Contemporary Advances in Adolescent Idiopathic Scoliosis: Precision Assessment, Individualized Nonoperative Care, and Evolving Surgical Strategies

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Abstract: ***Purpose**: Adolescent idiopathic scoliosis (AIS) management is moving from threshold-based algorithms toward individualized estimation of progression risk, treatment response, and patient priorities. This narrative state-of-the-art review critically summarizes recent developments in assessment, bracing, physiotherapeutic scoliosis-specific exercises (PSSE), radiation-sparing surveillance, artificial intelligence (AI), vertebral body tethering (VBT), and posterior spinal fusion (PSF). **Methods**: PubMed/MEDLINE and major society and regulatory sources were narratively reviewed, emphasizing randomized trials, prospective multicenter studies, systematic reviews, and guidance published from 2019 through August 2026. Seminal earlier studies were retained when necessary to define current standards. Because this was a narrative review of published literature, institutional review board approval was not required. **Results**: Full-time thoracolumbosacral orthosis remains the reference nonoperative treatment for skeletally immature patients at meaningful risk of progression, but nighttime hypercorrective bracing is supported as a pragmatic alternative for selected flexible curves or patients who reject full-time treatment. Objective wear monitoring and early in-brace correction increasingly guide brace optimization. PSSE produces small improvements in deformity and quality-of-life measures and is best considered an adherence-dependent adjunct; digitally supervised programs may improve delivery. Growth assessment increasingly combines Sanders or distal radius-ulna staging with curve magnitude and growth velocity. AI can automate radiographic measurements and prediction tasks, but limited external validation precludes autonomous clinical use. VBT preserves motion and can achieve satisfactory correction in carefully selected immature patients, although tether failure and unplanned reoperation remain important limitations. PSF remains the most predictable operation for progressive surgical-range AIS; current innovation focuses on three-dimensional alignment, selective fusion, navigation, patient-specific rods, blood conservation, and enhanced recovery. **Conclusions**: The most mature advances in AIS care are not wholesale replacements for established treatment, but tools that improve patient selection, adherence, surveillance, and perioperative recovery. Shared decision-making should explicitly distinguish proven benefits from promising technologies whose long-term comparative effectiveness remains uncertain.*

Keywords: adolescent idiopathic scoliosis; bracing; scoliosis-specific exercise; vertebral body tethering; posterior spinal fusion; artificial intelligence

1. Introduction

Adolescent idiopathic scoliosis is a three-dimensional spinal deformity presenting after 10 years of age without an identifiable underlying cause. Management has traditionally been organized around Cobb-angle thresholds: observation for smaller curves, bracing during growth for moderate curves, and fusion for progressive curves approaching 45–50°. These categories remain useful, but they incompletely represent biological maturity, curve flexibility, axial rotation, sagittal morphology, treatment adherence, and the priorities of the adolescent and family. The contemporary direction of the field is therefore precision rather than expansion: selecting the right patient, treatment intensity, and outcome for each stage of growth.

Several innovations have entered practice simultaneously. Skeletal maturity assessment is more granular; brace wear can be objectively measured; remote rehabilitation can support PSSE adherence; low-dose and non-ionizing technologies reduce surveillance burden; and AI can automate measurements. In surgery, growth modulation offers an alternative to fusion for a narrow population, while navigation, patient-specific planning, and enhanced recovery refine PSF. The central question is which developments are sufficiently validated to change routine care.

2. Methods

A narrative search of PubMed/MEDLINE was performed for English-language literature using combinations of "adolescent idiopathic scoliosis," "brace," "nighttime brace," "exercise," "Schroth," "skeletal maturity," "artificial intelligence," "ultrasound," "vertebral body tethering," "posterior spinal fusion," "navigation," "patient-specific rod," and "enhanced recovery." Priority was given to randomized controlled trials, prospective multicenter cohorts, systematic reviews, meta-analyses, society statements, and US Food and Drug Administration surveillance documents. The review focused on 2019–August 2026, supplemented by landmark earlier evidence. This approach was intended as a clinically oriented State-of-the-Art Review rather than a systematic review; no quantitative pooling or formal risk-of-bias assessment was undertaken.

Precision assessment and surveillance

Maturity and progression risk

Risser grade alone is an imprecise marker near peak height velocity. Contemporary assessment increasingly integrates Sanders digital skeletal age or distal radius-ulna classification, chronological age, menarchal status, longitudinal height velocity, curve magnitude, pattern, and recent progression. This matters because two patients with identical Cobb angles may have substantially different remaining growth and treatment benefit. Progression calculators can support discussion, but calibration across populations and treatment settings is essential. Commercial genetic prognostic tests have not demonstrated sufficient transportability to replace clinical-radiographic models.

Measurement, AI, and radiation reduction

AI algorithms have demonstrated high technical performance for vertebral landmark detection, Cobb measurement, curve classification, skeletal maturity estimation, and progression prediction. A 2026 scoping review reported a median area under the receiver-operating curve of 0.94, mean accuracy of 0.91, and mean Cobb-angle error of 3.1°. Nevertheless, only a minority of studies were prospective or multicenter, none directly compared AI screening with established Scoliosis Research Society screening, and economic evaluation was absent. AI should therefore function as a measurement and decision-support layer with clinician verification, not as an autonomous screening or treatment-selection system.

Low-dose slot-scanning radiography has substantially reduced ionizing exposure for serial standing assessment. Surface topography and three-dimensional ultrasound are attractive non-ionizing options for interim surveillance, particularly when frequent assessment is desirable. Their limitation is not merely measurement correlation; management thresholds were derived from standing radiographic Cobb angles. Until longitudinal decision thresholds are validated, non-ionizing tools should reduce- not eliminate- appropriately timed radiographs.

Individualized nonoperative treatment

Bracing: from prescription to delivered dose

The BrAIST trial established a dose-response relationship between brace wear and treatment success, and full-time rigid TLSO remains the reference intervention for skeletally immature patients with curves generally in the 20–40/45° range and meaningful progression risk. The important contemporary shift is from prescribed hours to delivered biomechanical dose. Temperature or force sensors provide objective wear time; in-brace radiographs quantify initial correction; and early follow-up identifies fit, skin, comfort, or behavioral barriers. Strong initial correction and sustained wear are complementary rather than competing targets.

Nighttime hypercorrective orthoses address the psychosocial and adherence burden of daytime bracing. In the CONTRAIS randomized trial, nighttime bracing prevented progression of more than 6° more effectively than physical activity alone among adolescents who declined full-time bracing, whereas the tested scoliosis-specific exercise strategy did not. A subsequent comparison suggested that nighttime bracing with escalation to full-time bracing after failure achieved broadly comparable progression control, but with a tendency toward more surgery. Thus, nighttime bracing is a defensible shared-decision option for selected flexible curves, especially when the realistic alternative is poor adherence or no brace; it should not be presented as universally equivalent to full-time TLSO.

CAD/CAM fabrication, finite-element simulation, and additive manufacturing may improve reproducibility, ventilation, and comfort. Evidence that these platforms outperform an expertly designed and adjusted conventional orthosis in definitive outcomes remains limited. Technology should support iterative orthotist-clinician collaboration rather than substitute for it.

Physiotherapeutic scoliosis-specific exercises

Recent meta-analyses suggest that PSSE, particularly Schroth-based programs, can produce small improvements in Cobb angle, trunk rotation, pain, and health-related quality of life in mild-to-moderate AIS. Heterogeneous protocols, small trials, variable controls, and limited follow-up reduce certainty. PSSE is best framed as an adjunct to observation or bracing and should not replace indicated bracing in a rapidly growing patient with a high-risk curve.

Delivery may be as important as exercise school. A 2025 randomized trial of 128 skeletally immature participants found that an individually tailored, digitally supervised home PSSE program improved Cobb angle more than a conventional model consisting of three therapist visits followed by unsupervised home training. The trial supports remote feedback and adherence infrastructure, but does not establish equivalence across digital systems or long-term prevention of surgery.

Table 1: Contemporary developments in nonoperative assessment and treatment of adolescent idiopathic scoliosis

Development	Current clinical role	Important limitation
Granular maturity staging	Combine Sanders/DRU stage, growth velocity, menarchal status, and curve behavior	No single maturity measure captures all remaining growth
Objective brace monitoring	Quantifies delivered wear time and supports targeted adherence counseling	Monitoring alone does not ensure corrective force or fit
Nighttime hypercorrective brace	Alternative for selected flexible curves or rejection of full-time TLSO	Potentially less reliable for some patterns; surgical risk equivalence uncertain
Digitally supported PSSE	Improves access, feedback, and exercise adherence	Small effect sizes and limited long-term comparative data
AI measurement/prediction	Clinician-verified automation and decision support	Insufficient prospective external validation for autonomous use
Surface topography/3-D ultrasound	Radiation-sparing interim surveillance	Radiographic thresholds remain the management reference

Fusionless surgical growth modulation

Vertebral body tethering

VBT applies compression across the convex anterior vertebral physes while preserving motion segments and avoiding arthrodesis. Its appeal is intuitive, but its success depends on a narrow interaction among remaining growth, curve flexibility, immediate correction, tether levels, and tension. Excessive remaining growth risks overcorrection;

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insufficient growth limits modulation; and mechanical failure can permit recurrence.

The first prospective multicenter cohort reported 127 patients from nine institutions with mean follow-up of 2.4 years. Mean preoperative major curve magnitude was 50°, improving to 29° on first erect imaging and 26° at final follow-up. Tether breakage occurred in 29%. When the first erect residual major curve was ≤35°, 88% met the study success definition of a final curve ≤35° without fusion, compared with 60% when early correction remained >35°. These findings reinforce that VBT is partly an immediate corrective operation and partly growth modulation; a poorly corrected construct should not be expected to be rescued reliably by growth.

Systematic reviews and comparative cohorts generally report clinical success in approximately three-quarters of selected patients, with unplanned reoperation near 15% and variable tether failure. Motion preservation is measurable, particularly across lumbar instrumented segments, but its long-term functional value relative to a judiciously selected fusion has not been established. Current best candidates are skeletally immature patients with flexible, predominantly thoracic curves, adequate but not excessive growth, and informed acceptance of surveillance and possible revision. VBT should be offered as an alternative with different trade-offs- not as a minimally invasive equivalent to PSF.

Other nonfusion implants

Posterior dynamic "internal brace" systems use limited fixation and an expandable or ratcheting mechanism. Their smaller surgical exposure and motion-preserving intent are attractive, but indications are narrow and the comparative evidence base is limited. FDA postmarket surveillance of the MID-C system has documented substantial medical-device reporting and reoperation concerns. These devices remain specialized options requiring transparent consent, registry participation, and continued surveillance.

Contemporary posterior spinal fusion

Three-dimensional goals and fusion-level selection

PSF with segmental pedicle-screw instrumentation remains the most predictable treatment for progressive surgical-range AIS. Contemporary planning emphasizes a balanced three-dimensional result rather than maximum coronal correction. Avoiding iatrogenic thoracic hypokyphosis, controlling axial rotation and rib prominence, balancing the shoulders, and preserving mobile lumbar segments may be more consequential than a few additional degrees of Cobb correction. Selective thoracic fusion remains valuable when the lumbar curve is compensatory and expected to balance; distal level selection should incorporate lumbar modifier, L4 tilt, apical translation and rotation, sagittal alignment, and bending response.

Enabling technologies

Intraoperative navigation and three-dimensional imaging improve pedicle-screw placement accuracy and are particularly useful for small, rotated, or dysplastic pedicles. Registry analyses suggest possible reductions in neurologic injury or transfusion, but causality is uncertain and consistent patient-reported benefit has not been demonstrated. Robotic assistance is feasible, although pediatric deformity-specific evidence remains early. Added radiation, operative workflow, capital cost, and the capacity for anatomic freehand rescue must be considered.

Patient-specific precontoured rods and computer-assisted planning seek to translate the planned sagittal profile into the final construct and reduce rod-flattening. Early comparative evidence suggests improved sagittal alignment, but longer follow-up is required to determine whether radiographic gains improve function or reduce mechanical complications. Similarly, AI-based operative planning is promising but vulnerable to dataset shift and should remain surgeon-supervised.

Blood conservation and enhanced recovery

Perioperative progress is among the most immediately generalizable advances. Tranexamic acid, meticulous positioning and hemostasis, controlled hypotension when appropriate, cell salvage in selected cases, and standardized transfusion pathways reduce allogeneic exposure. Enhanced recovery after surgery protocols combine preoperative education, multimodal analgesia, early transition to oral medication, early mobilization, nausea and bowel regimens, and standardized discharge criteria. A 2025 revised meta-analysis found reduced length of stay and opioid use without a clear increase in readmission or complications. Protocol content and institutional execution likely matter more than the ERAS label itself.

Table 2: Contemporary refinements in posterior spinal fusion for adolescent idiopathic scoliosis

Strategy	Expected benefit	Evidence caveat
Selective fusion and 3-D planning	Preserves lumbar motion and optimizes global balance	Requires pattern-specific judgment; radiographic perfection is not the sole outcome
Navigation/3-D imaging	Improved screw-placement accuracy in challenging anatomy	Cost, radiation, and inconsistent evidence for patient-reported benefit
Patient-specific rods	More faithful sagittal contour and reduced intraoperative rod manipulation	Limited long-term clinical comparative evidence
Tranexamic acid/blood pathway	Lower blood loss and transfusion exposure	Dosing and pathway details vary
Enhanced recovery	Shorter stay, earlier mobility, lower opioid use	Heterogeneous protocols; requires multidisciplinary implementation

Patient-centered outcomes and shared decision-making

Radiographic progression and avoidance of fusion remain important, but they do not fully represent the adolescent experience. Body image, brace visibility, school participation, sleep, sport, pain, self-efficacy, and family burden influence treatment adherence and satisfaction. SRS-

22/SRS-22r and age-appropriate quality-of-life instruments should complement radiographs. For bracing, discussions should include expected hours, likely in-brace correction, sensor use, and escalation rules. For VBT versus PSF, consent should compare predictability, motion, growth, pulmonary exposure, implant failure, surveillance, revision, and the possibility of later fusion. Shared decision-making is particularly important when evidence does not establish a single superior option.

Unresolved questions and research priorities

The field requires prospective multicenter studies that compare treatment strategies using consistent maturity measures, curve-pattern definitions, and patient-centered outcomes. Priority questions include: which flexible curves can reliably use nighttime rather than full-time bracing; whether digital PSSE prevents brace escalation or surgery; how non-ionizing surveillance can be embedded into validated decision pathways; which VBT candidates obtain durable functional benefit sufficient to justify revision risk; and whether navigation, robotics, patient-specific rods, or AI planning improve outcomes beyond technical accuracy. Core outcome sets should include progression, surgery, complications, reoperation, pulmonary function where relevant, activity, body image, and health-related quality of life through skeletal maturity and into adulthood.

3. Conclusions

AIS care is becoming more individualized, measurable, and patient centered. Full-time rigid bracing and PSF remain the reference treatments in their established indications. Nighttime bracing, sensor-informed brace optimization, and digitally supported PSSE expand the ways evidence-based nonoperative care can be delivered. Granular maturity assessment, low-dose imaging, and clinician-verified AI may improve surveillance and risk estimation. VBT offers motion-preserving correction for carefully selected immature patients but carries less predictable correction and greater implant-related revision risk than fusion. The appropriate contemporary posture is selective adoption: use innovation when it solves a defined clinical problem, measure its delivered effect, and communicate uncertainty explicitly.

Table Legends

Table 1: Contemporary developments in nonoperative assessment and treatment of adolescent idiopathic scoliosis

Table 2. Contemporary refinements in posterior spinal fusion for adolescent idiopathic scoliosis.

Declarations

Ethics approval: Not applicable; this article reviews previously published literature.

Consent to participate and publish: Not applicable.

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