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REVIEW ARTICLE

Patient and surgical predictors of 3D correction in posterior spinal fusion: a systematic review

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Abstract

Background Restoration of three-dimensional (3D) alignment is critical in correcting patients with adolescent idiopathic scoliosis using posterior spinal fusion (PSF). However, current studies mostly rely on 2D radiographs, resulting in inaccurate assessment of surgical correction and underlying predictive factors. While 3D reconstruction of biplanar radiographs is a reliable and accurate tool for quantifying spinal deformity, no study has reviewed the current literature on its use in evaluating surgical prognosis.

Purpose To summarize the current evidence on patient and surgical factors affecting sagittal alignment and curve correction after PSF based on 3D parameters derived from reconstruction of biplanar radiographs.

Methods A comprehensive search was conducted by three independent investigators on Medline, PubMed, Web of Science, and Cochrane Library to obtain all published information on predictors of postoperative alignment and correction after PSF. Search items included "adolescent idiopathic scoliosis," "stereoradiography," "three-dimensional," "surgical," and "correction." The inclusion and exclusion criteria were carefully defined to include clinical studies. Risk of bias was assessed with the Quality in Prognostic Studies tool, and level of evidence for each predictor was rated with the Grading of Recommendations, Assessment, Development, and Evaluations approach. 989 publications were identified, with 444 unique articles subjected to full-text screening. Ultimately, 41 articles were included.

Results Strong predictors of better curve correction included preoperative normokyphosis (TK > 15°), a corresponding rod contour, intraoperative vertebral rotation and translation, and upper and lower instrumented vertebrae selected based on sagittal and axial inflection points. For example, for Lenke 1 patients with junctional vertebrae above L1, fusion to NV-1 (1 level above the neutral vertebra) achieved optimal curve correction while preserving motion segments. Pre-op coronal Cobb angle and axial rotation, distal junctional kyphosis, pelvic incidence, sacral slope, and type of instrument were identified as predictors with moderate evidence. For Lenke 1C patients, > 50% LIV rotation was found to increase spontaneous lumbar curve correction. Pre-op thoracolumbar apical translation and lumbar lordosis, Ponte osteotomies, and rod material were found to be predictors with low evidence.

Conclusions Rod contouring and UIV/LIV selection should be based on preoperative 3D TK in order to achieve normal postoperative alignment. Specifically, Lenke 1 patients with high-lying rotations should be fused distally at NV-1, while hypokyphotic patients with large lumbar curves and truncal shift should be fused at NV to improve lumbar alignment. Lenke 1C curves should be corrected using > 50% LIV rotation counterclockwise to the lumbar rotation. Further investigation should compare surgical correction between pedicle-screw and hybrid constructs using matched cohorts. DJK and overbending rods are potential predictors of postoperative alignment.

Keywords Adolescent idiopathic scoliosis · Stereoradiography · Three-dimensional · Surgical · Posterior spinal fusion

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Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformity that can progress if untreated, causing chronic back pain and significant pulmonary impairment

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[1–7]. Generations of surgical procedures have aimed at correcting the frontal curve and truncal deformity while maintaining spinopelvic alignment [8–16]. As 40–46% of all AIS patients are hypokyphotic, special attention should be paid to restoring sagittal balance in these patients, with studies supporting that failure to restore thoracic kyphosis (TK) may predispose to proximal or distal junctional kyphosis, as well as late complications predisposing to future decompensation [17–21]. While pedicle-screw systems have been shown to demonstrate efficacious correction in the frontal and axial planes by the placement of powerful anchors, they have been shown to cause flattening of the sagittal spine [22–24].

To evaluate and improve postoperative correction, numerous factors have been extensively investigated using conventional 2D radiographs, with mixed consensus within the current literature regarding the difference in surgical correction from different factors [25–29]. Prior studies have shown such relationship with patient-related factors including preoperative curve magnitude and flexibility, and with surgical factors including implant density, fusion length, and the type of instrument and technique used, such as differential rod contouring, direct vertebral rotation, and Ponte osteotomies [30–39].

As many of the studies compared surgical correction rates using plain radiographs, the true deformity of the spine has been inaccurately evaluated. Notably, 2D thoracic kyphosis (TK) has been shown to be variably overestimated on 2D radiographs by an average of 10° due to technical difficulty in visualizing thoracic endplates and the varying magnitude of axial rotation among patients [40–46]. Due to vertebral rotation in the transverse plane, lateral radiographs do not allow for a true lateral assessment of the sagittal plane [41, 47]. In addition, while axial rotation causes rib hump deformity, it is often inaccurately assessed by the Nash–Moe method on 2D which results in a mean 8–10° error [48, 49]. Moreover, prior studies have shown statistically significant differences in 2D and 3D Cobb angles due to pelvic rotation. With increasing focus placed on tridimensional alignment, there comes a need for more accurate methods in quantifying spinal deformity, so as to improve rod contouring and selection of end-instrumented vertebrae to be better aligned to the true morphology of the spine [50, 51].

In recent years, three-dimensional reconstruction of biplanar radiographs has emerged as a method that allows accurate measurement of axial rotation and adjustment for axial rotation for a more accurate evaluation of the spine in its true planes [52–58]. After manual localization of the T1-L5 vertebral bodies, 3D spinal parameters will be automatically calculated with normalization of patient rotation. Notably, changes in 3D TK, wedging, intervertebral rotation, and orientation of the plane of maximum curvature are parameters unique to 3D reconstruction and may act as outcome variables to reflect the 3D morphology of the spine more accurately [59–64]. Therefore, this study aims to summarize the patient and surgical factors affecting three-dimensional correction after posterior spinal fusion (PSF) based on reconstruction of biplanar radiographs.

Methods

Literature search strategy and selection criteria

The protocol for this systematic review has been registered in PROSPERO (CRD42022373484) on 23/11/2022 [65]. The literature search and reporting of results in this review were conducted in accordance with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines [66]. An extensive search was performed on the following databases: PubMed, Web of Science, MEDLINE, and Cochrane Library. All fields were searched in the databases using the following keywords: "adolescent idiopathic scoliosis," "stereoradiography," "reconstruction," "three-dimensional," "surgical," "correction," "postoperative," and "junctional kyphosis." Detailed search items are included in Supplementary Material.

The search was limited to publications from 2010 to 2022 to exclude surgical techniques that are rarely used currently. The inclusion criteria included randomized controlled trials, cohort studies, case–control studies, and case series reporting predictors of postoperative alignment and surgical correction based on 3D reconstruction of biplanar radiographs. To maximize overall sample size, studies using validated algorithms to estimate 3D T4-T12 kyphosis based on biplanar radiographs were also included [41, 67]. The exclusion criteria included studies involving anterior spinal fusion, non-English publications, case reports, biomechanical studies, non-human or cadaveric studies, and studies with a sample size < 20. Studies evaluating thoracic volume and lung function were excluded since this was beyond the scope of this systematic review.

The search and screening process were conducted by three independent investigators (SW, ST, DW). Potentially relevant abstracts were screened based on the inclusion criteria, and full-text articles were obtained for eligible results. Three investigators discussed any disagreements regarding accepting full-text articles until consensus was achieved. References of each article were screened to look for potentially relevant studies.

Data extraction and critical appraisal

The primary outcome of this systematic review was the effects of patient-related predictors and surgery-specific predictors on 3D curve correction after PSF.

Patient-related predictors included preoperative 3D radiographic measurements, which included Cobb angle, thoracic kyphosis and lumbar lordosis, axial vertebral rotation, pelvic parameters, vertebral tilt and translation, and junctional kyphosis. Surgery-specific predictors included the type of instrument used, selection of upper instrumented vertebra (UIV) and lower instrumented vertebra (LIV), rod contouring, rod material, and number of Ponte osteotomies.

The amount of 3D curve correction was defined by intraoperative correction (preoperative to first standing postoperative X-ray) and spontaneous changes between follow-up visits. The parameters included changes in Cobb angle, thoracic kyphosis, axial rotation, pelvic parameters, and proximal junctional kyphosis in the fused and unfused spine. In addition, shoulder-height difference was included, as well as global sagittal alignment, as measured using sagittal vertical axis (SVA), the distance between the center of T1 and the central hip vertical axis (T1–CHVA), and odontoid-hip angle (OD-HA).

Details regarding each study's sample size, design, inclusion criteria, predictors identified, radiological definition of novel 3D parameters, risk of bias, phase of inquiry, and level of evidence are recorded in Table 1.

Risk of bias

The risk of bias of these publications was assessed using the six domains of the Quality in Prognostic Studies (QUIPS) tool by the three independent reviewers, and consensus was reached after discussion [68]. For retrospective studies, bias due to attrition is not applicable and therefore not assessed. The QUIPS risk of bias for these studies is detailed in Table 2.

Grading of evidence

The quality of evidence for each factor included was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach by the three independent reviewers [69]. Factors with evidence mainly coming from confirmatory studies were initially assigned with a high level of evidence, while factors with evidence mainly coming from exploratory studies were assigned a moderate level of evidence. The quality of evidence was downgraded by one level according to the following criteria: inconsistency, imprecision, indirectness, and publication bias. The quality of evidence was upgraded by one level for the following cases: strong evidence of association between independent variables and outcomes, evidence of dose–response gradient, and when all residual confounding was shown to reduce the demonstrated effect. The detailed evidence available for each factor and the GRADE quality of evidence rating is presented in Table 3.

Search results

The search results are illustrated in the PRISMA flowchart (Fig. 1). A total of 985 articles were yielded from the initial search, of which 253 articles were from Medline, 376 articles from Web of Science, 46 articles from Cochrane library, and 310 articles were from PubMed. Of the 985 articles, there were 545 duplicated articles, and 440 unique articles were screened for the inclusion and exclusion criteria. As a result, a total of 36 articles from 34 datasets were included in the final study for further analysis.

Among the 36 publications included, 18 were classified as confirmatory studies, and 18 were classified as exploratory studies. In terms of study design, 31 were retrospective cohort studies, 5 were retrospective case–control studies, and there were no cross-sectional studies or randomized controlled trials. The mean age of subjects across studies ranged from 10 to 21 years, and the length of follow-up ranged from 12 months to 2.4 years. Sample sizes of studies ranged from 20 to 1063 subjects.

Results

Patient-related predictors

For studies reporting patient-related predictors of 3D correction, the earliest study was published in 2016 [60], and the instrumentation was all pedicle-screw constructs.

Sagittal alignment

There is strong evidence that preoperative thoracic kyphosis affects 3D curve correction. In a multivariate analysis of 371 subjects, Pasha et al. [70, 71] found that preoperative clusters, which shared significant differences in TK, predicted three clusters of 3D surgical outcomes with an accuracy of 64%. Regarding global alignment, Yeung et al. [72] reported that hypokyphotic patients had adopted a more forward-leaning posture to compensate for global sagittal imbalance (indicated by SVA-SFD and sagittal OD-HA) compared to normokyphotic adolescent idiopathic scoliosis (AIS) subjects. However, this improved from immediate post-op to the 2-year postoperative follow-up. However, there is limited strength of evidence as there were only 7 hypokyphotic subjects in the whole cohort. There is moderate evidence that distal junctional kyphosis (DJK), pelvic incidence (PI), and sacral slope (SS) affect postoperative curve magnitude and alignment from a study by Pasha et al. [71]. For lumbar lordosis and thoracolumbar apical translation, which were also identified in the same study, there is low evidence that

Table 1 Details of included studies, including study design, sample size, inclusion criteria, the morphological predictors found, risk of bias, and the level of evidence

Study	Year	Study design	Sample size	Inclusion criteria	Morphological predictors found	Risk of bias	Phase of inquiry	Level of evidence
Abousamra et al. [1]	2019	RCS	837 AIS	(1) Lenke I and Lenke II; (2) Received tranexamic acid	N/A	Low	Exploratory	Prognostic level III
Alzakri et al. [2]	2019	RCS	85 AIS + 51 controls	1) Age 12–18 at time of surgery; (2) All-pedicle screw constructs	N/A	Low	Exploratory	Prognostic level III
Bodendorfer et al. [3]	2020	RCCS	1063 AIS	(1) Lenke types 1–4; 2) Preoperative thoracic hypokyphosis (< 10°)	Instrument systems	Low	Confirmatory	Prognostic level III
Ferrero et al. [4]	2018	RCS	47 AIS	(1) Posteromedial translation with lumbar pedicular screws, thoracic sublaminar bands, and proximal claws; (2) 5.5 CoCr rods; (3) No Ponte osteotomies	N/A	Low	Exploratory	Prognostic level III
Floccari et al. [5]	2021	RCCS	68 AIS	(1) Ages 10–18; (2) ≥ 2 Ponte osteotomies for P cohort	Ponte osteotomies	Low	Confirmatory	Prognostic level III
Homans et al. [6]	2020	RCS	60 AIS	AIS Lenke 1–6	Surgically corrected UIV position	Low	Confirmatory	Prognostic level III
Ilharreborde et al. [7]	2011	RCS	24 AIS	(1) Lenke 1 and 2; (2) All-pedicle screw constructs vs hybrid constructs	N/A	Low	Confirmatory	Prognostic level III
Ilharreborde et al. [8]	2013	RCS	49 AIS	(1) Lenke 1–4; (2) Posteromedial translation with lumbar pedicular screws and thoracic universal clamps, 5.5 mm Ti rods	N/A	Moderate	Exploratory	Prognostic level III
Ilharreborde et al. [9]	2013	RCS	49 AIS	1) Lenke 1–4; 2) Posteromedial translation with lumbar pedicular screws and thoracic universal clamps, 5.5 mm Ti rods	N/A	Moderate	Exploratory	Prognostic level III
Ilharreborde et al. [10]	2018	RCS	35 AIS	1) Lenke 1–2; 2) Thoracic hypokyphosis (T4-T12 < 15°); (3) Posteromedial translation with lumbar pedicular screws and thoracic sublaminar bands, 5 mm CoCr vs 5 mm Ti rods, no Ponte osteotomies	Rod material	Low	Exploratory	Prognostic level III
Ilharreborde et al. [11]	2019	RCS	60 AIS	(1) Lenke 1–2; (2) Posteromedial translation with pedicular screws, thoracic sublaminar bands, and proximal hooks, 5.5 CoCr rods, no Ponte osteotomies	N/A	Low	Confirmatory	Prognostic level III
Illés et al. [12]	2013	RCS	95 AIS	(1) Lenke 1–6; (2) CD instrumentation (hook and screw) with in situ contouring	Lateral translation of apical vertebral	Moderate	Exploratory	Prognostic level III
Jankowski et al. [13]	2018	RCS	55 AIS	AIS Lenke 1–6	N/A	Low	Exploratory	Prognostic level III
Jiang et al. [14]	2021	RCS	31 AIS	AIS Lenke 1–5	N/A	Low	Exploratory	Prognostic level III

Table 1 (continued)

Study	Year	Study design	Sample size	Inclusion criteria	Morphological predictors found	Risk of bias	Phase of inquiry	Level of evidence
Kato et al. [15]	2017	RCCS	153 AIS	1) Direct vertebral rotation; (2) All-screw construct vs hybrid constructs; 3) Ti or SS rods	All-screw vs hybrid construct; Rod material	Low	Exploratory	Prognostic level III
Kluck et al. [16]	2020	RCS	99 AIS	(1) AIS right MT curve; 2) Direct vertebral rotation, all-screw construct, 5.5 mm SS rods, Ponte osteotomies as needed; 3) No in situ rod bending	Rod contour	Low	Confirmatory	Prognostic level III
Kluck et al. [17]	2021	RCS	84 AIS	(1) AIS Lenke 1–4, with B or C modifier; (2) LIV ≤ L1	(For correction of unfused lumbar curve:) LIV tilt, thoracic coronal correction, restoration of TK	Low	Confirmatory	Prognostic level III
Le Navéaux et al. [18]	2017	RCS	35 AIS	(1) Lenke 1–3; (2) Direct vertebral rotation; 3) All-screw construct with 5.5 mm CoCr rods	Rod contour	Low	Confirmatory	Prognostic level III
Le Navéaux et al. [19]	2017	RCCS	42 AIS	(1) Lenke 1; (2) Pedicle screw > 80%; (3) Ti vs SS vs CoCr rods (5 mm)	Rod material	Low	Confirmatory	Prognostic level III
Machida et al. [20]	2022	RCS	66 AIS	(1) Lenke 1–6; (2) Age < 18 at time of surgery; (3) 5 mm SS vs CoCr rods	(For shoulder balance at 2-year FU:) Post-op Cobb and AVR	Low	Confirmatory	Prognostic level III
Newton et al. [21]	2015	RCS	120 AIS	(1) AIS with primary thoracic curves; (2) Segmental uniplanar pedicle-screw fixation, 5.5 mm SS rods, and segmental derotation	N/A	Low	Confirmatory	Prognostic level III
Newton et al. [22]	2019	RCS	134 AIS	(1) Lenke 1–4; (2) 5 mm SS vs CoCr rods	Operating surgeon, rod material, and Ponte osteotomies	Low	Confirmatory	Prognostic level III
Ohashi et al. [23]	2020	RCS	405 AIS	(1) Right main thoracic (Lenke 1–4); 2) Cobb angle > 45°	N/A	Low	Exploratory	Prognostic level III
Pasha et al. [24]	2017	RCS	21 AIS	1) Thoracic curves with B or C modifiers; (2) Direct vertebral rotation with all-screw constructs	(For correction of unfused lumbar curve:) post-op thoracic and lumbar Cobb and lumbar AVR	Low	Exploratory	Prognostic level III
Pasha et al. [25]	2018	RCS	64 AIS	1) Lenke 1–2; 2) Age 10–18 at time of surgery; 3) Selective thoracic fusion with segmental derotation	Pre-op coronal, sagittal, and axial parameters	Low	Exploratory	Prognostic level III
Pasha et al. [26]	2018	RCS	63 AIS	(1) Lenke 1; (2) Age 10–18 at time of surgery; 3) Selective thoracic fusion with segmental derotation	(For correction of unfused lumbar curve:) preoperative ratio of the thoracic to lumbar apical translation in the sagittal plane	Low	Confirmatory	Prognostic level III

Table 1 (continued)

Study	Year	Study design	Sample size	Inclusion criteria	Morphological predictors found	Risk of bias	Phase of inquiry	Level of evidence
Pasha et al. [27]	2018	RCS	23 AIS	(1) Lenke 1; (2) Age 10–18 at time of surgery; 3) Selective thoracic fusion with segmental derotation	% correction of LIV rotation	Low	Confirmatory	Prognostic level III
Pasha et al. [28]	2019	RCS	76 AIS	(1) Lenke 1–5; (2) Direct vertebral rotation	Pre-op 3D cluster, UIV and LIV	Low	Confirmatory	Prognostic level III
Pasha et al. [29]	2019	RCS	58 AIS	(1) Lenke 1 with B or C modifier; (2) Ages 13–17 at time of surgery; (3) Selective thoracic fusion	N/A	Low	Exploratory	Prognostic level III
Pasha et al. [30]	2021	RCS	371 AIS	Lenke 1–6	Pre-op coronal, sagittal, and axial parameters	Low	Confirmatory	Prognostic level III
Pasha et al. [31]	2021	RCS	371 AIS	Lenke 1–6	Pre-op coronal, sagittal, and axial parameters; Operating surgeon, UIV and LIV selection	Low	Confirmatory	Prognostic level III
Seoud et al. [32]	2015	RCS	25 AIS	Lenke 1A	Surgical technique (derotation maneuver)	Moderate	Exploratory	Prognostic level III
Shen et al. [33]	2016	RCS	93 AIS	Right Lenke 1	Preoperative torsion	Low	Exploratory	Prognostic level III
Sikora-Klak et al. [34]	2021	RCCS	82 AIS	Lenke 1–2	Segmental vertebral rotation with all-screw construct, vs posteromedial translation with sublaminar bands	Moderate	Confirmatory	Prognostic level III
St-Georges et al. [35]	2020	RCS	20 AIS	(1) Lenke 1–6; (2) Age 10–18 at time of surgery	Preoperative Cobb angle	Low	Exploratory	Prognostic level III
Yeung et al. [36]	2021	RCS	27 AIS + 36 controls	(1) Female AIS with right thoracic main curve	Preoperative TK	Low	Exploratory	Prognostic level III

Table 2 Quality in Prognostic Studies risk of bias based on study participation, measurement of prognostic factor and outcomes, study confounding, and quality of statistical analysis and reporting. 31 studies had a low overall risk of bias, while 5 studies had a moderate risk of bias

Study	Study participation	Study attrition	Prognostic factor measurement	Outcome measurement	Study confounding	Statistical analysis and reporting	Overall risk of bias
Abousamra et al. [1]	Low	N/A	Low	Low	Low	Low	Low
Alzakri et al. [2]	Low	N/A	Low	Low	Low	Low	Low
Bodendorfer et al. [3]	Low	N/A	Low	Low	Low	Moderate	Low
Ferrero et al. [4]	Moderate	N/A	Moderate	Low	Low	Low	Low
Floccari et al. [5]	Low	N/A	Low	Low	Low	Low	Low
Homans et al. [6]	Low	N/A	Low	Low	Low	Low	Low
Ilharreborde et al. [7]	Moderate	N/A	Low	Low	Low	Low	Low
Ilharreborde et al. [8]	Moderate	N/A	Low	Low	Low	Moderate	Moderate
Ilharreborde et al. [9]	Moderate	N/A	Low	Low	Low	Moderate	Moderate
Ilharreborde et al. [10]	Moderate	N/A	Low	Low	Low	Low	Low
Ilharreborde et al. [11]	Low	N/A	Low	Low	Low	Low	Low
Illés et al. [12]	Low	N/A	Moderate	Low	Low	Moderate	Moderate
Jankowski et al. [13]	Low	N/A	Low	Low	Low	Low	Low
Jiang et al. [14]	Low	N/A	Low	Low	Low	Moderate	Low
Kato et al. [15]	Low	N/A	Low	Low	Low	Low	Low
Kluck et al. [16]	Low	N/A	Low	Low	Moderate	Low	Low
Kluck et al. [17]	Low	N/A	Low	Low	Low	Low	Low
Le Navéaux et al. [18]	Moderate	N/A	Low	Low	Low	Low	Low
Le Navéaux et al. [19]	Moderate	N/A	Moderate	Low	Low	Low	Low
Machida et al. [20]	Low	N/A	Low	Low	Low	Low	Low
Newton et al. [21]	Low	N/A	Low	Low	Low	Low	Low
Newton et al. [22]	Low	N/A	Low	Low	Low	Low	Low
Ohashi et al. [23]	Low	N/A	Low	Low	Moderate	Low	Low
Pasha et al. [24]	Moderate	N/A	Low	Low	Low	Low	Low
Pasha et al. [25]	Low	N/A	Low	Low	Low	Low	Low
Pasha et al. [26]	Low	N/A	Low	Low	Low	Low	Low
Pasha et al. [27]	Moderate	N/A	Low	Low	Low	Low	Low
Pasha et al. [28]	Low	N/A	Low	Low	Low	Low	Low
Pasha et al. [29]	Low	N/A	Low	Low	Low	Low	Low
Pasha et al. [30]	Low	N/A	Low	Low	Low	Low	Low
Pasha et al. [31]	Low	N/A	Low	Low	Low	Low	Low
Seoud et al. [32]	Moderate	N/A	Low	Low	Moderate	Moderate	Moderate
Shen et al. [33]	Low	N/A	Low	Low	Moderate	Low	Low
Sikora-Klak et al. [34]	Low	N/A	Low	Moderate	Moderate	Low	Moderate
St-Georges et al. [35]	High	N/A	Low	Low	Low	Low	Low
Yeung et al. [36]	Moderate	N/A	Low	Low	Low	Moderate	Low

Table 3 Patient-related and surgical predictors included in the study, with key findings from respective studies and the attributed strength of evidence for each parameter

Predictors	Study	Population	Key findings	Strength of evidence
Type of instrumentation	Ilharreborde et al. [37]	Hypokyphotic	Using posteromedial translation with hybrid constructs, a mean T4–T12 gain of 14.5° ± 10° and a mean C2–C6 kyphosis decrease of 18.8° ± 10° were reported, which was maintained from post-op to the 2-year follow-up visit. At latest follow-up, 94% of the patients were normokyphotic and 67% had a CSA in the physiological range. Sagittal balance of the thoracolumbar spine was not significantly modified after curve correction. For global balance, C2–CHVA increased from − 12 mm preoperatively to 1 mm postoperatively, but returned to preoperative values at final follow-up	High
	Ilharreborde et al. [9]	Normokyphotic and hypokyphotic	Using posteromedial translation with hybrid constructs, mean T4-T12 kyphosis increased by 18.8° ± 9° in the subgroup of hypokyphotic patients, while L1-L5 lumbar lordosis remained unchanged. Mean correction in main thoracic, proximal thoracic, and lumbar curves was 64.4 ± 18, 31 ± 10 and 69 ± 20%, respectively. AVR was significantly reduced from 19.9 ± 7° to 11 ± 6°	
	Ilharreborde et al. [10]	Hypokyphotic	Using sublaminar bands with hybrid constructs, T4-T12 thoracic kyphosis increased by 8 ± 7° on average, but 11 patients (31.4%) still remained hypokyphotic (T4T12 < 10°)	
	Ilharreborde et al. [11]	Normokyphotic	Using sublaminar bands with hybrid constructs, mean T4-T12 kyphosis was maintained in 74% of subjects. Sagittal location of the UIV was maintained after surgery. Mean AVR was significantly reduced from 19 ± 6° to 11 ± 5°	
	Illés et al. [38]	Normokyphotic and hypokyphotic	In patients treated with CD instrumentation, mean thoracic Cobb angle was reduced from 49.4° to 16.8°, while T4-T12 kyphosis was changed from 28.4 ± 16.1° to 31.2 ± 9.9°	
	Kato et al. [15]	Normokyphotic	Axial correction was reported to be greater in all-screw constructs than in hybrid constructs (55% vs. 36%, P = 0.03)	
	Sikora-Klak et al. [34]	Hypokyphotic	In a two-center comparison between screw and band constructs, the screw cohort achieved better coronal correction (76% vs 61%, p < 0.001). A significantly higher degree of postoperative T5-T12 TK was also observed (27 ± 5 vs 14 ± 8, p < 0.001) in the screw cohort, though the screw cohort had a higher baseline T5-T12 TK (7 ± 12 vs 2 ± 14, p < 0.05)	

Table 3 (continued)

Predictors	Study	Population	Key findings	Strength of evidence
Thoracic kyphosis	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	9 preoperative clusters based on 3D spinal parameters were able to predict postoperative clusters in > 50% of cases. Statistically significant differences in thoracic kyphosis were found between the preoperative clusters ($p = 0.030$) and postoperative clusters ($p = 0.033$)	High
	Yeung et al. [36]	Normokyphotic and hypokyphotic	Hypokyphotic patients had a mean 10° lower thoracic kyphosis postoperatively and at final follow-up ($p < 0.05$). They were observed to have a more forward-leaning posture to compensate for global sagittal imbalance (indicated by SVA-SFD and sagittal OD-HA) compared to normokyphotic subjects. However, this improved from post-op to the 2-year follow-up. Coronal Cobb angle, cervical lordosis, lumbar lordosis, and pelvic parameters were also comparable at the 2-year follow-up	
UIV and LIV selection	Pasha et al.[25]	Normokyphotic and hypokyphotic	Following preoperative 3D classification of 64 subjects, fusion levels were significantly associated with 2-year spinal morphology ($\chi 2 = 132.52$, $p = 8.3825e\text{-}11$)	High
	Pasha et al. [28]	Normokyphotic and hypokyphotic	Following preoperative 3D classification of 76 subjects, UIV and LIV selection had different impacts on the surgical outcomes in each of the five subtypes. For example, LIV at T12 in Type 1 and UIV at T2 in Type 2 were associated with improved frontal balance and lower PJK, respectively	
	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, UIV and LIV were identified as predictors of postoperative correction	

Table 3 (continued)

Predictors	Study	Population	Key findings	Strength of evidence
Rod contour	Kluck et al. [16]	Hypokyphotic	The preoperative rod angle difference (concave – convex rod angle) was decreased from 18° to –9° on average after correction maneuvers, with the convex rod generally being more curved than the concave rod post-instrumentation. A novel 3D parameter, the rod-to-spine distance (RSD) was used to quantify rod contour in relation to the scoliotic curve. Thepreoperative RSD moderately correlated with 3D thoracic kyphosis change ($R^2 = 0.633$)	High
	Le Navéaux et al. [18]	Normokyphotic and hypokyphotic	Intra-op correction maneuvers resulted in a significant flattening of concave rods (21° ± 9°) after implantation, such that the pre-insertion concave rod curvature was not predictive of postoperative thoracic kyphosis. In addition, the planes of maximum curvature of both rods were deviated from the sagittal plane after surgical instrumentation. There was a significant association between kyphosis change and the relative concave rod to spine contour (rod curvature to pre-op kyphosis) ($R^2 = 0.58$). A modest positive association was found between the amount of differential deflection performed between the concave and convex rods and the degree of AVR correction ($R^2 = 0.28$; $p < 0.01$)	
Vertebral rotation and translation during surgery	Homans et al. [6]	Normokyphotic and hypokyphotic	A higher PJK angle was associated with a larger anterior shift of UIV during surgical correction ($R^2 = 0.61$) and a more posterior position of UIV at the most recent follow-up ($R^2 = 0.32$)	High
	Illés et al. [38]	Normokyphotic and hypokyphotic	Magnitude of frontal Cobb correction was more dependent on the lateral translation of the apical vertebra ($r = 0.7$) than the apical vertebral rotation ($r = 0.5$)	
	Pasha et al. [41]	Lenke 1C	> 50% correction of LIV rotation correlated to improved 2-year outcomes of spontaneous lumbar Cobb correction ($P < 0.05$). For patients with a B modifier and a pre-op sagittal thoracic to lumbar Cobb ratio of < 1.5, > 50% correction of LIV rotation only had small effects on spontaneous lumbar Cobb correction	
	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, EIV angulation and translation were identified as third- and fourth- strongest predictors of postoperative correction	

Table 3 (continued)

Predictors	Study	Population	Key findings	Strength of evidence
Axial rotation	Machida et al. [42]	Normokyphotic	Preoperative PT AVR was not associated with radiographic shoulder height difference (RSHD), but postoperative PT AVR was weakly associated with RSHD postoperatively and at final follow-up ($r = -0.26$)	Moderate
	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	9 preoperative clusters based on 3D spinal parameters were able to predict postoperative clusters in > 50% of cases. Statistically significant differences in thoracic and lumbar AVR were found between the preoperative clusters and postoperative clusters	
	Shen et al. [33]	Normokyphotic and hypokyphotic	Subjects with higher preoperative torsion had higher post-operative torsion and larger angle of plane of maximum deformity ($p < 0.05$). Postoperative coronal and sagittal parameters were comparable	
Coronal Cobb angle	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	9 preoperative clusters based on 3D spinal parameters were able to predict postoperative clusters in > 50% of cases. Statistically significant differences in PT, MT and TL/L Cobb angle were found between preoperative clusters	Moderate
	Machida et al. [42]	Normokyphotic	Preoperative PT and MT Cobb angle were not associated with postoperative radiographic shoulder height difference (RSHD), but postoperative PT Cobb angle was weakly associated with RSHD ($r = -0.27$)	
Junctional kyphosis	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, distal junctional kyphosis was identified as the top predictor of postoperative correction	Moderate
Pelvic parameters	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, sacral slope and pelvic incidence were identified as second- and fifth- strongest predictors of postoperative correction	Moderate
Thoracolumbar apical translation (preoperative)	Pasha et al. [43]	Lenke B or C modifier	Good spontaneous lumbar correction was associated with lower pre-operative ratio of the thoracic to lumbar apical translation in the sagittal plane ($p < 0.05$)	Low
	Pasha et al. [27]	Lenke B or C modifier	Patients with lumbar modifier C and apical vertebrae translation ratios > 1.5 showed improved lumbar Cobb correction in 2-years when 50% or more LIV rotation correction was achieved surgically	
	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, thoracolumbar apical translation was identified as the eighth-strongest predictor of postoperative correction	

Table 3 (continued)

Predictors	Study	Population	Key findings	Strength of evidence
Ponte osteotomies	Floccari et al. [5]	Hypokyphotic	Ponte osteotomies were reported to provide small radiographic gains in the coronal plane (66.6% vs 58.7%, $p<0.003$) with no improvement in the sagittal plane and no change in truncal rotation	Low
	Newton et al. [22]	Hypokyphotic	Use of Ponte osteotomies was only weakly associated with improved thoracic kyphosis ($p<0.025$, $\eta^2=0.04$)	
Rod material	Newton et al. [22]	Hypokyphotic	TK restoration was moderately associated with the use of SS rods rather than CoCr rods ($p<0.01$, $\eta^2=0.08$)	Low
	Ilharreborde et al. [44]	Hypokyphotic	No significant differences were found between Ti and CoCr rods in terms of 3D outcomes	
	Kato et al. [15]	Normokyphotic and hypokyphotic	No difference in AVR correction was observed between Ti and SS rods	
	Le Navéaux et al. [18]	Normokyphotic and hypokyphotic	Comparing all three rod materials, no significant 3D shape change of the instrumented spine or of the rods was found from 1-week post-op to the 2-year follow-up	
Lumbar lordosis	Pasha et al. [39, 40]	Normokyphotic and hypokyphotic	In a multivariate prediction model, L1-S1 lordosis was identified as the 13th-strongest predictor of postoperative correction, with statistically significant differences between preoperative clusters ($p=0.038$)	Low

these two parameters affect postoperative alignment due to lack of effect size measurement and relatively low variable importance in the predictive model.

Axial rotation

There is moderate evidence that preoperative axial rotation affects surgical correction. The preoperative 3D clusters with high prognostic value reported by Pasha et al. [70] had significant differences in the magnitude of apical vertebral rotation (AVR) and comprised two types of axial projections as viewed from above — lemniscate-shaped and loop-shaped projections, with the former having two significant rotations and the latter only having one significantly rotated curve. Shen et al. [73] reported that patients with higher preoperative torsion showed comparable postoperative coronal Cobb angle, but there were differences in the orientation of the plane of maximum deformity in the thoracolumbar segment between the high and low torsion groups (47.95° vs. 30.03°).

Coronal Cobb angle

There is moderate evidence that preoperative Cobb angle affects surgical correction, as most studies focused on planes with greater difference between 2D and 3D imaging. The preoperative clusters demonstrated by Pasha et al. [70] had statistically significant differences in proximal thoracic (PT), main thoracic (MT), and thoracolumbar/lumbar (TL/L) Cobb angle. Machida et al. [74] reported that postoperative Cobb angle and AVR in the PT curve had small to moderate association with radiographic shoulder height differences up to the 2-year follow-up.

Surgical factors

Type of instrumentation

There is moderate evidence that the instrumentation affects surgical outcomes. Sikora-Klak et al. [75] reported that the use of all-screw instrumentation was associated with significantly better coronal correction and slightly better restoration of TK when compared to hybrid constructs, while Kato et al. [76] reported greater axial correction using all-screw systems. However, both studies did not adjust for preoperative curve parameters, which were unequal between the case–control groups, and other surgical factors were not accounted for.

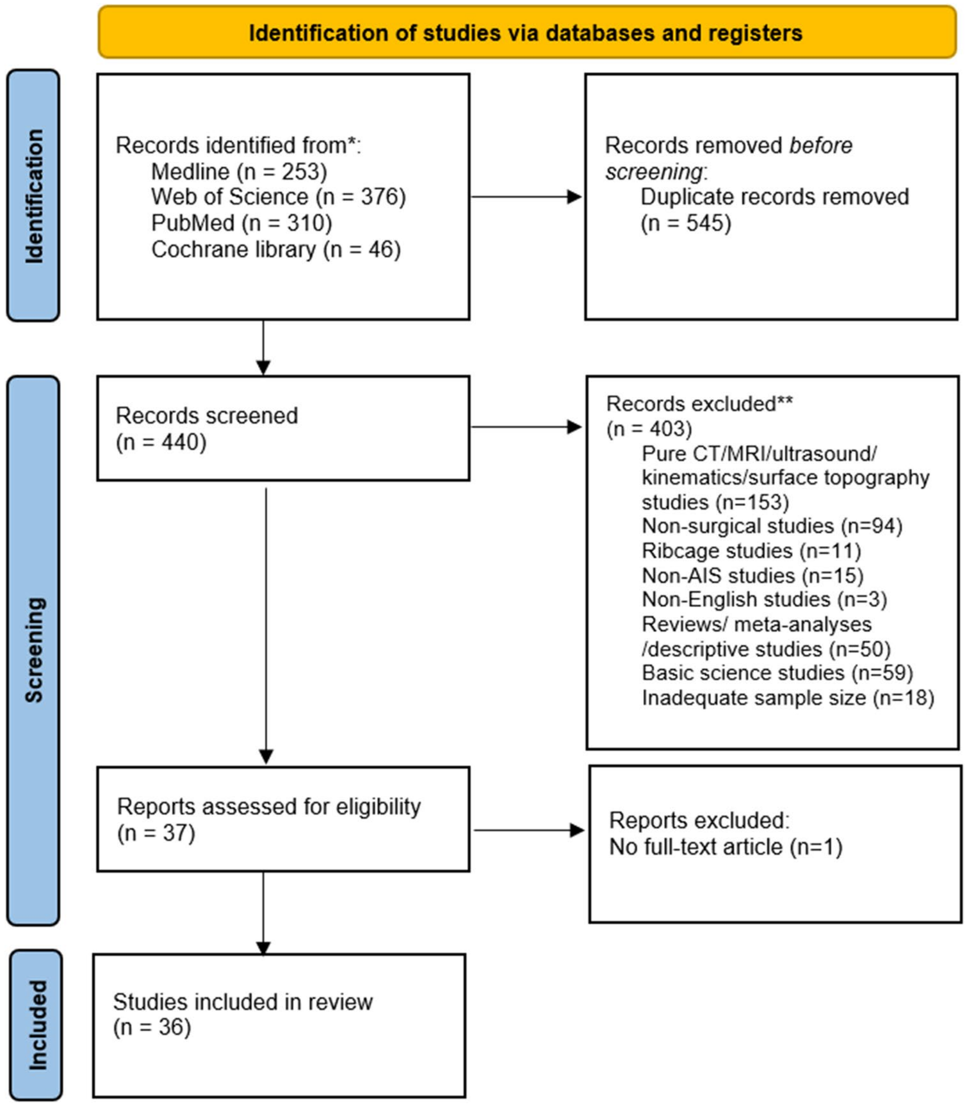

Fig. 1 PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) Flowchart detailing the data screening process. A total of 985 articles were yielded from the initial search, of which 440 unique articles were screened for the inclusion and exclusion criteria. As a result, a total of 36 articles were included in the final study for further analysis

UIV and LIV selection

There is strong evidence that the amount of surgical correction is associated with UIV and LIV selection. Pasha et al. [77] found that following preoperative 3D classification of 76 patients, UIV and LIV selection had different impacts on the surgical outcomes in each of the five subtypes. For example, LIV at T12 in Type 1 and UIV at T2 in Type 2 were associated with improved frontal balance and lower proximal junction kyphosis (PJK), respectively. This association was also found in a larger study of 371 subjects by Pasha et al. [70].

Vertebral tilt and translation

There is strong evidence that the amount of surgical correction is associated with the relative positioning of the apical and end-instrument vertebrae, a function of the degree of translation and derotation during correction. Homans et al. [78] reported that a higher PJK angle was correlated with a larger anterior shift of UIV during surgical correction and a more posterior position of UIV at the most recent follow-up. Regarding selective thoracic fusion in patients with main thoracic curves and lumbar modifiers, Pasha et al. [79] found that in addition to thoracic curve correction, leveling of the LIV (i.e., reducing frontal tilt) was the factor most likely to result in greater 3D correction of the uninstrumented lumbar curve.

Rod material

There is weak evidence that rod material influences 3D surgical correction. Among 10 studies, 5 studies each reported the use of titanium (Ti), stainless steel (SS), and cobalt–chromium (CoCr) rods, respectively. Comparing all three rod materials, Le Navéaux et al. [80] reported that there was no significant 3D shape change of the instrumented spine or of the rods from 1-week post-op to the 2-year follow-up. However, there were only 14 subjects in each group. Ilharreborde et al. [81] also reported no significant differences between Ti and CoCr rods in 3D outcomes in 35 hypokyphotic subjects. In another study of 153 AIS patients by Kato et al. [76], no difference in AVR correction was observed between Ti and SS rods. In a study of 134 AIS patients with severe thoracic lordosis, Newton et al. [82] found that better TK restoration was moderately associated with the use of SS rods rather than CoCr rods ($p < 0.01$, $\eta^2 = 0.08$).

Rod contouring

There is strong evidence that rod shape in relation to spine contour influences surgical correction. To quantify rod contour in relation to the scoliotic curve, Kluck et al. reported a novel 3D parameter, the rod-to-spine distance (RSD), while Le Navéaux et al. [83] measured the difference between rod curvature and kyphosis (°). Both parameters moderately correlated with change in 3D thoracic kyphosis. Le Navéaux et al. [50] reported that pre-insertion concave rod curvature itself was not predictive of postoperative thoracic kyphosis due to rod flattening during instrumentation. In addition, the plane of maximum curvature of the rods deviated from the sagittal plane after surgical instrumentation. This was supported by Kluck et al. [84], who found that preoperative rod angle difference was decreased by 9° on average, with the convex rod generally being more curved than the concave rod post-instrumentation. For axial correction, Le Navéaux et al. [80] reported a modest positive association between the amount of differential contouring performed between the concave and convex rods and the degree of AVR correction ($R^2 = 0.28$).

Ponte osteotomies in patients with severe thoracic lordosis

There is weak evidence that Ponte osteotomies influence surgical outcomes. In a matched comparison of severe AIS patients by Floccari et al. [67], Ponte osteotomies were reported to provide small radiographic gains in the coronal plane (66.6% vs 58.7%) with no improvement in the sagittal plane and no change in truncal rotation. This was reciprocated in a study by Newton et al. [82], which found that use of Ponte osteotomies was only weakly associated with improved thoracic kyphosis ($\eta^2 = 0.04$).

Discussion

In recent decades, sagittal alignment has been highlighted as an important surgical aim in the correcting scoliotic deformities, yet this is often sacrificed using pedicle-screw systems in favor for correction in the coronal and axial planes. Despite thorough investigations into the effect of various factors on postoperative correction, results remain inconsistent. This may be explained by the reliance on 2D imaging for the measurement of spinal parameters, which results in inaccurate estimation of surgical correction, especially for patients with severe curves. While reconstruction of low-dose biplanar images serves as a safe and reliable method for evaluating three-dimensional curve deformities, a full modeling process for each patient is time-consuming and labor intensive, potentially limiting large-scale studies. In this review, we have collected and summarized the key predictors of 3D postoperative alignment and correction for PSF. Preoperative 3D thoracic kyphosis, UIV and LIV selection, rod contour, and intraoperative vertebral rotation were found to be predictive of postoperative outcomes with strong evidence (Fig. 2). Pre-op coronal Cobb angle and axial rotation, DJK, pelvic parameters (PI and SS), and type of instrument were found to be predictive of postoperative outcomes with moderate evidence, while pre-op TL apical translation, Ponte osteotomies, rod material, and lumbar lordosis were found to be predictors with low evidence.

Patient-related factors and EIV selection

Preoperative coronal Cobb angle, thoracic kyphosis and axial rotation were identified as important predictors of postoperative sagittal and axial alignment, which reflects residual deformities in patients with severe curves, hypokyphosis or high torsion with less flexibility initially. While there may be associations between initial curve characteristics and postoperative outcomes across different planes, these are mostly due to aggressive intraoperative correction maneuvers causing disturbances in other planes [83]. The key value of assessing preoperative 3D spinal morphology arises from the comparison of surgical correction within subgroups of 3D curves, so as to achieve patient-specific surgical treatment. In a series of studies by Pasha et al. [70, 77, 85], UIV and LIV selection had different impacts on the surgical outcomes among preoperative clusters based on 3D spinal morphology. Where to fuse Lenke 1A curves distally has been a long-debated topic, with distal adding-on, PJK, and residual motion as the main concerns. For patients with NV close to EV, Suk et al. [86] recommended fusion to the neutral vertebra (NV) or NV-1. However, manual identification of NV and EV has been criticized to be unreliable among observers [87, 88]. Based on 3D analysis of axial rotation, Pasha et al. [70] suggested that the shape of axial projection may reflect the relationship between NV and EV and could be a potential determinant of fusion level for optimal postoperative alignment. For example, Lenke 1 patients with lemniscate-shaped axial projections have higher junctional vertebrae and should be fused to NV-1. For preoperative sagittal parameters, Vidal et al. [89] suggested that for hypokyphotic subjects with a low PI, overcorrection of LL in distal fusions led to poor sagittal balance postoperatively. Based on analysis of 3D spinal parameters, Pasha et al. [70] suggested that for hypokyphotic patients who have a high sagittal inflection point, fusion should be extended to the lumbar spine to improve postoperative sagittal balance. With this information, surgeons may optimize postoperative alignment while sparing motion segments and avoiding PJK and adding-on in selected patients.

Moderate predictive ability was attributed for the following parameters. Though distal junctional kyphosis, PI, and SS were identified as three of the top 5 predictors of postoperative 3D outcome clusters based on a random forest model by Pasha et al. [51, 90], the utility of these parameters as independent predictors remains uncertain, as the top predictors were selected based on mean decrease accuracy, which mostly reflects overall model performance rather than individual effect. In the same study, thoracolumbar apical translation on the sagittal plane and lumbar lordosis was identified as predictors with low evidence due to low mean decrease accuracy. Though the authors did not elaborate on the possible mechanism of these parameters, these sagittal parameters might reflect lumbar and pelvic compensation for sagittal imbalance in hypokyphotic patients [89, 91].

Surgical factors

Studies comparing outcomes of current systems [75, 76] had a generally moderate risk of bias due to important unadjusted factors such as the operating surgeon, fusion length, and baseline patient characteristics. Ilharreborde et al. [35, 81] have extensively reported on the postoperative correction rates of posteromedial translation with sublaminar bands, which shows satisfactory correction in hypokyphotic patients. Whether this method is superior to all-screw systems relies on further investigation with 3D analyses, as the current literature likely has overestimated preoperative thoracic kyphosis using 2D parameters [17, 92], which may account for the reported lordotic effect of pedicle-screw constructs.

End-instrumented vertebrae (EIV) rotation and translation during surgery were significantly predictive of postoperative

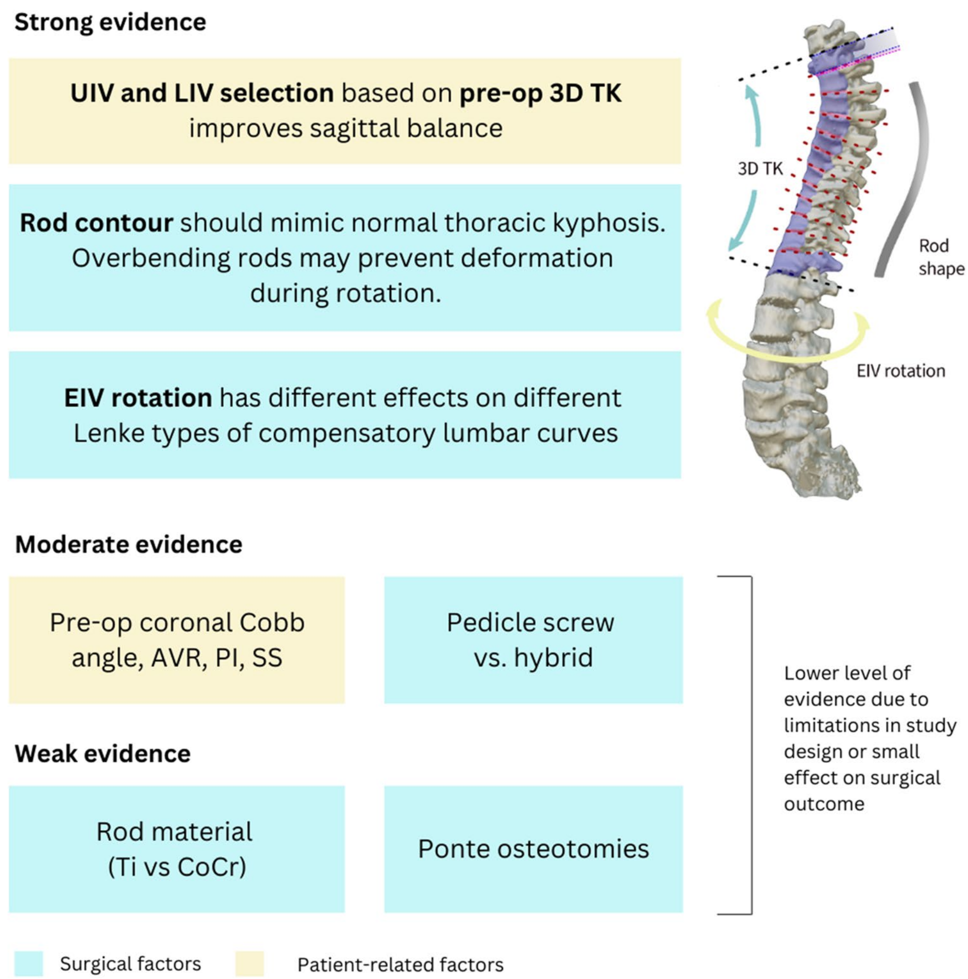

Fig. 2 A summary of the findings of this systematic review. UIV and LIV selection, preoperative 3D TK, rod contour, and EIV rotation were identified as predictors of surgical outcome with strong evidence. Predictors with moderate evidence included preoperative coronal Cobb angle, AVR, PI, SS, and type of instrument. Predictors with weak evidence included rod material and Ponte osteotomies. *UIV = upper instrumented vertebra, LIV = lower instrumented vertebra, 3D TK = three-dimensional thoracic kyphosis, EIV = end-instrumented vertebra, AVR = apical vertebral rotation, PI = pelvic incidence, SS = sacral slope

correction and alignment in several confirmatory studies. The concept of selective thoracic fusion was introduced by King et al. [93] in the 80 s, with the goal of preserving motion segments while allowing spontaneous correction of the compensatory lumbar curve. However, unsatisfactory outcomes including adding-on and overcorrection have been reported, which may be remedied using direct vertebral rotation or translation. Using 3D analysis, Pasha et al. [70, 71] found that leveling EIV tilt and reducing rotation were associated with reduced coronal Cobb angle and rotation in the unfused lumbar spine postoperatively and at latest follow-up. This was also found by Kim et al. [94] and Chang et al. [95] using the Nash–Moe method to measure change in AVR. Using 3D analyses, Zuckerman et al. [96] also found that direct vertebral rotation produced significant improvements in thoracic AVR and AVR in the unfused lumbar curve. In another study by Pasha et al. [79], % EIV derotation was found to have different impacts on surgical outcome across subgroups of lumbar modifiers and sagittal alignment, and patients with C lumbar modifiers were found to benefit from more LIV rotation. Kim et al. [94] supported the findings, noting that for B and C modifiers, LIV rotation counterclockwise to lumbar rotation produced better curve correction, while for A modifiers, LIV rotation clockwise to lumbar rotation prevented overcorrection and distal adding-on.

As for the effect of EIV shift on sagittal alignment, Homans et al. [78] reported that a larger anterior shift of UIV during surgery was moderately associated with a higher PJK angle. This was attributed to the subsequent rebound of the UIV to a posterior position, which aligned with the hypothesis shared by Alzakri et al. [97, 98] that PJK develops as a compensatory mechanism to restore global sagittal balance in patients with reduced thoracic kyphosis. This further highlights the significance of sagittal alignment, even in patients with normal preoperative kyphosis.

Regarding rod curvature, preoperative rod-to-spine contour was reported to be predictive of change in thoracic kyphosis from two studies with low risk of bias. Kluck et al. [84] quantified rod contour prior to insertion using the rod-to-spine distance, while Le Navéaux et al. [83] measured the difference between rod curvature and kyphosis. Both parameters were found to moderately correlate with change in thoracic kyphosis, and their predictive ability was limited due to flattening of the rods during derotation maneuvers. This has been also identified in a study by Newton et al. [99] based on 2D measurements, and it was suggested that rod overcontouring by 20° could prevent in vivo deformation. For axial correction, differential rod contouring is often performed between the concave and convex rods, in which the concave rod is bent sagittal to a larger degree to rotate the concavity of the curve backward and bring the convexity of the curve anteriorly. Using 3D analysis, Le Navéaux et al. [83] found positive associations between the amount of differential contouring performed and the degree of AVR correction ($R^2 = 0.28$) and orientation of the main thoracic PMC ($R^2 = 0.41$). In a CT study by Seki et al. [100], differential rod contouring > 10° resulted in significant improvement of AVR and rib hump indices.

Rod material was identified as a predictor with low evidence. While SS rods are less popular due to higher infection rates and smaller corrective ability [82, 101, 102], recent studies have converged to compare the surgical outcomes between Ti and CoCr rods, which have different mechanical properties. Ti rods are more elastic, which may undermine in situ bending. Two prior comparative studies [38, 103] have shown that CoCr rods resulted in a mean 3–4° improvement in correction of 2D TK with no difference in other planes. While we identified two studies comparing Ti and CoCr rods [80, 81], both did not find significant changes in any 3D parameters.

Ponte osteotomies were identified as a predictor of postoperative alignment with low evidence. Floccari et al. [67] reported that Ponte osteotomies provided an 8% gain in coronal correction with no differences in other planes. Newton et al. [82] reported that it was weakly associated with improved TK, though preoperative flexibility was not accounted for in this study. While cadaver and biomechanical studies generally demonstrate that Ponte osteotomies increase curve flexibility, human studies have yielded insufficient evidence supporting the efficacy in radiographic correction [104]. However, prior studies did not include matched control groups [104–106] and one included normokyphotic subjects [107]. While a large study by Abousamra et al. [108] has shown that intraoperative blood loss was not associated with the number of Ponte osteotomies, its use should still be carefully considered given increased surgical time and potential neurological complications [109].

This is the first review to evaluate the predictors of 3D postoperative alignment and correction after PSF, which includes 3D preoperative spinal parameters and surgical factors. Several limitations were present in this review. First, a meta-analysis could not be conducted due to the lack of comprehensive information on patient characteristics and detailed surgical technique in most of the included studies. However, unless explicitly mentioned otherwise, all included studies used pedicle-screw constructs. Further prognostic studies should include a multivariable analysis adjusted for a set of predictors confirmed in the literature, such as baseline spinal parameters and fusion length. This would be beneficial for identifying new predictors with independent prognostic value. Secondly, publication bias could not be assessed since most studies did not report effect sizes and confidence intervals. However, the strength of evidence was mostly assessable via other domains. Thirdly, no randomized controlled trials or prospective studies were identified during our search. Nevertheless, the predictors extracted from included studies were rigorously examined for quality of evidence.

While it is encouraging to see the emergence of studies on 3D spinal correction, the review identified a paucity in high-quality studies contrasting surgical correction between pedicle-screw and hybrid constructs. Additionally, axial rotation and DJK were recognized as promising factors with potential value in prediction of surgical outcome. We recommend 3D preoperative assessment for patients with severe coronal Cobb angles to identify hypokyphotic candidates and to facilitate surgical planning in these patients. Overbending rods are a potential method to prevent rod flattening during intraoperative correction that requires further investigation. Future work may be expanded using validated algorithms to predict 3D parameters based on 2D ones, which may save time from manual input. Lastly, further research should include comprehensive information on patient and surgical details, taking into consideration the wide array of factors affecting early postoperative as well as long-term outcomes.

Conclusions

In summary, rod contouring and selection of UIV and LIV should be based on sagittal alignment measured using 3D TK. Rods should be contoured to mimic normal thoracic kyphosis while avoiding excessive anterior shift of the UIV in order to prevent PJK. LIV rotation produced favorable outcomes in patients with unfused lumbar curves, while there was low evidence supporting the use of Ponte osteotomies in lordotic patients. Further investigations should compare surgical correction between pedicle-screw and hybrid constructs using matched cohorts.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00586-023-07708-2.

Declarations

Conflict of interest The authors have no conflict of interest to disclose.

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