



HAL
open science

3D external shape analysis and barycentremetry can provide early signs of progression in adolescent idiopathic scoliosis

Tristan Langlais, Claudio Vergari, Nicolas Mainard, Xavier Du Cluzel, Matthieu Baudoux, Laurent Gajny, Kariman Abelin-Genevois, Jean-Claude Bernard, Zongshan Hu, Jack Chun-Yiu Cheng, et al.

► To cite this version:

Tristan Langlais, Claudio Vergari, Nicolas Mainard, Xavier Du Cluzel, Matthieu Baudoux, et al.. 3D external shape analysis and barycentremetry can provide early signs of progression in adolescent idiopathic scoliosis. *Spine Deformity*, 2024, Vol. 13, p. 551-560. <10.1007/s43390-024-01001-y>. <hal-05350239>

HAL Id: hal-05350239

<https://hal.science/hal-05350239v1>

Submitted on 6 Nov 2025


HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

3D external shape analysis and barycentremetry can provide early signs of progression in adolescent idiopathic scoliosis

Tristan Langlais^{1,2}  · Claudio Vergari¹ · Nicolas Mainard³ · Xavier du Cluzel⁴ · Matthieu Baudoux^{4,5} · Laurent Gajny¹ · Kariman Abelin-Genevois⁵ · Jean Claude Bernard⁵ · Zongshan Hu⁶ · Jack Chun Yiu Cheng⁶ · Winnie Chiu Wing Chu⁷ · Ayman Assi^{1,8} · Mohamad Karam⁸ · Ismat Ghanem^{8,9} · Tito Bassani¹⁰ · Fabio Galbusera¹¹ · Luca Maria Scorfienza^{10,12} · Marco Brayda-Bruno¹⁰ · Isabelle Courtois¹³ · Eric Ebermeyer¹³ · Raphael Vialle³ · Jean Dubousset¹ · Wafa Skalli¹

Abstract

Purpose Our objective was to analyse the barycentremetry, obtained from the external envelope reconstruction of biplanar radiographs, in adolescent idiopathic scoliosis (AIS) and to determine whether assessing would help predict the distinction between progressive and stable AIS at the early stage.

Methods A retrospective study with a multicentre cohort of 205 AIS was conducted. All AIS underwent a biplanar X-ray between 2013 and 2020. Inclusion criteria were Cobb angle between 10° and 25°; Risser sign lower than 3; age higher than 10 years; and no previous treatment. A 3D spine reconstruction was performed, and the barycentremetry parameters were computed, i.e., the center of mass position at the apex and the axial torque at the apex, the upper and lower junction. A severity index, helping to distinguish stable and progressive AIS, was computed on the first radiograph, and weighted according to these parameters. A clinical and radiographic monitoring determined if AIS were classified such a stable or progressive scoliosis.

Results One hundred and sixty-two AIS were included (i.e., 87 were classified as stable and 75 as progressive). The apex center of mass position was different between the stable and progressive AIS groups (6 mm, SD=4 mm for the whole cohort; 5 mm, SD=4 mm for stable AIS versus 7 mm, SD=4 mm for progressive AIS; $p=0.02$). In AIS thoracic, the specificity and positive predictive value of the severity index increased by 19% and 16%, respectively, by adding the apex vertebral axial torque.

Conclusion Early assessment of the external envelope from biplanar X-ray reconstruction of idiopathic scoliosis showed that the apex centre of mass position was significantly different between progressive and stable scoliosis. The inclusion of the axial torque of the apex vertebra in the severity index is promising to help the clinician distinguish between stable and progressive thoracic AIS at an early stage.

Level of evidence II - Prognostic studies

Keywords Idiopathic scoliosis · Adolescent · Barycentremetry · Progressive scoliosis · Biplanar radiograph

Introduction

Idiopathic scoliosis is a three-dimensional (3D) spinal deformity of uncertain aetiology defined in the coronal plane by a Cobb angle of at least 10° and an axial vertebral rotation [1]. Its aetiopathogeny is multifactorial and the causal factors are poorly understood [2] but several preliminary studies emphasize a possible sensory imbalance at an early stage [3, 4]. Early detection is a public health issue to implement

early treatment. On the other hand, being able to distinguish a stable scoliosis from a progressive form at an early stage would make it possible to avoid over-treatment and save the costs associated with brace treatment and also reduce the risk of surgery [5].

A validated predictive models based on 3D biplanar reconstruction (i.e., the severity index described by Skalli et al. [6] was developed to make this distinction at the first visit. However, this predictive model still needs to be improved and is based solely on the 3D reconstruction of the spine. More recently, it was shown that including the growth

stage of the patient (i.e., their Risser stage) in the severity index could improve the detection of progressive scoliosis [7]. It is acknowledged that scoliosis is a multifactorial 3D process and includes other anatomical abnormalities such as muscle balance [8] and disc mechanical properties [9] among others. In a recent previous study [10], we reported alterations in the distribution of masses resulting from the analysis of the external shape associated with density models in a population of scoliotic patients. The current work aims to ascertain whether barycentremetry could further improve the early detection of progressive scoliosis and thus complement the predictive model, which is currently based on bone parameters.

To this end, the balance and barycentremetry of a cohort of adolescent idiopathic scoliosis (AIS) was assessed at an early stage and compared with their curve progression. Moreover, the effect of combining the external shape parameters on the severity index was assessed.

Materials and methods

Subjects

A cohort of 205 scoliotic patients was considered. Data were collected, between 2013 and 2020 from 6 centres in 4 countries (with a minimal of 10% inclusions per centre), and they were previously reported in studies using a severity index to predict scoliosis progression [6, 7, 11, 12], which did not include any assessment of barycentremetry. Parents, children, and adults were informed about the protocol and consented to participate before inclusion. This study was approved by the local ethical committees.

Inclusion criteria were: (1) confirmed diagnosis of AIS; (2) Cobb angle between 10° and 25° ; (3) European Risser sign lower than 3 [13]; (4) age superior to 10 years; and (5) no previous treatment (such as brace or spine surgery). Patients for whom reconstruction of the external envelope was not feasible (i.e., the patient's external envelope was outside the limits of the radiograph) were excluded.

Protocol

All subjects underwent a low-dose biplanar X-ray (EOS system, EOS Imaging), in the free-standing position [14], at the onset of inclusion. Patients were classified by location of the main curve following according to the location of the apex: thoracic (apex between the T2 vertebra and the T11-T12 intervertebral disc), thoracolumbar (apex between the T12 and L1 vertebrae), and lumbar (apex between the L1-L2 intervertebral disc and the L4 vertebra) [15–17]. The follow-up could be stopped at either of two points in time: (1) when the patient reached a Risser sign greater than or equal to 3,

without prescription of brace and without progression of the curvature over 6 months between two successive follow-up visits (i.e., a Cobb angle of the main curvature less than 25°). These patients were classified as “stable”; (2) when a corrective brace was prescribed, in which case patients were classified as “progressive”. Quantitative and objective criteria were used to decide on brace treatment according to the International Society on Scoliosis Orthopaedic and Rehabilitation Treatment guidelines, i.e., a Cobb angle of the main curvature greater than 25° and a Risser sign less than or equal to 2, or an increase of 5° in Cobb angle or vertebral axial rotation within 6 months [18], as well as an assessment of the clinical profile.

Imaging data and external shape analysis

A quasi-automatic 3D reconstruction of the spine was performed, from the biplanar radiography acquired at inclusion, using a previously validated method [11, 19]. An automatic algorithm provided an initial solution of 3D reconstruction, on which the operator could perform fast manual adjustment of some key vertebrae (the apex, junctions and the adjacent to the junctions) to improve accuracy. The 3D reconstruction allowed for the automatic computation of coronal and sagittal OD-HA [20] and the 6 parameters of the severity index, previously validated [6], i.e., the Cobb angle, the apex vertebral axial rotation, the upper and lower intervertebral axial rotation, the torsion index, and the hypokyphosis index. The coronal and sagittal OD-HA angles were computed automatically from the specific anatomical landmarks: OD, the most superior point of dentiform apophyse of C2, as an estimate of the head centre of mass, and HA was the midpoint of pelvic acetabula [20]. External shape was reconstructed, retrospectively, using a validated technique [21] (Fig. 1A, B). The reconstruction takes about 15 min, and it allows automatic estimation of body segments weights, according to a recent estimation of segmental mass density [22], calculation of the apex center of mass position (Fig. 1C), and the apex, the upper and the lower junction spinal axial torque [23] (Fig. 1D–F). The centre of mass position for the slice corresponding to the apex of the curvature was calculated to determine its distance from the vertical line passing through the middle of the HA axis in the coronal plane (Fig. 1C). The spinal axial torque applied to each vertebra (apex, upper and lower boundary) resulted from its lateral displacement and inclination in the sagittal plane, due to the mass of the body above the vertebra and the position of this segment's center of mass (Fig. 1D–F).

S-index calculation and weighting protocol

For each patient, the severity index (ranging from 0 to 1) was automatically computed [6, 11] and it included the stage of

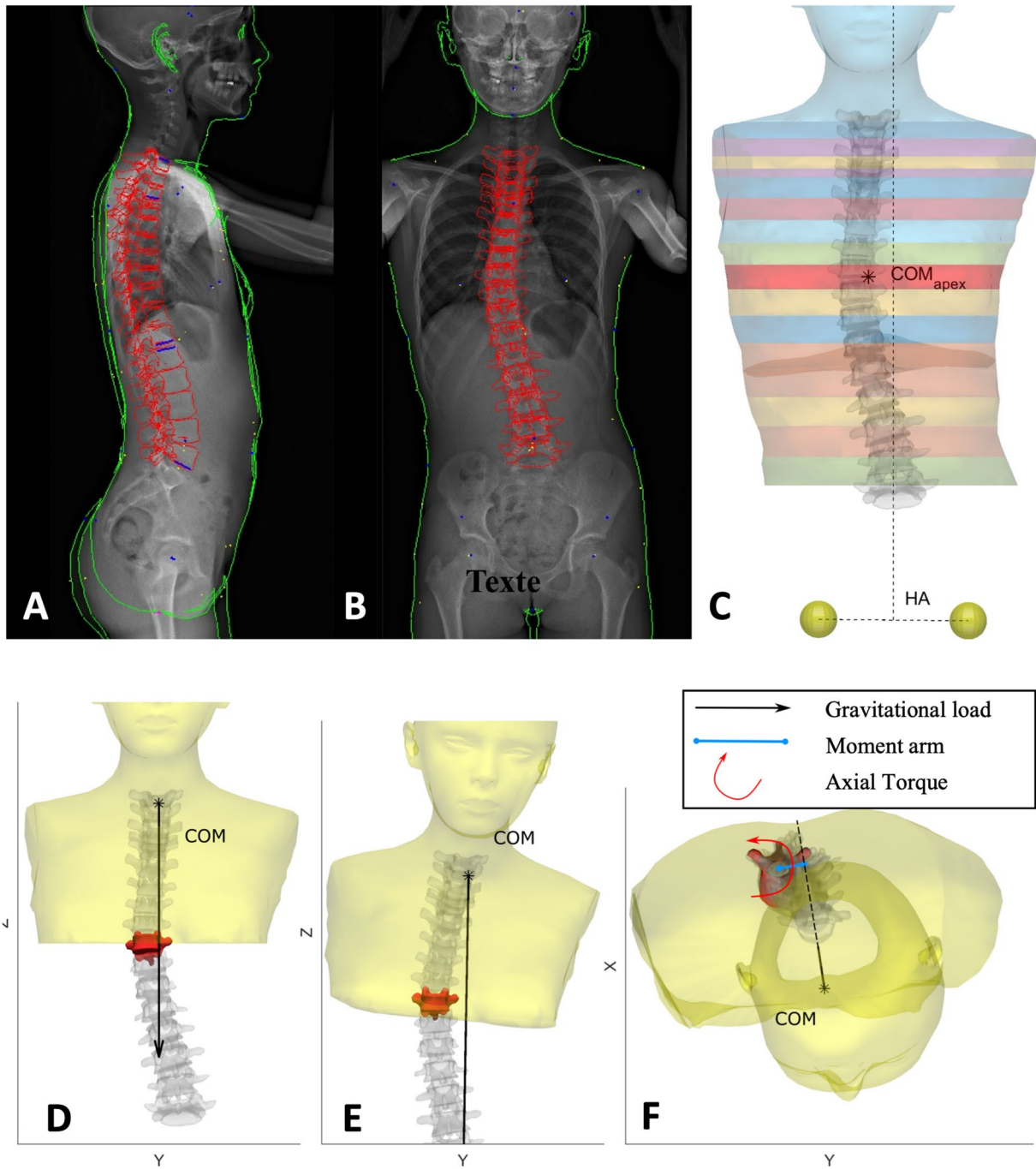


Fig. 1 Example of external envelope reconstruction in sagittal (**A**) and frontal (**B**) from a biplanar radiograph of a right thoracic scoliosis. Image **C** illustrates the measurement of the apex centre of mass position. Horizontal slices of the outer shell were virtually cut at each vertebral level. The centre of mass position for the slice corresponding to the apex of the curvature was calculated to determine its distance from the vertical line passing through the middle of the HA axis in the coronal plane. Frame **D**, **E**, **F** is a visual representation of the apex axial torque. Panel **D** shows the 3D reconstruction of the

spine, with the apex vertebra highlighted in red, as well as the part of the trunk above this vertebra and its centre of mass (COM). The gravitational load is indicated by the arrow. Panel **E** shows the same 3D reconstruction, but the patient (and the gravitational load) has been virtually rotated so that the apex vertebra is now perfectly horizontal. Panel **F** shows the same configuration as **E** from a top view so that the apex vertebra is now horizontal and seen from above. The blue line represents the lever arm and in red, the apex axial torque was plotted

the European Risser sign as a weighing factor [7]. The index was further weighted according to the external shape parameters, and the weights were calculated as follows: first, the 5th and 95th percentiles of each parameter were determined in a cohort of asymptomatic subjects [10]. Then, if a patient showed a given parameter greater than the 95th percentile from the asymptomatic cohort, a multiplication factor of 1.5 was applied to the severity index. For the upper, apex, and lower axial torque, a multiplication factor of 1.5 was applied when the parameter was greater than the 95th percentile, while if the scoliotic patient's value was lower than 5th percentile, a multiplication factor of 0.8 was applied. A severity index lower than 0.4 was considered indicative of a stable curve, while an index higher than 0.6 was indicative of a progressive one. No prediction was issued for values in-between, and patient corresponding was unclassified.

Statistics

Numeric variables were expressed as mean (SD) and discrete outcomes as absolute and relative (%) frequencies. Stable and progressive scoliosis were compared for external shape parameters. Normality and heteroskedasticity of continuous data were assessed with Shapiro–Wilk and Levene's test, respectively. Continuous outcomes were compared with unpaired Student *t*-test, Welch *t*-test or, Mann–Whitney *U* test according to data distribution. Spearman's correlation was used to assess the linear dependence between the severity index and external shape parameters. Correlation was judged very strong from 1 to 0.9, strong from 0.9 to 0.7, moderate from 0.7 to 0.5, low from 0.5 to 0.3 and poor from 0.3 to 0. A multivariate linear regression was performed to assess the relation between the external shape parameters with the severity index parameters and OD-HA. Data were checked for multicollinearity with the Belsley-Kuh-Welsch technique. Heteroskedasticity and normality of residuals were assessed, respectively, by the Breusch-Pagan test and the Shapiro–Wilk test. The alpha risk was set to 5% and two-tailed tests were used. To analyze the weighting of the severity index with the external shape parameters, we reported the sensitivity, specificity, positive and negative predictive value of the test according to the locations of the curvature. We reported the results of the weighting only when the performance of the test was to improve by at least 5%. Statistical analysis was performed with EasyMedStat (version 3.19; Neuilly-sur-Seine).

Results

Population

One hundred and sixty-two scoliosis (12 years old, SD = 1; 139 females and 23 males; 73 thoracic, 40 thoraco-lumbar

and 49 lumbar) were included in the external shape analysis. Forty-three patients were excluded because the external shape reconstruction was not feasible. Mean Cobb angle of scoliotic patients was 16.0°, SD = 3.7°; range from 10.0° to 24.8°. After the clinical and biplanar radiographic follow-up, 87 AIS (53%) were classified as stable and 75 (47%) as progressive. The demographic characteristics are resumed in Table 1. The values of the 6 severity index parameters and OD-HA are reported in Table 2.

External shape parameters

The external shape parameters are reported in Table 3. Only the apex center of mass position was statistically different between the stable and progressive AIS groups (6 mm, SD = 4 mm for whole cohort; 5 mm, SD = 4 mm and 95%CI from 4.4 to 6.2 mm for stable scoliosis versus 7 mm, SD = 4 mm and 95%CI from 5.9 to 8 mm for progressive group; *p* = 0.02) but this difference was not found in the analysis by curvature type (*p* > 0.05 for all curve locations).

Correlation between external shape parameters, the severity index parameters and OD-HA

In multivariate analysis, apex vertebral axial rotation ($\beta = 0.3$, [0.2;0.5], *p* < 0.0001) and coronal OD-HA ($\beta = 1$, [0.5;1.5], *p* < 0.0001) were associated with higher values of the apex center of mass position. Torsion index ($\beta = 0.04$, [0.01;0.08], *p* = 0.021) and Cobb angle ($\beta = 0.05$, [0.03;0.08], *p* < 0.0001) were associated with higher

Table 1 Demographics characteristics of population

	AIS population		
	Total (n = 162)	Stable (n = 87)	Progressive (n = 75)
Age: yo, SD (range)	12, 1 (10;15)	12.5, 1 (10;15)	11.5, 1 (10;14.5)
Risser sign: n (%)			
0	94 (58%)	33 (38%)	61 (81%)
1	35 (22%)	25 (29%)	10 (14%)
2	33 (20%)	29 (33%)	4 (5%)
Gender: n (%)			
Girls	139 (85%)	74 (85%)	65 (87%)
Boys	23 (14%)	13 (15%)	10 (13%)
Curve topography: n (%)			
Thoracic	73 (45%)	40 (46%)	33 (44%)
Thoraco-lumbar	40 (25%)	19 (22%)	21 (28%)
Lumbar	49 (30%)	28 (32%)	21 (28%)

n represents the number of patients

SD standard deviation

Table 2 Values of the 6 index severity parameters and OD-HA

	AIS population		
	Total (<i>n</i> = 162)	Stable (<i>n</i> = 87)	Progressive (<i>n</i> = 75)
Cobb angle (°)	16 (3.7)	15 (3.2)	17 (3.9)
Apex VAR (°)	5.9 (4.2)	4.7 (3.4)	7.3 (4.6)
Upper IAR (°)	-3 (3.2)	-1.8 (3.1)	-4.4 (2.8)
Lower IAR (°)	2 (3.1)	1.4 (3.2)	2.7 (2.9)
Torsion index (°)	4.2 (2.5)	3.3 (1.8)	5.1 (2.8)
Hypokyphosis index (°)	-1 (3.1)	-0.3 (3.1)	-2 (2.9)
Coronal OD-HA (°)	0.3 (1.2)	0.3 (1)	0.4 (1.4)
Sagittal OD-HA (°)	-0.9 (2.3)	-1.03 (2.3)	-0.9 (2.4)

Results are presented such as mean (SD)

n represents the number of patients

SD standard deviation, *VAR* vertebral axial rotation, *IAR* intervertebral axial rotation

Table 3 Parameters from external shape analysis

	AIS population			<i>p</i> value
	Total (<i>n</i> = 162)	Stable (<i>n</i> = 87)	Progressive (<i>n</i> = 75)	
Apex center of mass position (mm)	6.1 (4.4)	5.34 (4.1)	6.9 (4.6)	0.02*
Thoracic curve	5.3 (3.4)	4.7 (3.4)	6.03 (3.4)	0.09
Thoraco-lumbar curve	6.1 (4.4)	6.7 (5.4)	7.9 (5.5)	0.4
Lumbar curve	6.2 (4.5)	5.32 (4)	7.5 (5.1)	0.09
Apex intersegmental moment (N/m)	0.4 (0.4)	0.39 (0.5)	0.4 (0.4)	0.9
Thoracic curve	0.39 (0.4)	0.37 (0.4)	0.41 (0.4)	0.5
Thoraco-lumbar curve	0.42 (0.4)	0.36 (0.3)	0.59 (0.5)	0.4
Lumbar curve	0.35 (0.3)	0.29 (0.2)	0.4 (0.4)	0.9
Upper intersegmental moment (N/m)	0.96 (0.5)	0.9 (0.5)	1.03 (0.6)	0.2
Thoracic curve	0.99 (0.5)	0.9 (0.5)	1 (0.6)	0.3
Thoraco-lumbar curve	0.96 (0.5)	1 (0.5)	0.8 (0.6)	0.4
Lumbar curve	0.93 (0.4)	0.87 (0.4)	1 (0.5)	0.3
Lower intersegmental moment (N/m)	0.72 (0.4)	0.77 (0.4)	0.7 (0.4)	0.1
Thoracic curve	0.75 (0.4)	0.8 (0.5)	0.66 (0.4)	0.1
Thoraco-lumbar curve	0.64 (0.4)	0.67 (0.4)	0.65 (0.4)	0.9
Lumbar curve	0.67 (0.4)	0.67 (0.3)	0.68 (0.4)	0.6

Values in bold are statistically significant

Results are presented such as mean (SD)

n represents the number of patients

*Mann–Whitney test

values of upper junctional axial torque. Hypokyphosis index ($\beta=0.03$, [0.01;0.05], $p=0.01$) and sagittal OD-HA ($\beta=0.05$, [0.02;0.08], $p=0.003$) were associated with higher values of lower junctional axial torque.

External shape analysis and performance of S-index

The performance of the severity index predictive power with the addition of barycentremetry parameters is detailed in Table 4 for the whole cohort and according to curve location. In particular, the specificity and positive predictive value of S-index in thoracic scoliosis increased by 19% and 16%,

respectively, when considering the apex vertebral axial torque. In other words, this parameter increased the likelihood that a severity index greater than 0.6 corresponds to a truly progressive patient. This is reflected (Table 4) by reducing the number of misclassified patients by 9% while increasing the number of unclassified by 15% (Fig. 2).

Discussion

In this study, we assessed the biomechanical markers issued from the reconstruction of the external shape, which were previously validated in a population of healthy subjects and patients [10]. These biomarkers reflect the distribution of body masses and provide an original, modern approach to assess spinal deformity. Previous studies focused [24, 25] on the analysis of external deformity using a surface topography device and focusing on torso asymmetry. The correlation of this tool with bone deformation characteristics (either Cobb angle or vertebral rotation) remains controversial [26, 27]. On the other hand, such analysis appears to be a good indicator of outcomes for quality-of-life scores and measures related to the external physical appearance of the trunk [27]. Recently, a new tool, allowing 3D and 360° reconstruction of the torso has been evaluated and validated in a healthy population [28]. However, to our knowledge, there are no studies on the external shape analysis from low-dose biplanar radiographs used in daily clinical practice.

The main finding of the present work is that the apex center of mass (CoM) values was significantly different between progressive and stable scoliosis. The CoM represents the lateral mass displacement at apex regions (Fig. 1C), and we found that it correlates with the coronal

OD-HA and the apex vertebral axial rotation. The hypothesis is that this displacement requires scoliotic patients to adjust their balance to maintain the CoM above the pelvis. In their assessment of CoM using a force plate, Dalleau et al. showed that in scoliotic patients there is a compensatory action due to the frontal deformation, resulting in a backward offset of the CoM to maintain postural balance [29]. This backward trunk displacement was previously described in studies by Nault et al. [30] and Damavandi et al. [31]. In our study, we could not demonstrate this backward displacement difference between progressive and stable scoliosis on the first visit biplanar radiograph, which suggests that this trunk shift could develop later in the progression of the deformity. The open question is to understand why the other barycenter parameters at this stage of deformation are not different between progressive and stable forms. According to previous studies [10, 23], the upper junction axial torque correlates with the severity of scoliosis. In this study, we found a correlation of the upper axial torque with the Cobb angle and the torsion index. One of the hypotheses is that the differences between the biomarkers are still small at this stage of deformation. The uncertainty of these biomechanical markers had been evaluated and did not exceed 0.8 mm for the lateral position of CoM at all vertebral levels and 0.5 N/m for the axial torque [10]. It is likely that there are no significant differences due to this uncertainty. One

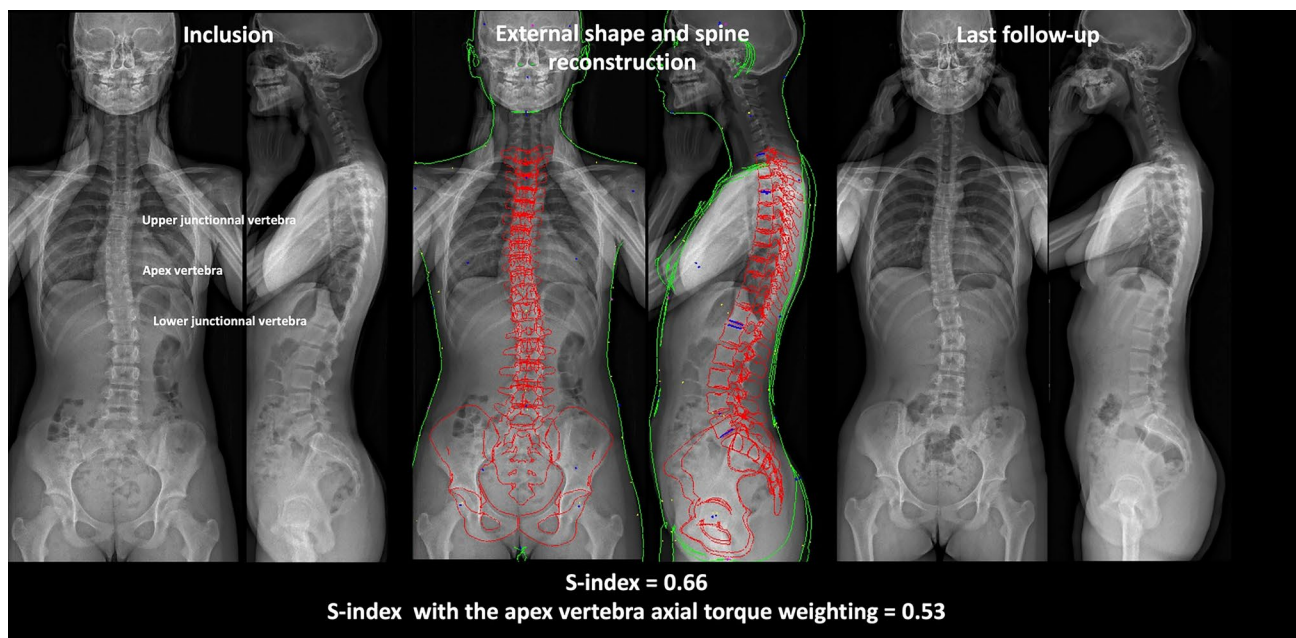


Fig. 2 Example of stable thoracic scoliosis. The inclusion and the last follow-up radiographic were reported. The middle frame shows the external shape and spine reconstruction. The calculated severity index was 0.66, i.e. a so-called “progressive” scoliosis and therefore misclassified with the risk of unsuitable treatment. The weighting

with the apex axial torque decreases the severity index to 0.53, i.e. so-called unclassified scoliosis and calls for particular attention by the clinician. The radiograph of the last follow-up (i.e., Risser 4) shows that this is a stable scoliosis which has not undergone brace treatment

solution could be to improve the 3D reconstruction method to lower its uncertainty or increase the number of patients included. Nevertheless, early alterations in the centre of mass of the apex vertebrae can disrupt the distribution of body masses in AIS. Finally, the parameters derived from the analysis of the external shape analysis are linked to a risk of progression but taken separately this would not be sufficient to predict progression (like the other parameters of the severity index).

An important result of this study was the analysis of biomarkers resulting directly from bone reconstruction and their relationship with the displacement of the CoM. The apex CoM displacement was explained by the increase of the apex vertebra axial rotation and the coronal OD-HA. Recently, Karam et al. showed that frontal malalignment was related to the apex vertebra axial rotation [32]. The important information for the clinician is that the frontal Cobb angle, measured in daily clinical practice, does not influence the position of the CoM in scoliotic deformities at an early stage. Furthermore, we found that this lateral displacement of the trunk was positively correlated with the apex vertebra axial rotation. This result is supported by J. Dubousset's and W. Skalli's theory that it is important to evaluate the deformity in the axial plane, especially at an early stage [33, 34].

The last important finding of the study was the preliminary assessment of the impact of including barycentremetry to the S-index. For thoracic scoliosis, including the axial torque of the apex vertebra improves the specificity and positive predictive value (by 19% and 17%, respectively) without significantly altering the sensitivity and negative predictive value (by -3% and 1%, respectively). This result is promising as it decreases the number of misclassified patients by 9%, which means a decrease in the probability of “over-treating” a stable scoliosis (Fig. 2). On the other hand, it increases the number of unclassified patients by 15%, which leads in clinical practice to continued radiographic monitoring. The other point to note is that the center of mass position, although the values were different between stable and progressive scoliosis, did not influence overall test performance. Future prospective studies should take this parameter into account to determine its clinical significance.

This study presents some limitations, but these results are promising and is the first study of its kind. This is a retrospective assessment, which explains why 43 subjects were excluded for issues concerning the framing of the external envelope. Nevertheless, the cohort was included prospectively for the validation of the severity index and this study showed how the assessment of axial torque, centre of mass position could improve the prediction of progressive scoliosis. Furthermore, the weighing factors modifying the severity index were chosen arbitrarily. Another limitation of this study is the time of the external shape reconstruction which is around 15 to 20 min of operator time per patient

but a partial automated process should be available soon. Another limitation is that the percentage of Risser sign was not homogeneous between the stable and progressive cohorts (ie: Risser 0 = 38% in stable, and 81% in progressive). Although its weighting is considered in the severity index described above [7], a difference in the new barycentremetry parameters could also be attributed to significant growth remaining in the progressive cohort. Finally, the main limitation of this work is that this study focuses on a static approach to assess balance and barycentremetry. However, it has been established that the dynamic proprioceptive system is affected in patients with idiopathic scoliosis [4]. The remaining question is how these external shape parameters would be affected under dynamic conditions.

Conclusion

Early assessment of the external envelope from biplanar X-ray reconstruction of idiopathic scoliosis showed that the apex centre of mass position was significantly different between progressive and stable scoliosis. The inclusion of the axial torque of the apex vertebra in the severity index improves the specificity by 19% and the positive predictive value by 17% of the index. This promises to help the clinician distinguish between stable and progressive thoracic scoliosis at an early stage.

Acknowledgements The authors are grateful to the BiomecAM chair program on subject-specific musculoskeletal modelling (with the support of ParisTech and Yves Cotrel Foundations, Société Générale, Covea, and Proteor).

Author contributions Conception or design: T. Langlais, C. Vergari, W. Skalli. Acquisition, analysis or interpretation of data: T. Langlais, C. Vergari, N. Mainard, X. du Cluzel, M. Baudoux, L. Gajny, K. Abelin Genevois, J.C Bernard, Z. Hu, JCY. Cheng, WCW. Chu, A. Assi, M. Karam, I. Ghanem, T. Bassani, F. Galbusera, LM. Sconfienza, M. Brayda-Bruno, I. Courtois, E. Ebermeyer, R. Vialle, J. Dubousset, W. Skalli. Statistical analysis: T. Langlais, C. Vergari. Draft or revised the work: T. Langlais, C. Vergari, N. Mainard, X. du Cluzel, M. Baudoux, L. Gajny, K. Abelin Genevois, J.C Bernard, Z. Hu, JCY. Cheng, WCW. Chu, A. Assi, M. Karam, I. Ghanem, T. Bassani, F. Galbusera, LM. Sconfienza, M. Brayda-Bruno, I. Courtois, E. Ebermeyer, R. Vialle, J. Dubousset, W. Skalli. Approved final version: T. Langlais, C. Vergari, N. Mainard, X. du Cluzel, M. Baudoux, L. Gajny, K. Abelin Genevois, J.C Bernard, Z. Hu, JCY. Cheng, WCW. Chu, A. Assi, M. Karam, I. Ghanem, T. Bassani, F. Galbusera, LM. Sconfienza, M. Brayda-Bruno, I. Courtois, E. Ebermeyer, R. Vialle, J. Dubousset, W. Skalli.

Funding This study has received funding from the BiomecAM chair program on subject-specific musculoskeletal modelling (with the support of ParisTech and Yves Cotrel Foundations, Société Générale, Covea, and Proteor).

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest Wafa Skalli has a patent related to biplanar X-Rays and associated 3D reconstruction methods, with no personal financial benefit (royalties rewarded for research and education) licensed to EOS Imaging. Raphael Vialle reports personal fees and grants (unrelated to this study) from Stryker Spine (Consultant), Spineguard (Consultant), Nuvasive (Consultant). The other authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Ethical approval Institutional Review Board approval was obtained. Written informed consent was obtained from all subjects (patients) in this study.

References


1. Coonrad RW, Murrell GA, Motley G, Lytle E, Hey LA (1998) A logical coronal pattern classification of 2000 consecutive idiopathic scoliosis cases based on the scoliosis research society-defined apical vertebra. *Spine (Phila Pa 1976)* 23:1380–1391. <https://doi.org/10.1097/00007632-199806150-00016>
2. Kouwenhoven JWM, Castelein RM (2008) The pathogenesis of adolescent idiopathic scoliosis: review of the literature. *Spine (Phila Pa 1976)* 33:2898–2908. <https://doi.org/10.1097/BRS.0b013e3181891751>
3. Guo X, Chau WW, Hui-Chan CWY, Cheung CSK, Tsang WWN, Cheng JCY (2006) Balance control in adolescents with idiopathic scoliosis and disturbed somatosensory function. *Spine* 31:E437–E440. <https://doi.org/10.1097/01.brs.0000222048.47010.bf>
4. Assaiante C, Mallau S, Jouve J-L, Bollini G, Vaugoyeau M (2012) Do adolescent idiopathic scoliosis (AIS) neglect proprioceptive information in sensory integration of postural control? *PLoS ONE* 7:e40646. <https://doi.org/10.1371/journal.pone.0040646>
5. Nachemson AL, Peterson LE (1995) Effectiveness of treatment with a brace in girls who have adolescent idiopathic scoliosis. A prospective, controlled study based on data from the brace study of the scoliosis research society. *J Bone Joint Surg Am* 77:815–822. <https://doi.org/10.2106/00004623-199506000-00001>
6. Skalli W, Vergari C, Ebermeyer E, Courtois I, Drevelle X, Kohler R, Abelin-Genevois K, Dubousset J (2017) Early detection of progressive adolescent idiopathic scoliosis: a severity index. *Spine* 42:823–830. <https://doi.org/10.1097/BRS.0000000000001961>
7. Vergari C, Skalli W, Abelin-Genevois K, Bernard J, Hu Z, Cheng J, Chu W, Assi A, Karam M, Ghanem I, Bassani T, Galbusera F, Sconfienza L, Brayda-Bruno M, Courtois I, Ebermeyer E, Vialle R, Langlais T, Dubousset J (2021) Effect of curve location on the severity index for adolescent idiopathic scoliosis: a longitudinal cohort study. *Eur Radiol* 31:8488–8497. <https://doi.org/10.1007/s00330-021-07944-4>
8. Jung J-Y, Cha E-J, Kim K-A, Won Y, Bok S-K, Kim B-O, Kim J-J (2015) Influence of pelvic asymmetry and idiopathic scoliosis in adolescents on postural balance during sitting. *Biomed Mater Eng* 26(1):S601–S610. <https://doi.org/10.3233/BME-151351>
9. Langlais T, Vergari C, Pietton R, Dubousset J, Skalli W, Vialle R (2018) Shear-wave elastography can evaluate annulus fibrosus alteration in adolescent scoliosis. *Eur Radiol* 28:2830–2837. <https://doi.org/10.1007/s00330-018-5309-2>
10. Langlais T, Vergari C, Rougereau G, Gajny L, Assi A, Ghanem I, Dubousset J, Vialle R, Pietton R, Skalli W (2021) Balance, bar-centremetry and external shape analysis in idiopathic scoliosis: what can the physician expect from it? *Med Eng Phys* 94:33–40. <https://doi.org/10.1016/j.medengphys.2021.06.004>
11. Vergari C, Gajny L, Courtois I, Ebermeyer E, Abelin-Genevois K, Kim Y, Langlais T, Vialle R, Assi A, Ghanem I, Dubousset J, Skalli W (2019) Quasi-automatic early detection of progressive idiopathic scoliosis from biplanar radiography: a preliminary validation. *Eur Spine J* 28:1970–1976. <https://doi.org/10.1007/s00586-019-05998-z>
12. Langlais T, Vergari C, Rougereau G, Gaume M, Gajny L, Abelin-Genevois K, Bernard JC, Hu Z, Cheng JCY, Chu WCW, Assi A, Karam M, Ghanem I, Bassani T, Galbusera F, Sconfienza LM, Brayda-Bruno M, Courtois I, Ebermeyer E, Vialle R, Dubousset J, Skalli W (2024) Assessment of malalignment at early stage in adolescent idiopathic scoliosis: a longitudinal cohort study. *Eur Spine J* 33:1665–1674. <https://doi.org/10.1007/s00586-024-08178-w>
13. Duval-Beaupère G, Lamireau T (1985) Scoliosis at less than 30 degrees. Properties of the evolutivity (risk of progression). *Spine (Phila Pa 1976)* 10:421–424
14. Faro FD, Marks MC, Pawelek J, Newton PO (2004) Evaluation of a functional position for lateral radiograph acquisition in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)* 29:2284–2289. <https://doi.org/10.1097/01.brs.0000142224.46796.a7>
15. Stagnara P, Queneau P (1953) Developmental scolioses during the period of growth; clinical and radiological aspects and therapeutic considerations. *Rev Chir Orthop Reparatrice Appar Mot* 39:378–452
16. Perdriolle R (1979) La scoliose: son étude tridimensionnelle
17. Lenke LG, Betz RR, Clements D, Merola A, Maher T, Lowe T, Newton P, Bridwell KH, Blanke K (2002) Curve prevalence of a new classification of operative adolescent idiopathic scoliosis: does classification correlate with treatment? *Spine (Phila Pa 1976)* 27:604–611. <https://doi.org/10.1097/00007632-200203150-00008>
18. Negrini S, Donzelli S, Wynes J, Zaina F (2018) 2016 SOSORT guidelines: orthopaedic and rehabilitation treatment of idiopathic scoliosis during growth—PubMed. <https://pubmed.ncbi.nlm.nih.gov/29435499/>. Accessed 8 Oct 2022
19. Gajny L, Ebrahimi S, Vergari C, Angelini E, Skalli W (2019) Quasi-automatic 3D reconstruction of the full spine from low-dose biplanar X-rays based on statistical inferences and image analysis. *Eur Spine J* 28:658–664. <https://doi.org/10.1007/s00586-018-5807-6>
20. Amabile C, Pillet H, Lafage V, Barrey C, Vital J-M, Skalli W (2016) A new quasi-invariant parameter characterizing the postural alignment of young asymptomatic adults. *Eur Spine J* 25:3666–3674. <https://doi.org/10.1007/s00586-016-4552-y>
21. Nérot A, Choisne J, Amabile C, Travert C, Pillet H, Wang X, Skalli W (2015) A 3D reconstruction method of the body envelope from biplanar X-rays: evaluation of its accuracy and reliability. *J Biomech* 48:4322–4326. <https://doi.org/10.1016/j.jbiomech.2015.10.044>
22. Amabile C, Choisne J, Nérot A, Pillet H, Skalli W (2016) Determination of a new uniform thorax density representative of the living population from 3D external body shape modeling. *J Biomech* 49:1162–1169. <https://doi.org/10.1016/j.jbiomech.2016.03.006>
23. Thenard T, Vergari C, Hernandez T, Vialle R, Skalli W (2019) Analysis of center of mass and gravity-induced vertebral axial torque on the scoliotic spine by barycentremetry. *Spine Deformity* 7:525–532. <https://doi.org/10.1016/j.jspd.2018.11.007>
24. Bolzinger M, Bernardini I, Thevenin Lemoine C, Gallini A, Accadbled F, Sales de Gauzy J (2021) Monitoring adolescent idiopathic scoliosis by measuring ribs prominence using surface topography device. *Spine Deform* 9:1349–1354. <https://doi.org/10.1007/s43390-021-00327-1>
25. Groisser BN, Hillstrom HJ, Thakur A, Morse KW, Cunningham M, Hresko MT, Kimmel R, Wolf A, Widmann RF (2022) Reliability of automated topographic measurements for spine deformity. *Spine Deform* 10:1035–1045. <https://doi.org/10.1007/s43390-022-00505-9>

26. Mínguez MF, Buendía M, Cibrián RM, Salvador R, Laguña M, Martín A, Gomar F (2007) Quantifier variables of the back surface deformity obtained with a noninvasive structured light method: evaluation of their usefulness in idiopathic scoliosis diagnosis. *Eur Spine J* 16:73–82. <https://doi.org/10.1007/s00586-006-0079-y>
27. Gorton GE, Young ML, Masso PD (2012) Accuracy, reliability, and validity of a 3-dimensional scanner for assessing torso shape in idiopathic scoliosis. *Spine* 37:957–965. <https://doi.org/10.1097/BRS.0b013e31823a012e>
28. Michalik R, Siebers H, Eschweiler J, Quack V, Gatz M, Dirrachs T, Betsch M (2019) Development of a new 360-degree surface topography application. *Gait Posture* 73:39–44. <https://doi.org/10.1016/j.gaitpost.2019.06.025>
29. Dalleau G, Damavandi M, Leroyer P, Verkindt C, Rivard CH, Allard P (2011) Horizontal body and trunk center of mass offset and standing balance in scoliotic girls. *Eur Spine J* 20:123–128. <https://doi.org/10.1007/s00586-010-1554-z>
30. Nault ML, Allard P, Hinse S, Le Blanc R, Caron O, Labelle H, Sadeghi H (2002) Relations between standing stability and body posture parameters in adolescent idiopathic scoliosis. *Spine (Phila Pa 1976)* 27:1911–1917. <https://doi.org/10.1097/00007632-200209010-00018>
31. Damavandi M, Dalleau G, Stylianides G, Rivard C-H, Allard P (2013) Head and trunk mass and center of mass position estimations in able-bodied and scoliotic girls. *Med Eng Phys* 35:1607–1612. <https://doi.org/10.1016/j.medengphy.2013.05.010>
32. Karam M, Ghanem I, Vergari C, Khalil N, Saadé M, Chaaya C, Rteil A, Ayoub E, Saad E, Kharrat K, Skalli W, Assi A (2022) Global malalignment in adolescent idiopathic scoliosis: the axial deformity is the main driver. *Eur Spine J* 31:2326–2338. <https://doi.org/10.1007/s00586-021-07101-x>
33. Castelein RM, Pasha S, Cheng JC, Dubousset J (2020) Idiopathic scoliosis as a rotatory decompensation of the spine. *J Bone Miner Res* 35:1850–1857. <https://doi.org/10.1002/jbmr.4137>
34. Illés TS, Lavaste F, Dubousset JF (2019) The third dimension of scoliosis: the forgotten axial plane. *Orthop Traumatol Surg Res* 105:351–359. <https://doi.org/10.1016/j.otsr.2018.10.021>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Tristan Langlais^{1,2}  · Claudio Vergari¹ · Nicolas Mainard³ · Xavier du Cluzel⁴ · Matthieu Baudoux^{4,5} · Laurent Gajny¹ · Kariman Abelin-Genevois⁵ · Jean Claude Bernard⁵ · Zongshan Hu⁶ · Jack Chun Yiu Cheng⁶ · Winnie Chiu Wing Chu⁷ · Ayman Assi^{1,8} · Mohamad Karam⁸ · Ismat Ghanem^{8,9} · Tito Bassani¹⁰ · Fabio Galbusera¹¹ · Luca Maria Scorfienza^{10,12} · Marco Brayda-Bruno¹⁰ · Isabelle Courtois¹³ · Eric Ebermeyer¹³ · Raphael Vialle³ · Jean Dubousset¹ · Wafa Skalli¹

✉ Tristan Langlais
tristanlanglais@yahoo.fr

¹ Institut de Biomécanique Humaine Georges Charpak, Arts et Métiers, HESAM Université, Paris, France

² Service Orthopédie et Traumatologie, Hôpital des enfants, Toulouse III Université, Purpan Toulouse, France

³ University Institute for Spine Surgery, Armand Trousseau Hospital, APHP-Sorbonne Université, Paris, France

⁴ Service Orthopédie et Traumatologie, Hôpital Necker Enfants Malades, Paris cite Université, APHP, Paris, France

⁵ Department of Orthopaedic Surgery and Children Conservative treatment, Croix-Rouge française. Centre Médico-Chirurgical et de Réadaptation des Massues, Lyon, France

⁶ SH Ho Scoliosis Research Laboratory, Department of Orthopaedics and Traumatology, Faculty of Medicine, The Prince of Wales Hospital, The Chinese University of Hong Kong, Shatin, Hong Kong SAR

⁷ Department of Imaging and Interventional Radiology, Faculty of Medicine, The Prince of Wales Hospital, The Chinese University of Hong Kong, Shatin, Hong Kong SAR

⁸ Laboratory of Biomechanics and Medical Imaging, Faculty of Medicine, Saint-Joseph University of Beirut, Beirut, Lebanon

⁹ Department of Orthopedic Surgery, Hotel-Dieu de France Hospital, Saint Joseph University, Beirut, Lebanon

¹⁰ IRCCS Istituto Ortopedico Galeazzi, Milan, Italy

¹¹ Spine Center, Schulthess Clinic, Zurich, Switzerland

¹² Dipartimento di Scienze Biomediche per la Salute, Università degli Studi di Milano, Milan, Italy

¹³ Unite Rachis, CHU–Hopital Bellevue, Saint-Etienne, France