.82 [0.41; 0.93]	− 4.1 [− 14; 5.4]	0.63 [− 0.069; 0.87]	− 7.5 [− 18; 3.3]	0.75 [− 0.013; 0.93]	− 7.1 [− 18; 3.5]

Influence of structural components of the deformity on T10L2 variability

The highest variability was observed for T10L2. Therefore, we analyzed the influence of the two measureable structural components of the scoliotic deformity, the main curve magnitude given by Cobb angle and the AVR. We observed that differences between 2D and 3D measurements were greater when the Cobb angle increased (Fig. 2). However, we found no influence of AVR on the concordance between 2D and 3D measurements (Fig. 3).

Following the guidelines of the new AIS sagittal classification, we separately classified patients based first on 2D and second on 3D data. We found that 82% were similarly classified in 2D and 3D according to this new classification. Misclassified patients became all type 3 based on 3D analysis, thoracolumbar junction (TLJ) lordosis being higher on 3D measurements.

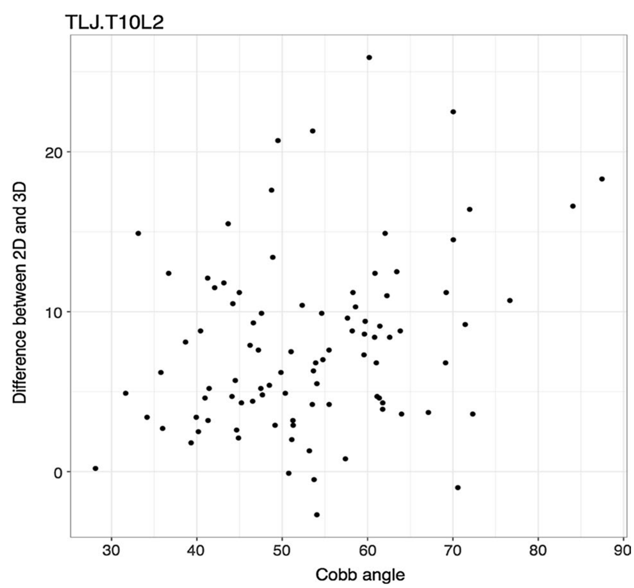

Fig. 2 Difference between 2D and 3D measures for T10L2 angle. Influence of main curve magnitude (Cobb angle). Red line represents the mean Cobb angle value in the global cohort

Discussion

Comparison global 2D and 3D

The present study demonstrates a good-to-excellent concordance between 2D and 3D analysis for the usual parameters describing curve magnitude, spinal and spinopelvic parameters in an AIS population candidate for surgery. The accuracy of the sterEOS® software measurements has been validated in the past, and our results support the previous studies [17, 21, 24, 25]. Differences between 2D and 3D measurements in AIS have been previously been analyzed by Pasha et al. [26]. These authors demonstrated much higher differences and a higher variability that was justified by the role of the transverse plane movement in AIS that could explain an underestimation of sagittal modifications in scoliotic patients. As we used a semi-automated detection of spinal shape on 2D using Keops® Analyzer, we believe that this method has highly reduced the margin of error that manual measurement of only end vertebra can produce. Indeed, when placing the end plate of a remarkable

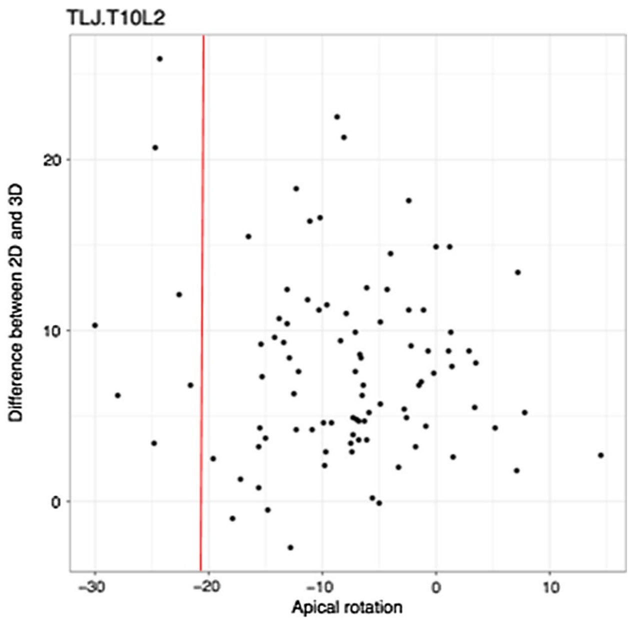

Fig. 3 Difference between 2D and 3D measures for T10L2 angle. Influence of AVR (apical vertebral rotation). Red line represents the mean AVR value in the global cohort

vertebra, especially T1 or T12 which might be less visible than L1 and S1, especially in severe scoliotic deformity, the operator might have a high intra-rater variability. Using a semi-automated 2D system which first draws the general line followed by the global sagittal curves, and given that the level characterization by the operator is limited to the placement of the center of the vertebral plateau for each level, the margin of error is significantly reduced explaining a better accuracy and concordance between 2D and 3D measurements compared to non-automated 2D measures as shown by Pasha et al.

When Lenke described sagittal modifiers, he included T10L2 angle as a possible variable as thoracolumbar junction kyphosis may occur as a response to sagittal changes in AIS, especially thoracic hypokyphosis [11]. In the new sagittal classification, TLJ behavior is one of the discriminant parameters, in addition to TK and T1 slope [19]. Although we found a good-to-excellent concordance for TK and T1 slope, correlation was weak for T10L2 angle. As sterEOS® does not provide this sagittal angle as an automated value, we obtained a calculated value from the sum of the sagittal intervertebral angles from T10T11 to L1L2. This value may be an approximation that should be further tested to determine whether it could itself explain the variability that we found in our study or if it is related to the underestimation of TLJ lordosis by 2D.

To our knowledge, this is the first study that uses this calculation to provide T10L2 angle when using sterEOS®. Therefore, one should consider the fact that this way of calculating T10L2 angle might not correspond to the 2D measure (sagittal Cobb angle between T10 and L2 plateau). Moreover, due to this variability, T10L2 absolute value might not be the right parameter to use in the new AIS sagittal classification. Position of the inflection point between TK and LL might be considered as an alternative discriminant parameter. It seems that the absolute value of the TLJ sagittal angle could lead to confusion and that a more qualitative analysis based on the position of the transitional zone between lordosis and kyphosis would be more relevant. Specific study will be necessary to validate this proposal. For now, sterEOS® cannot provide the inflection point in the real curve, which also requires further research.

Validation of classification by 3D

Despite the differences observed for T10L2 angle, the sagittal classification could be used for both 2D and 3D analysis. 2D analysis may underestimate the proportion of patients that should be classified as type 3, as we showed that thoracolumbar extension was more frequent based on 3D analysis. These findings share the results of Newton et al. [21] that 2D view masks the importance of the lordotic movement of scoliotic, especially around the apex of the curve.

Influence of Cobb angle and AVR

We found an influence of the curve magnitude on T10L2 variability, showing that the higher the Cobb angle, the lower the 2D/3D concordance. On the other hand, AVR had no influence. Indeed, sagittal deformity, even though modulated by the magnitude of scoliosis and the transverse movement, is mainly related to the structural intersegmental sagittal movement. Newton et al. revisited the theories of Somerville, and they highlighted from 3D modeling the importance of the lordotic movement created within the segments concerned by the structural scoliotic deformity [1, 2, 21].

Conclusion

In conclusion, for the majority of cases 2D analysis may provide enough information for decision making. However, in severe cases 3D analysis should be used to get a more accurate view, especially for TLJ.

T10L2 was the most variable parameter. We could find a tendency to larger differences between 2D and 3D measurements when Cobb angle was > 50° (Fig. 2). Variability for T10L2 was not influenced by apical rotation. Moreover, the intra-rater reproducibility was excellent for this angle (ICC = 0.97, 95% = [0.93; 0.99]). These data show that T10L2 angle in 2D may underestimate the intersegmental lordosis which is related to the structural deformity. However, we do not know whether the value calculated from sterEOS represents the same parameter as the value given by KEOPS. These findings advocate for a more qualitative analysis of the TLJ, based on the position of the transitional zone between lordosis and kyphosis (inflection point), which is for now not routinely provided by 3D analysis software.

Even though 3D analysis seemed more accurate for TLJ analysis, most of the patients (82%) were classified similarly based on 2D and 3D values. If patients were classified differently, they were changed to type 3 due to higher absolute values of TLJ extension.

In conclusion, for the majority of cases 2D analysis will provide enough information for decision making. However, in severe cases 3D analysis should be used to get a more accurate view on the scoliosis. Despite the differences between 2D and 3D analysis, we can conclude that the sagittal classification is validated when using 3D analysis. Our findings advocate for the adjunction of a qualitative analysis of inflection points position in the new AIS sagittal classification proposed by Abelin-Genevois et al. [19].

Authors contribution This paper is the result of the Masters of Science project conducted by Mareille Post under the responsibility of Pr Barend Van Royen, MD, PhD and under the supervision of Dr Kariman Abelin-Genevois, MD, PhD. The authors acknowledge Pr Barend Van Royen, MD, PhD for his support and supervision of Mareille Post, MSc, in the achievement of her scientific work, as a collaboration between the research group of Orthopedic Department of the Centre Medico Chirurgical des Massues Croix Rouge Francaise and the Medical Science School of VU Amsterdam. KAG and MP designed and wrote the manuscript. KAG conceived the study and the cohort. KAG, PR and MP collected the patients' data. SV was in charge of the methodology of the study and analyzed the data, and as biostatician was entirely and independently in charge of the statistical analysis. KAG, MP and SV reviewed and edited the manuscript. All authors read and approved the manuscript.

Conflict of interest None of the authors have conflict of interest, except Pierre Roussouly as shareholder of Keops(R), Smaio, France.

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