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Investigation of the Phenomenon of Coronal-sagittal Curvature Coupling on Curve Progression: An Exploratory Study using Three-dimensional Ultrasound

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ABSTRACT

Three-dimensional (3D) ultrasound system was demonstrated to provide reliable and valid results for scoliosis assessment in the coronal and sagittal planes. The objective of this study is to investigate whether 3D ultrasound can detect coronal-sagittal coupling and to study its potential effect on curve progression in patients with adolescence idiopathic scoliosis (AIS) as per the traditional Cobb angle classification. Radiographic and ultrasonic coronal and sagittal curvatures of 126 patients with AIS were evaluated. Thoracic kyphosis (TK) and lumbar lordosis (LL) with different coronal deformity were compared correspondingly based on either main thoracic or (thoraco)lumbar curve groups. TK and LL of patients with single curves were also compared to study the curve effect on sagittal curvatures. A prospective cohort of 51 patients was followed for an average of 23 months for preliminary progression investigation. TK in patients with larger main thoracic Cobb angles was significantly smaller than those with smaller main thoracic Cobb angles, judging by the results obtained from ultrasound and X-ray. TK of patients which possess only single right main thoracic curves was significantly smaller than those who possesses only single left (thoraco)lumbar curves. In addition, patients with progressive curves were observed to be relative hypokyphotic during early visit.

Keywords: 3D ultrasound; Scoliosis; Coronal; Sagittal; Coupling; Hypokyphosis; Progression

INTRODUCTION

Scoliosis is classically defined as a spinal curvature in the coronal plane of more than 10 degrees (Cobb 1948). Treatment depends on the severity of the curve, for those with an immature skeleton and Cobb's angle of between 20 to 40 degrees, physiotherapeutic scoliosis specific exercise (PSSE) or brace treatment will be considered (Negrini et al. 2016). Surgical management may be recommended if the deformity is worsening. Follow-up posterior-anterior radiographs are necessary for skeletally immature patients at least once a year since they are at maximum risk for curve progression (Thomsen and Abel 2006). Since Cobb angle on standing postero-anterior X-ray radiograph is the gold standard to evaluate the severity of scoliosis and sagittal curvature of the spine for current clinical practice, mass screening or frequent therapy outcome measurements are not recommended due to radiation applied to the patient. Female patients with scoliosis had a 4.2% increased risk of breast cancer (Bone and Hsieh 2000; Doody et al. 2000). In some clinics, sagittal X-ray may even be avoided unless necessary to avoid patients from overexposing to radiation. Though improvements have been made in radiographical technology to minimize radiation exposure, such as the invention of the EOS system, long-term health complications remain an inherent risk, also from limited doses of radiation exposure (Lee et al. 2013).

Upright full spine ultrasound has become more popular as a radiation free application for scoliosis evaluation due to its three-dimensional (3D) nature, reliability, ability to perform dynamic investigations and its lack of ionizing radiation (Li et al. 2012; Ungi et al. 2014; Young et al. 2015; Wang et al. 2015; Cheung et al. 2015; He et al. 2017). Currently, it is the only clinically available imaging modality which provides non-ionizing imaging for scoliosis evaluation in standing position with measurement directly on vertebrae spine. The customized

3D ultrasound system used in this study has been demonstrated to evaluate coronal deformation using spinous process shadows and sagittal curvatures using bilateral laminae for patients with adolescence idiopathic scoliosis (AIS) with reliable and valid results (Zheng et al. 2016; Brink et al. 2018; Lee et al. 2019a; Lee et al. 2019b; Wong et al 2019).

Scoliosis is a 3D deformity that consists of a rotated lordosis (Somerville 1952). Various factors were found to be related to curve progression in patients with scoliosis in previous studies, such as growth rate difference within or between vertebral bodies and the posterior elements such as spinal cord (Porter 2000; Guo et al. 2003; Chu et al. 2006), asymmetric loading on growing vertebrae (Aronsson et al. 1999; Stokes et al. 1996), increased spine flexibility in younger individuals (Roussouly and Nnadi 2010), earlier growth spurt in girls comparing to boys (Dickson et al. 1984), increased of height and slenderness of an individual (Nissinen et al. 1993). Coincidently a smaller value of thoracic kyphosis was observed in the AIS patients of the above studies, suggesting that hypokyphosis may closely relate with the progression of AIS (Schlösser et al. 2014). A study has further demonstrated that patients with progressive AIS were relatively hypokyphotic at the first visit comparing to those with non-progressive curves (Nault et al. 2014), thus detection of hypokyphosis in AIS patients could be a prognostic index during evaluation. Hence the objective of this study was to demonstrate that 3D ultrasound can reliably reflect the coronal-sagittal coupling phenomenon in patients with AIS using 3D ultrasound as compared to traditional Cobb angle classification, and to investigate the possible effect of the hypokyphotic phenomenon on the prognosis of curve progression through a preliminary investigation.

MATERIALS AND METHODS

Total 191 AIS patients, who were age between 10 to 18 years old and with main thoracic and/or (thoraco)lumbar Cobb angle within 10° to 40° were invited for this retrospective study. The study was approved by the local institutional review board (Joint Chinese University of Hong Kong-New territories East Cluster Clinical Research Ethics Committee) and informed consent was obtained from all patients. The patients received standing plain upright low dose posterior-anterior and lateral radiographs and one ultrasound scanning on the same day. To investigate the coupling phenomenon, patients with the following criteria were excluded: 1) Cobb angle > 40° (N = 54); 2) Apparent global kyphosis in the lumbar region detected by ultrasound (N = 6); 3) Poor scanning quality in the thoracic region due to the hindrance of the scapula (N = 5). The final total number of subjects involved for the coupling study was 126. Among these patients, 51 subjects received a second X-ray and ultrasound scanning during subsequent visit, which was at least 1 year after the first ultrasound assessment. These patients were all included in the progression session. Brace treatments were allowed for the patients during the period, but braces were required to be removed the night before the visits.

The coupling relationship between coronal deformity and sagittal curvatures was investigated using both X-ray and ultrasound, which the radiographic results were considered as the ground truth. Coronal curvatures, in terms of main thoracic and (thoraco)lumbar regions and sagittal curvatures, in terms of thoracic kyphosis (TK) and lumbar lordosis (LL), were measured from X-ray and ultrasound images. Whole body coronal and sagittal radiographs of all subjects were captured simultaneously using upright EOS (EOS imaging, Paris, France) with a standardized radiographic protocol by a team of experienced radiographer. Subjects were requested to stand with extended hips and knees and with hands on a support, which was the inner wall of the EOS system. Upright EOS captured simultaneously the radiographs of frontal and lateral views with two pairs of X-ray sources which positioned perpendicular to each other. Ultrasound imaging of the spine of the subjects were achieved through free-hand scanning with the usage of a linear ultrasound probe with center frequency of 7.5 MHz and width of 7.5 cm, d with a spatial sensor to detect the position and the orientation of the probe. The subjects received ultrasound scanning in an upright posture, with the arms and hands resting aside. The 3D ultrasound imaging system came with four adjustable supporters for the subjects to minimize motion, by aligning with the bilateral clavicle anterior concavities anterior superior iliac spines during scanning (Zheng et al. 2016). The operator then started the scanning from L5 to T1 level. After the scanning was completed, the ultrasound images collected together with the corresponding spatial orientation of the ultrasound images were used for 3D image reconstructions to generate the coronal and sagittal ultrasound images. The technical specifications and generation methods of coronal and sagittal ultrasound images were elaborated in previous studies (Zheng et al. 2016).

For coronal analysis, Cobb angle(s) was considered as the angle formed between the lines drawn on the most tilted upper endplate and the most tilted lower endplate of a curve (Figure 1a); whereas spinous process angle(s) (SPA), the angle used for sonographic measurement on the central dark spinous process shadow, was considered as the angle formed between the lines drawn on the uppermost tilted spinous process shadow and the lowermost tilted lower endplate of a curve (Figure 1c) (Zheng et al. 2016). For X-ray, curves would be considered as main thoracic if the apex of the curves lied between T2 and T11-12 disc, and as (thoraco)lumbar if the apex of the curves lied within T12 and L4 levels. Similarly for ultrasound, curves would be considered as main thoracic if the apex of the curves lied on or above T12 transverse processes, and as thoraco(lumbar) if the apex of the curves lied below T12 transverse processes. For sagittal analysis, radiographic TK and LL were defined by the angle formed between the lines drawn on the upper endplate of T4 vertebra and the lower endplate of the T12 vertebra, and on the upper endplate of L1 vertebra and the lower endplate of the L5 vertebra respectively (Figure 1b) (Schlösser et al. 2014, Yeung et al. 2020); whereas sonographic TK and LL, the mean angle acquired using the bilateral laminae features on two sagittal ultrasound images (Lee et al. 2019b). TK was defined by the angle formed between the line connecting T3 and T4 laminae and the line connecting T11 and T12 laminae, whereas LL was defined by the angle formed between the line connecting T12 and L1 laminae and the line connecting L4 and L5 laminae respectively (Figure 1d). To study the effect of sagittal parameters on curve progression, the coronal curve type would be separately analyzed based on the curve location, i.e. main thoracic and (thoraco)lumbar respectively. Age, duration between visits, initial Cobb / SPA, TK and LL value between progressive and non-progressive patients were compared. For X-ray, patients would be assigned to the progressive group if an increment of more than 5° of Cobb angle was detected during the two visits, while patients would be assigned to the non-progressive group if the Cobb difference between the two visits is less than or equal to 5°. For ultrasound, 2 cut-off angles were assigned and analyzed independently, patients would be assigned to the progressive group if there was an increment of more than 3.7° / 4.5° of SPA between the two visits, while patients would be assigned to the non-progressive group if the SPA difference between the two visits was less than or equal to 3.7° / 4.5°. The 5-degree and 3.7-degree cut-off for X-ray and ultrasound were selected based on the measurement error on X-ray (Morrissy et al. 1990) and ultrasound (Zheng et al. 2016) respectively. The 4.5-degree cut-off for ultrasound was selected so to include all patients who were considered as non-progressive using X-ray results, since the radiographic results were also considered as the ground truth in this session.

All the measurements were performed on RadiAnt DICOM Viewer software (Medixant, Poland). Two raters, who have experience working on spinal ultrasound images for more than five years, were involved for the evaluation of coronal and sagittal ultrasound angles respectively. Radiographic measurements were conducted by a doctor in an orthopedics department who has over 10 years of experiences in studying radiographs of patients with AIS. All measurements for both modalities were conducted once and all the raters were blinded to the clinical information.

To analysis the coronal-sagittal coupling effect, Pearson coefficients between X-ray and ultrasound angles for both coronal and sagittal planes were calculated. TK and LL of the subjects were compared between groups with smaller and larger Cobb (Cut-off: 20º) and SPA angle (Cut-off: 17º), depending on either the angle was a main thoracic or (thoraco)lumbar type (Figure 2). In addition, to study the effect of curve types on sagittal parameters, TK and LL of patients who possess only either single main thoracic or (thoraco)lumbar curves were compared Figure 3. The cut-off angle for SPA, 17º, was deduced from substituting 20º Cobb into the linear regression equation between coronal Cobb and SPA obtained in Figure 4 and rounded up to the nearest degree, to compensate the difference between two modalities. For the progression investigation, independent t-tests were used to compare the age, duration between visits, initial Cobb / SPA, TK and LL value between progressive and non-progressive patients, dependently based on the curve location, i.e. main thoracic / (throaco)lumbar curves. All data was reported as mean ± standard deviation (SD). Statistical analysis was conducted using SPSS Version 20.0 (IBM, SPSS Inc., USA). Sagittal parameters were compared using independent t-tests for both X-ray and 3D ultrasound. All the significance level was set at 0.05.

RESULTS

For the coupling investigation, the mean age of the subjects was 14.9 ± 2.0 years, made up of 104 females and 22 males. The average main thoracic and (thoraco)lumbar Cobb were 23.0 ± 7.8° and 23.4 ± 6.6° respectively, while the average main thoracic and (thoraco)lumbar SPA were 17.1 ± 6.6° and 19.2 ± 6.3° respectively. Radiographic TK and LL were in average 24.4 ± 10.6° and 44.1 ± 10.1°, whereas sonographic TK and LL were in average 32.9 ± 10.6° and 29.2 ± 11.9°. The correlations and the corresponding linear regressions between X-ray and ultrasound angles in the coronal and sagittal planes were shown in Figure 4 and 5 respectively. All these angles were significantly correlated ($p<0.001$). Radiographic TK in patients with main thoracic Cobb > 20° was significantly smaller than those with main thoracic Cobb ≤ 20º ($p<0.001$), similarly sonographic TK in patients with main thoracic SPA > 17° was significantly smaller than those with smaller main thoracic SPA ≤ 17º ($p<0.001$). No significant differences in LL were observed in patients with different degree of main thoracic Cobb and SPA. In addition, no significant differences were observed in both X-ray and sonographic TK and LL in patients with different degree of (thoraco)lumbar Cobb and SPA. All the above X-ray and ultrasound data were shown in Table 2 and 3 respectively.

Among the 126 patients, 20 patients possessed single right main thoracic curves and 21 patients possessed single left (thoraco)lumbar curves (Table 1). Radiographic and ultrasonic TK in patients who possessed single main thoracic curve was significantly smaller than those who possessed single main thoracic curve ($p \leq 0.002$), but no significant difference was observed for LL between patients possessing main thoracic and (thoraco)lumbar curves. The corresponding data were shown in Table 4 and 5.

For the progression investigation, the mean age of the subjects during the first ultrasound assessment was 15.1 ± 2.0 years, made up of 42 females and 9 males, with the average main thoracic and (thoraco)lumbar Cobb were 24.1 ± 8.0° and 22.9 ± 6.7° respectively, while the average main thoracic and (thoraco)lumbar SPA were 18.5 ± 6.7° and 19.7 ± 6.3° respectively. The average duration between the two visits involved in this preliminary study was 23 ± 6 months. Main thoracic progressive group was significantly older (p=0.015), possessed larger initial main thoracic Cobb angle (p=0.004) and smaller TK (p=0.004) from the results obtained from X-ray, whereas (thoraco)lumbar progressive group was only significantly older (p=0.032). Similar findings were observed from the results obtained from ultrasound for both 3.7° and 4.5° cut-off, where main thoracic progressive groups had a significant higher age (3.7° cut off: p=0.003; 4.5° cut off: p=0.015), larger initial main thoracic Cobb angle (3.7° cut off: p=0.041; 4.5° cut off: p=0.006) and smaller TK (3.7° cut off: p=0.005; 4.5° cut off: p=0.020), whereas (thoraco)lumbar progressive groups had a significant higher age only (3.7° cut off: p=0.044; 4.5° cut off: p=0.032). All the comparison results were presented in Table 6, 7 and 8 respectively.

DISCUSSION

This study investigated the coronal-sagittal coupling features of scoliotic spine on 126 AIS patients using 3D ultrasound and bi-planar X-ray. Our ultimate goals were to demonstrate that the coronal-sagittal coupling exists between patients with mild and moderate AIS curves and that hypokyphosis could be a prognostic factor for curve progression in these patients. Since in previous studies, we have demonstrated that ultrasound could provide reliable and valid coronal and sagittal measurements, yet discrepancies could be observed between the angles obtained in the two imaging modalities. Therefore, in this study we would like to first demonstrate that the ultrasound results were capable to exhibit the coupling effects between the two planes, despite the angle discrepancies between ultrasound and X-ray and provided that the X-ray results were reflecting the ground truth. Second, a preliminary study was conducted to justify whether the hypokyphotic phenomenon could predict curve progression, by comparing the sagittal spinal parameters between progressive and non-progressive curve group of patients with AIS.

The differences of the angles between the two modalities, especially in the sagittal plane, were caused by intrinsic factors such as measurements were made on different structures and using different measurement methods, and different postures were adopted during X-ray and ultrasound scanning (Marks et al. 2009; Zheng et al. 2016; Lee et al. 2019b). In a previous study, an extra set of X-ray measurement were conducted using the centre of posterior tangent as a reference to evaluate sagittal curvature (Lee et al. 2019b). Similar to the method adopted for the evaluation of sagittal curvatures on ultrasound images, TK was re-defined in that study by the angle formed between the line connecting the centre of T3 and T4 posterior border and the line joining the centre of T11 and T12 posterior border, whereas LL was defined by the intersection angle between the line connecting the centre of T12 and L1 posterior border and the line joining the centre of L4 and L5 posterior border. Surprisingly, the TK and LL obtained using this alternative method were found to be significantly larger and smaller, in average of 7.3° and 9.1° respectively, when compared to that obtained using the traditional Cobb method. In addition, the posture adopted for the patients during X-ray in this study was similar to the fist-over-ipsilateral clavicle posture adopted in the study of Marks et al. (2009), where an average increase of 3° on thoracic kyphosis and decrease of 4° degrees on lumbar lordosis were observed when compared to those adopted a natural posture, which was also the posture adopted for the ultrasound scanning for the patients in this study. The above two reasons could mainly explain why there was such a large discrepancy between X-ray and ultrasound results. Nevertheless, this study demonstrated that ultrasound was capable to demonstrate the coupling phenomenon of scoliotic spines of patients with AIS independently, which were also reflected from the X-ray results, considered as the ground truth.

In this study, patients with larger main thoracic curve deformity were found to be significantly hypokyphotic, when compared with those who possessed a smaller main thoracic curve. These findings were similar as those reported in previous studies (de Jonge et al. 2002; Ilharreborde et al. 2018; Mac-Thiong et al. 2003; Hong et al. 2017; Sullivan et al. 2017). However, no significant differences were observed in lumbar lordosis. One of the possible reasons that no significant difference was observed in terms of lumbar lordosis could be possibly due to the severity of curves involved in this study. Generally significant lumbar lordosis differences were observed in patients with severe AIS, for instance pre-operative patients, when compared to those with smaller curves or even normal individuals. In the study of Hong et al. (2017), significant higher lumbar lordosis was observed only in cases with Cobb angle larger than 40 degrees than those with smaller angles, but no significant difference was found between patients possess Cobb angles less than 20° and 40°. In addition, lumbar lordosis were found to have no significant difference among normal individuals and AIS patients who possessed only mild single thoracic or lumbar curve (Schlösser et al. 2014). The patients involved in this study only possessed coronal Cobb angle not more than 40 degrees, thus this could explain why no difference could be observed in lumbar lordosis. Furthermore, even for some study that involved patients with severe AIS, no significant difference of lumbar lordosis was demonstrated between those who possessed larger lumbar curves than those did not (Mac-Thiong et al's 2003), suggesting that different lumbar lordosis values may not be a common phenomenon among patients with lumbar AIS. In addition, patients who possessed single main thoracic curves were found to be significantly hypokyphotic than those who possessed single (thoraco)lumbar curves with comparable degree of deformity, which showed that patients who possessed main thoracic curves, with or without the present of (thoraco)lumbar curves, were relatively hypokyphotic.

Patients with main thoracic curve with relative hypokyphosis tended to progress more than those with a larger kyphosis value during the first ultrasound scan. One of the potential reasons was that the rotational instability induced to vertebrae due to unlocked facet joints within vertebrae in the hypokyphotic regions (Castelein et al. 2005; Kouwenhoven et al. 2007). Such phenomenon was similar to a previous study using EOS, a bi-planar X-ray system, where patients with progressive AIS were found to be hypokyphosis than non-progressive AIS (Nault et al. 2014). However, this study did not categorize the coronal Cobb angle and thus the localized effects of sagittal parameters on coronal angle were not well studied. Hence the advantage of this study was to investigate the effect of TK and LL on either main thoracic or (thoraco)lumbar curve in the coronal plane separately during the first ultrasound scan, so to have a better understanding on the localized effect of sagittal parameters on coronal curve progression. No significant differences were observed in sagittal parameters between progressive and non-progressive (thoraoc)lumbar groups. This suggested that TK and LL seemed to play no role on (thoraco)lumbar curve progression, possible effects of any other sagittal parameters should be investigated in future studies. The average X-ray and ultrasound TK of AIS patients were about 27° and 37° respectively for in progressive and non-progressive main thoracic group patients, which matched with those who possessed a larger deformity in the main thoracic region in the coupling study, i.e. Cobb > 20° or SPA > 17°. Furthermore, progressive subjects in terms of either main thoracic or (throaco)lumbar curve were shown to be younger. All the above evidences suggested that younger AIS patients who possesses main thoracic curve with kyphosis much smaller than these values using either X-ray or ultrasound would suffer from curve progression with a much higher tendency if no interventions would be made.

There are several limitations in this study. First, patients with Cobb angle larger than 40° were not included. The reason is that evaluation of the sagittal curvature on radiograph would be highly affected by the coronal deformity and vertebral rotation, thus it was not suggested to be conducted on patients with severe scoliosis by the clinicians. In addition, another objective of this study was to demonstrate that hypokyphosis could be a prognostic factor for curve progression on patients with mild to moderate AIS, in order to avoid surgery ultimately. Second, the baselines of the subjects involved in this study, such as the Risser's sign, treatment status and the Premenarche status, were not controlled during recruitment. All the patients with AIS in a certain time point were recruited, some were their first visits while some of them were follow-ups. Generally bracing was suggested to the patients with AIS with immature bone and Cobb angle larger than 20° from the corresponding hospital. Since it has been known that bracing could create hypokyphosis to patients, therefore the hypokyphotic phenomenon could possibly cause by the effect of bracing. Therefore, the sagittal profile of patients with mild or moderate curves who underwent bracing could be compared with those who only undergone therapeutic exercise treatment could be compared in future study to investigate whether bracing would be playing a role in the hypokyphotic phenomenon. Third, because of the limited number of thoracolumbar curves involved, this type of curves were combined with lumbar curves as one category, known as (thoraco)lumbar curves. Fourth, patients with metallic implants and BMI higher than 25.0 kg/m^2 were also excluded, since metallic implants could affect the accuracy of ultrasound probe spatial sensing and high BMI could cause poor image quality in the lumbar region. Nevertheless, the capability of ultrasound providing coupling, together with the reliability of ultrasound demonstrated in previous study (Zheng et al. 2016; Lee et al. 2019b), suggested that 3D ultrasound imaging could be a tool to evaluate coronal and sagittal spinal profiles and investigate the coupling effects between these two planes. Due to its non-ionizing nature, 3D ultrasound could provide more frequent follow-up examinations on spine for AIS patients, which generally cannot be done in clinical routine as X-ray involves radiation and is not available in all clinics.

CONCLUSIONS

To our knowledge, this is the first study which had evaluated the coronal-sagittal coupling effect with positive findings and investigated the hypokyphotic phenomenon on curve progression using ultrasound, and with X-ray results as the ground truth. Hypokyphosis was observed for patient with AIS who possess larger thoracic curves. However, the coronal-sagittal coupling phenomenon was only observed in the thoracic region, but not in the (thoraco)lumbar region. In addition, the preliminary progression study showed that the hypokyphotic phenomenon observed in the main study could be a prognostic factor for thoracic curve progression. This could become of critical importance in future for management planning of patients with AIS.

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FIGURE LEGENDS

Figure 1. Diagram illustrating the measurements made on coronal and sagittal X-ray [(a) and (b)] and ultrasound [(c) and (d)]

Figure 2. The three images on the left were the coronal (a) and sagittal ultrasound images illustrating the left (b) and right (c) laminae of a patient with adolescence idiopathic scoliosis (AIS) who possessed smaller main thoracic curvature, whereas the three images on the right were the coronal (d) and sagittal ultrasound images illustrating the left (e) and right (f) laminae of an AIS patient who possessed larger main thoracic curvature. The red line indicates the T12 vertebrae level.

Figure 3. The three images on the left were the coronal (a) and sagittal ultrasound images illustrating the left (b) and right (c) laminae of a patient with adolescence idiopathic scoliosis (AIS) who possessed a single main thoracic curve, whereas the three images on the right were the coronal (d) and sagittal ultrasound images illustrating the left (e) and right (f) laminae of an AIS patient who possessed a single lumbar curve. The red line indicates the T12 vertebrae level.

Figure 4. Correlation and the corresponding linear regression between coronal X-ray Cobb angles and ultrasound spinous process angles for main thoracic and (thoraco)lumbar curves. The correlation value and the equation were obtained by combing the two types of angles. SPA: Spinous Process Angle.

Figure 5. Correlations and the corresponding linear regressions between X-ray angles and ultrasound angles in terms of thoracic kyphosis and lumbar lordosis in the sagittal plane

Table 1 Descriptive parameters of the patients involved in the study

Curve type	RT	RT-LTL	LTL-RT	Triple	LTL	Other
N (Female /male)	20 (16 / 4)	26 (21 / 5)	37 (33 / 4)	15 (11 / 4)	21 (18 / 3)	7 (5 / 2)
Age (year)	14.6 ± 2.0	14.3 ± 2.0	14.9 ± 2.1	15.0 ± 2.0	15.5 ± 1.8	14.1 ± 1.3
Mean Cobb (°)	21.7 ± 8.8	24.0 ± 6.8	22.0 ± 6.4	23.3 ± 8.0	23.9 ± 6.8	27.3 ± 10.0

RT: right thoracic; RT-LTL: right thoracic-left (thoraco)lumbar; LL-RT: left (thorac)lumbar-right thoracic; LTL, left (thoraco)lumbar; other, left thoracic and/or right (thoraco)lumbar; N: number of patients

Table 2 Comparison of sagittal parameters between patients with different extent of Cobb value based on either main thoracic or (thoraco)lumbar curve respectively using X-ray

	AIS patients divided into groups based on the possession of					
X-ray	**Main Thoracic Curve**			**(Thoraco)lumbar Curve**		
	Cobb ≤ 20º	**Cobb > 20º**	**p**	**Cobb ≤ 20º**	**Cobb > 20º**	**p**
TK (º)	26.9 ± 9.6	20.7 ± 11.0	0.001*	24.4 ± 9.3	24.3 ± 11.9	0.942
LL (º)	44.4 ± 10.3	43.5 ± 10.2	0.606	45.0 ± 10.4	43.0 ± 9.9	0.269

*P < 0.05

AIS: adolescence idiopathic scoliosis; TK: Thoracic kyphosis; LL: Lumbar lordosis

Table 3 Comparison of sagittal parameters between patients with different extent of Cobb value based on either main thoracic or (thoraco)lumbar curve respectively using ultrasound

US	AIS patients divided into groups based on the possession of					
	Main Thoracic Curve			(Thoraco)lumbar Curve		
	SPA ≤ 17º	SPA > 17º	p	SPA ≤ 17º	SPA > 17º	p
TK (º)	35.6 ± 9.2	27.9 ± 11.2	<0.001*	33.5 ± 10.8	32.3 ± 10.4	0.498
LL (º)	27.7 ± 11.1	31.8 ± 13.0	0.066	29.5 ± 12.3	28.8 ± 11.5	0.746

*P < 0.05

AIS: adolescence idiopathic scoliosis; US: Ultrasound; SPA: Spinous Process Angle; TK: Thoracic kyphosis; LL: Lumbar lordosis

Table 4 Comparison of sagittal parameters between patients who possess either single main thoracic or (thoraco)lumbar curve respectively using X-ray

X-ray	AIS patients divided into groups based on the possession of single		
	Main Thoracic Curve	(Thoraco)lumbar Curve	p
TK (º)	20.4 ± 9.4	30.6 ± 10.4	0.002*
LL (º)	43.3 ± 10.7	44.5 ± 10.8	0.739

*P < 0.05

AIS: adolescence idiopathic scoliosis; TK: Thoracic kyphosis; LL: Lumbar lordosis

Table 5 Comparison of sagittal parameters between patients who possess either single main thoracic or (thoraco)lumbar curve respectively using ultrasound

US	**AIS patients divided into groups based on the possession of single**		
	Main Thoracic Curve	**(Thoraco)lumbar Curve**	**p**
TK (º)	27.5 ± 10.8	38.4 ± 8.0	0.001*
LL (º)	27.6 ± 12.7	26.4 ± 10.5	0.747

*P < 0.05

AIS: adolescence idiopathic scoliosis; US: Ultrasound; TK: Thoracic kyphosis; LL: Lumbar lordosis

Table 6 Values of different parameters measured during the first visit that received ultrasound scan that received ultrasound scan between non-progressive and progressive main thoracic / (thoraco)lumbar Cobb angles using X-ray, with the cut off degree set as 5º

	AIS patients divided into groups based on the possession of					
	Main Thoracic Cobb (Cut off: 5º)			**(Thoraco)lumbar Cobb (Cut off: 5º)**		
X-ray	**Non-progressive**	**Progressive**	**p**	**Non-progressive**	**Progressive**	**p**
Number of patients	35	16	N/A	39	12	N/A
Age (year)	15.5 ± 2.1	14.0 ± 1.8	0.015*	15.4 ± 1.9	13.9 ± 2.4	0.032*
Main thoracic Cobb (º)	21.0 ± 8.2	29.0 ± 7.5	0.004*	24.7 ± 8.4	22.3 ± 6.7	0.419
(Thoraco)lumbar Cobb(º)	23.2 ± 6.8	22.0 ± 7.3	0.620	23.4 ± 6.8	21.5 ± 7.3	0.429
TK (º)	26.8 ± 3.0	18.7 ± 10.9	0.007*	25.1 ± 9.6	21.6 ± 12.3	0.316
LL (º)	44.2 ± 9.0	45.5 ± 9.9	0.657	44.7 ± 9.4	44.3 ± 8.8	0.897

*$P < 0.05$

TK: Thoracic kyphosis; LL: Lumbar lordosis.

Table 7 Values of different parameters measured during the first visit that received ultrasound scan between non-progressive and progressive main thoracic / (thoraco)lumbar SPA using ultrasound, with the cut off degree set as 3.7 º

	AIS patients divided into groups based on the possession of					
	Main Thoracic SPA (Cut off: 3.7º)			**(Thoraco)lumbar SPA (Cut off: 3.7º)**		
X-ray	**Non-progressive**	**Progressive**	**p**	**Non-progressive**	**Progressive**	**p**
Number of patients	31	20	N/A	36	15	N/A
Age (year)	15.7 ± 2.0	14.0 ± 2.0	0.003*	15.4 ± 1.9	14.1 ± 2.3	0.044*
Main thoracic SPA (º)	16.6 ± 6.2	21.0 ± 6.8	0.041*	18.2 ± 6.5	19.1 ± 7.3	0.706
(Thoraco)lumbar SPA(º)	19.9 ± 7.0	19.4 ± 5.0	0.782	20.1 ± 6.5	18.9 ± 6.1	0.612
TK (º)	37.6 ± 8.4	27.5 ± 13.2	0.005*	33.3 ± 10.3	34.6 ± 14.4	0.709
LL (º)	34.6 ± 9.4	31.8 ± 12.2	0.371	34.9 ± 10.6	30.2 ± 10.1	0.148

*$P < 0.05$

SPA: Spinous Process Angle; TK: Thoracic kyphosis; LL: Lumbar lordosis.

Table 8 Values of different parameters measured during the first visit that received ultrasound scan between non-progressive and progressive main thoracic / (thoraco)lumbar SPA using ultrasound, with the cut off degree set as 4.5 º

	AIS patients divided into groups based on the possession of					
	Main Thoracic SPA (Cut off: 4.5º)			**(Thoraco)lumbar SPA (Cut off: 4.5º)**		
X-ray	**Non-progressive**	**Progressive**	**p**	**Non-progressive**	**Progressive**	**p**
Number of patients	35	16	N/A	39	12	N/A
Age (year)	15.5 ± 2.1	14.0 ± 1.8	0.015*	15.4 ± 1.9	13.9 ± 2.4	0.032*
Main thoracic SPA (º)	16.5 ± 6.1	22.6 ± 6.3	0.006*	19.1 ± 7.1	16.6 ± 5.4	0.315
(Thoraco)lumbar SPA(º)	19.6 ± 6.8	20.0 ± 5.0	0.863	20.1 ± 6.5	18.9 ± 6.1	0.612
TK (º)	36.7 ± 8.7	27.0 ± 14.3	0.020*	33.3 ± 10.4	34.9 ± 15.1	0.679
LL (º)	34.0 ± 10.1	32.5 ± 11.8	0.653	34.1 ± 10.3	30.9 ± 10.2	0.315

*$P < 0.05$

SPA: Spinous Process Angle; TK: Thoracic kyphosis; LL: Lumbar lordosis.