Bone & Joint Open

Supplementary Material

doi: 10.1302/2633-1462.53.BJO-2023-0176.R1.

Table i. Search strategy.

MEDLINE	(adolescent idiopathic scoliosis and (biplanar or 3D or three-dimensional) and (progression or alignment or prognosis)).mp. [mp=title, book title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms, population supplementary concept word, anatomy supplementary concept word]
PubMed	1. Adolescent idiopathic scoliosis.mp 2. (biplanar or 3D or three-dimensional).mp 3. 1 and 2 4. Progression.mp 5. Prognosis.mp 6. Alignment.mp 7. 4 or 5 or 6 8. 3 and 7
EMBASE	1. Adolescent idiopathic scoliosis.mp 2. (biplanar or 3D or three-dimensional).mp 3. 1 and 2 4. Progression.mp 5. Prognosis.mp 6. Alignment.mp 7. 4 or 5 or 6 8. 3 and 7
Web of Science	1. (ALL=(Adolescent idiopathic scoliosis)) AND ALL=(biplanar or 3D or three-dimensional) 2. ((ALL=(progression)) OR ALL=(prognosis)) OR ALL=(alignment) 3. #2 and #1
Cochrane Library	1. (adolescent idiopathic scoliosis) AND (biplanar or 3D or three-dimensional) 2. (progression) OR (alignment) OR (prognosis) 3. 1 and 2

Table ii. Details of included studies.

Study	Year	Study design	Sample size	Patient population
Almansour et al. (1)	2019	Cross-sectional	38 AIS	All curve types, braced
Begon et al. (2)	2015	Retrospective cohort study	19 AIS	Mild thoracic and thoracolumbar curves
Bisson et al. (3)	2023	Cross-sectional	45 AIS	Moderate to severe curves
Courvoisier et al. (4)	2013	Retrospective cohort study	30 AIS	Braced, thoracic-curve predominant
Courvoisier et al. (5)	2013	Cross-sectional	111 AIS	Mild curves
Drevelle et al. (6)	2010	Retrospective cohort study	12 AIS and 8 controls	Mild thoracolumbar curves only
Fitzgerald et al. (7)	2019	Cross-sectional	94 AIS	Lenke 1 patients who are PSF candidates (mean Cobb angle of 50°)
Garcia-Cano et al. (8)	2018	Retrospective cohort study	150 AIS	Mild curves at first visit, curve type not specified
Hayashi et al. (9)	2009	Cross-sectional	66 AIS	Right thoracic curves, ranging from moderate to severe
Kadoury et al. (10)	2014	Cross-sectional	65 AIS and 5 controls	All curve types
Kadoury et al. (11)	2017	Cross-sectional	40 AIS	Mild curves, all curve types
Karam et al. (12)	2020	Cross-sectional	274 AIS and 84 controls	All curve types
Karam et al. (13)	2022	Cross-sectional	200 AIS	Mild to severe curves, al curve types
Karam et al. (14)	2022	Retrospective cohort study	254 AIS and 64 controls	Mild to moderate curves, al curve types
Lau et al. (15)	2019	Retrospective cohort study	60 AIS	Age 10-14, varying skeletal age
Nault et al. (16)	2014	Prospective cohort study	133 AIS	Moderate curves, all curve types
Nault et al. (17)	2020	Prospective case-control study	195 AIS	Mild to moderate curves, Risser 0 to 1
Pasha et al. (18)	2016	Cross-sectional	73 AIS	Moderate curves, right thoracic with left lumbar curves only
Pasha et al. (19)	2018	Cross-sectional	73 AIS	Right thoracic curves
Scherrer et al. (20)	2013	Cross-sectional	27 AIS	Mild to moderate curves
Skalli et al. (21)	2017	Retrospective cohort study	65 AIS	Mild curves at first visit, curve type not specified
Sullvian et al. (22)	2017	Cross-sectional	442 AIS	Mild to severe thoracic curves
Thenard et al. (23)	2019	Cross-sectional	53 AIS and 27 controls	Mild to severe curves
Vergari et al. (24)	2015	Retrospective cohort study	10 AIS	Mild to severe curves
Vergari et al. (25)	2019	Retrospective cohort study	42 AIS	Braced, thoracic curve predominant
Vergari et al. (26)	2019	Cross-sectional	55 AIS	Mild curves at first visit, mix of curve types, proportion not specified
Vergari et al. (27)	2020	Cross-sectional	321 AIS and 83 controls	Mild to moderate curves
Vergari et al. (28)	2021	Retrospective cohort study	205 AIS	Mild curves at first visit, all curve types

Vergari et al. (29)	2022	Retrospective cohort study	138 AIS and 93 controls	Mild curves at first visit, curve type not specified
Villemure et al. (30)	2001	Retrospective cohort study	28 AIS	Mild to severe curves
Wang et al. (31)	2021	Retrospective cohort study	52 AIS	Mild curves at first visit, fair mix of curve types in training set, not specified for testing set

Table iii. Risk of bias assessed using Quality in Prognostic Studies (QUIPS).

Study	Study participation	Study attrition	Prognostic factor measurement	Outcome measurement	Study confounding	Statistical analysis and reporting	Overall risk of bias
Begon et al. (2)	High	Low	Low	Low	Low	Low	Moderate
Courvoisier et al. (5)	Low	Low	Low	Low	Low	Low	Low
Drevelle et al. (6)	High	Low	Low	Low	Low	Moderate	Moderate
Garcia-Cano et al. (8)	Moderate	Low	Low	Low	Low	Low	Low
Karam et al. (14)	Low	Low	Low	Low	Low	Moderate	Low
Lau et al. (15)	Low	Low	Low	Low	Low	Low	Low
Nault et al. (16)	Low	Low	Low	Low	Low	Moderate	Low
Nault et al. (32)	Low	Low	Low	Low	Moderate	Moderate	Moderate
Skalli et al. (21)	Moderate	Low	Low	Low	Low	Low	Low
Vergari et al. (24)	Moderate	Low	Low	Low	Low	Low	Low
Vergari et al. (26)	Moderate	Low	Low	Low	Low	Low	Low
Vergari et al. (28)	Low	Low	Low	Low	Low	Low	Low
Vegari et al. (29)	Low	Low	Low	Low	Low	Low	Low
Villemure et al. (30)	High	Low	Low	Low	Moderate	Low	Moderate
Wang et al. (31)	Low	Low	Low	Moderate	Low	Low	Low

Cross-sectional studies were assessed using the Appraisal tool for Cross-Sectional Studies (AXIS) and reported in the Results section.

Table iv. Coronal parameters.

Study	Key findings	Strength of evidence
Vergari et al. (28)	(1) Initial Cobb angle was 17.4 ± 3.79° in the progressive group and 14.7 ± 4.57° in the non-progressive group. Statistical significance was not reported for the differences in spinal parameters. (2) Addition of curve type (T, TL, L) did not significantly increase predictive accuracy, ROC curves were comparable among curve types.	Moderate
Wang et al. (31)	Difference in initial Cobb angle was not statistically significant comparing the progressive group and non-progressive group (22.2 ± 4.5° vs 19.7 ± 3.8°). Initial truncal shift (C7PL-CSVL) was also comparable between the two groups.	Moderate
Vergari et al. (26)	Initial Cobb angle was 17.4 ± 3.9° for the progressive group and 14.2 ± 3.3° for the non-progressive. Results of post-hoc statistical analysis were not reported.	Moderate
Skalli et al. (21)	Compared to patients with non-progressive curves, the progressive group had slightly higher Cobb angle (16 ± 3° vs 14 ± 3°, $p < 0.05$).	Moderate

Nault et al. (17)	A general linear model was applied to 172 subjects to predict final 3D Cobb angle based on 3D spinal morphology at first visit. The adjusted R^2 was 0.618, and coronal disk wedging (particularly of T3-T4 and T8-T9) were identified as significant predictors, among curve type, skeletal maturity, and angle of plane of maximum curvature.	Moderate
Nault et al. (16)	There was no statistical difference in initial 3D Cobb angle (mean 30° vs 27.8°, p=0.20), coronal apical vertebral wedging (p=0.9), and coronal apical disc wedging (p=0.6) between the non-progressive group and progressive group.	Moderate

Table v. Sagittal parameters.

Study	Key findings	Strength of evidence
Hayashi et al. (9)	The TK obtained by the standard lateral view was significantly higher compared to that obtained by 3D reconstruction (11 ± 10° vs 1 ± 9°).	Weak
Sullivan et al. (22)	2D Cobb has strong correlations with 3D TK (R^2=0.56) and AVR (R^2 = 0.63), while having weak correlations with 2D TK (R^2=0.02).	Weak
Nault et al. (16)	The progressive group had lower initial 3D TK compared to the non-progressive group (mean 20.6° vs 25.0°, p = 0.02).	Weak
Nault et al. (17)	3D TK at first visit had a weak inverse correlation with final 3D Cobb angle (r = -0.288, p = 0.01).	Weak
Wang et al. (31)	No difference in initial 3D T4-T12 TK was found between progressive and non-progressive groups (22.3 ± 8.5 vs 21.4 ± 9.2, p=0.635).	Weak
Skalli et al. (21)	A hypokyphosis index was incorporated into a predictive score for progression, based on 45 AIS subjects and 53 normal subjects. It was defined as the difference between the local kyphosis (or lordosis) of the given subject at the apex and the mean value at the equivalent level for the nonscoliosis subjects. The predictive score was reported with a sensitivity of 89% and a specificity of 84%.	Weak
Karam et al. (13)	Hypokyphosis index was comparable among thoracic, thoracolumbar, and lumbar curve types.	Weak
Begon et al. (2)	Sagittal vertebral wedging (mean 4.48 ± 0.86°) was reported to be present at diagnosis of mild curves. However, this sagittal vertebral wedging did not increase with Cobb angle.	Weak
Scherrer et al. (20)	Sagittal wedging was observed to result in a hypokyphosis pattern, which increased as coronal Cobb angle increased. Wedging was also reported to be greater at inferior levels of curves.	Weak

Vergari et al. (27)	Vertebral and disc wedging were both measured, and wedging was reported to be greater at lower junctional discs.	Weak

Table vi. Axial parameters.

Study	Key findings	Strength of evidence
Skalli et al. (21)	A severity index including torsion and AVR for predicting progression was validated on 65 subjects with 89% sensitivity and 84% specificity.	Moderate
Courvoisier et al. (5)	(1) Torsion index was generally comparable between T and L curves. (2) Prediction analysis showed that torsion index, followed by AVR and IAR were the best predictors of progression. Cut-off were generated. For the torsion index, a threshold of 3.7 gives a SN of 81 % and a specificity of 81 %. It was also noted that Cobb angle had poor predictive power for progression (AUC = 0.74 [0.63 to 0.85]).	Moderate
Wang et al. (31)	A deep learning model was used to predict progression at the first visit, and was validated on 162 subjects with an accuracy of 76.6%. Spinal parameters were analysed combining the training and testing cohort. At first visit, the progressive group had higher AVR (7.3 ± 4.9° vs 4.3 ± 3°) and torsion (6.1 ± 3° vs 3.3 ± 2.1°), while Cobb, TK, and LL were comparable to non-progressive subjects.	Moderate
Karam et al. (13)	Only up to 60% (R^2) of the axial deformity could be determined by the frontal deformity. While TL curves had the highest AVR, T curves had the highest torsion index, characterised by highest upper and lower IAR. T curves also had the largest Cobb angle and stronger association between 3D parameters.	Moderate
Nault et al. (17)	A general linear model was applied to 172 subjects to predict final 3D Cobb angle. The adjusted R^2 was 0.618, and plane of maximum curvature was identified as a significant predictor, among curve type, skeletal maturity, and coronal disc wedging. Torsion and AVR were not applied to the model due to having weak to moderate correlations with final Cobb angle.	Moderate
Nault et al. (16)	The progressive group had higher initial angle of plane of maximum curvature (mean 63.5° vs 51.4°, p = 0.001), torsion (mean 4.5° vs 3.1°, p=0.02), and AVR (mean 8.1° vs 5.7°, p=0.006).	Moderate
Fitzgerald et al. (7)	Comparing Lenke 1AR and 1AL curves, 1AR curves had greater thoracic AVR (21 ± 6° vs. 14 ± 6°) and smaller lumbar AVR (1 ± 5° vs. 6 ± 5°). To correlate this with other planes, 1AR curves generally had more distal thoracic and lumbar curve apices. While the two curve types had comparable thoracic Cobb and TK, 1AR curves had smaller TL/L Cobb angle.	Moderate

Karam et al. (14)	Frontal malignment (OD-HA) was most significant in Lenke 5-6 subjects (i.e., TL curves), and was associated with higher torsion and AVR. While multivariate analysis showed that OD-HA was partly attributable to AVR and curve type, the overall statistical relationship was weak (adjusted R^2 = 0.22).	Moderate
Kadoury et al. (10)	High torsion in transitional zones were correlated with highly angulated plane of maximum curvature, reflecting the large change in curve orientation. This was particularly significant in double major curves.	Moderate
Almansour et al. (1)	While there were no statistically significant pre- to in-brace changes in AVR and torsion for thoracic and lumbar curves, a mean 30% de-rotation (mean 4.4 ± 4.2° decrease in AVR) was noted in thoracolumbar curves. It should be noted that TL curves had the highest pre-brace AVR, while T curves had the highest pre-brace torsion. Though the average time between pre- and in-brace radiographs in this study was 4 months, the results suggest a need for overall improvement in 3D design of Chêneau-type braces.	Moderate
Courvoisier et al. (4)	Out-of-brace and in-brace (Boston brace) spinal parameters were compared 1 hour apart. Only 50% of patients had improvement in Cobb angle. Flattening of TK was observed in 27%. AVR remained unchanged in 51%, improved > 5° in 26%, and worsened in 23%. Torsion remained unchanged in 73%, suggesting that in cases where AVR was changed, the spine was globally rotated without intervertebral rotation.	Moderate
Vergari et al. (26)	A severity index for predicting progression was validated on 55 subjects with 92% sensitivity and 78% specificity. In the first radiographs, the progressive group had lower Risser, large Cobb angle, lower HI, lower torsion index and higher AVR.	Moderate
Thenard et al. (23)	IAR and torque were highest at the junctional vertebrae and lowest at the apex.	Moderate

Table vii. Machine learning methods.

Study	Description of geometric model	Extraction of predictors	Prediction model	Prediction model
Garcia-Cano et al. (8)	1994 Scoliosis Research Society reference frame	Independent component analysis (ICA) vs autoencoders	Random forest (RF) model with two prediction schemes compared. Scheme A, which based on 3D shape from the last visit, was less accurate than Scheme B, which were based on 3D shapes of all prior visits.	RMSE of MT Cobb angle using ICA and scheme B: 5.18°
Kadoury et al. (11)	Automated vertebral detection technique based on interpolation theory	Discriminant manifold modelling	Probabilistic classification model compared against SVM (nonlinear RBF kernel), a locally linear embedding (LLE) model and a locally linear latent variable model (LL-LVM).	Proposed model: SN=87.9%, SP=75.3%, AUC=0.85

Skalli et al. (21)	1994 Scoliosis Research Society reference frame	Selected based on existing literature	An unspecified linear combination of the above predictors was computed on patients to mild curves to obtain the probability of progressing to curves of varying severity.	SN=89%, SP=84%
Vergari et al. (26)	1994 Scoliosis Research Society reference frame	Selected based on existing literature	As above (different reconstruction algorithm, different training and testing data)	SN=92%, SP=74%
Drevelle et al. (6)	FEM model	Selected based on existing literature	Mechanical modelling applied with gravity and variation in disc stiffness.	N/A
Nault et al. (32)	N/A	Selected based on correlation to outcome	A general linear model was used to predict final Cobb angle	Adjusted R^2 = 0.618 Mean standard error = 2.3 ± 0.3°

Table vii. Details of included 3D parameters.

For studies utilizing the Scoliosis Research Society (SRS) 3D reporting system, all 3D parameters were expressed on a vertebral plane ('the patient plane') which traverses the centres of the acetabula of the patient.

Cobb angle (°)	This refers to the coronal angle between two lines normal to the superior and inferior vertebral endplates of a curve. Nault et al. (16, 17)measured Cobb angle both in the frontal plane and in the plane where the Cobb angle is maximal.
Coronal vertebral wedging (°)	Wedging is measured for all vertebrae. According to Vergari et al. (27), vertebral endplates are defined as planes using least square regression. Coronal wedging is calculated by measuring the angle between endplates' normal vectors projected on the coronal plane.
Coronal tilt	According to Almansour et al (1), this was defined as the coronal angle between the normal vector of each vertebra and the horizontal plane.
Thoracic kyphosis (TK) (°)	According to Fitzgerald et al. (7) and Nault et al. (16, 17), this refers to the sum of kyphosis of each individual vertebra and disc between T5 and T12, after axial derotation of all vertebrae.

	According to Pasha et al. (19), this refers to the angle between the normal vectors of the superior endplate of T1 and the inferior endplate of T12, based on the Cobb method.
Sagittal vertebral wedging (°)	According to Vergari et al. (27), vertebral endplates are defined as planes using least square regression. Sagittal wedging is calculated by measuring the angle between endplates' normal vectors projected on the sagittal plane. According to Scherrer et al. (20), for each vertebra, a smallest edge (SE) is measured on the posterior face of the vertebral body on the concave side of the scoliotic curve. Another anterior line is drawn on the same side of the smallest edge. Two spatial angles are obtained from joining lines between the two edges. Sagittal wedging is calculated as the sum of the two spatial angles subtracted by 180°.
'Hypokyphosis index'	Vergari et al. (21, 28) defined this as the difference between the kyphosis measured from the vertebrae immediately adjacent to the apex (i.e. apex+1 and apex-1) and the same value computed at the same value in their cohort of asymptomatic subjects.
Lumbar lordosis (LL) (°)	According to Fitzgerald et al. (7), this refers to the sum of lordosis of each individual vertebra and disc between L1 and L5, after axial derotation of all vertebrae. According to Pasha et al. (19), this refers to the angle between the normal vectors of the superior endplate of L1 and the superior endplate of S1, based on the Cobb method.
Apical vertebral rotation (AVR) (°)	This was commonly defined as the rotation of the apical vertebra in the patient plane. Clockwise rotation was defined as positive.
Intervertebral rotation at the upper junctional zone (upper IAR) (°)	Almansour et al. (1) and Courvoisier et al. (4) defined this as the axial rotation of the upper vertebra in the plane of the lower vertebra at the upper neutral zone, as described by Perdriolle et al. (33).
Intervertebral rotation at the lower junctional zone (lower IAR) (°)	Almansour et al. (1) and Courvoisier et al. (4) defined this as the axial rotation of the upper vertebra in the plane of the lower vertebra at the lower neutral zone, as described by Perdriolle et al. (33).

Torsion index (°)	This was generally defined as the mean of the two sums of IAR from the lower junction to the apex, and from the apex to the upper junction, as described by Steib et al. (16, 17, 34). Karam et al. (13) and Vergari et al. (28, 29) defined this as the mean of the sums of the intervertebral axial rotations within the scoliotic segment. Kadoury et al. (10) defined torsion index based on weighted least squared fitting, i.e. by fitting a circle to sample points within a curve. Torsion is obtained by the inverse of the radius of the fitted circle.
Angle of the plane of the maximum curvature (POMC) (°)	According to Nault et al. (16, 17), this is defined as the axial angle of the plane in which the Cobb angle is maximal.

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