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Recent Advances in Adult Spinal Deformity

From Personalized Alignment and Physiologic Optimization to Minimally Invasive Correction, Junctional Protection, Robotics, and Predictive Analytics

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Key Message

The field is moving from radiograph-centered correction toward patient-specific, risk-adjusted reconstruction. The most consequential advances are not a single implant or approach, but the integration of age- and morphology-adjusted alignment, bone and muscle health, frailty-informed selection, less invasive circumferential strategies, proximal-junctional transition planning, and data-driven prediction. The evidence is strongest for comprehensive optimization and avoidance of overcorrection; many technologies remain promising but incompletely validated.

Abstract: ***Adult spinal deformity (ASD) surgery can provide durable improvements in pain, disability, and health related quality of life, but it remains associated with major medical, neurologic, and mechanical complications. Recent development has therefore focused on improving value rather than maximizing correction. This narrative review synthesizes contemporary advances in diagnosis, patient selection, alignment planning, perioperative optimization, minimally invasive and hybrid reconstruction, osteotomy strategy, fixation and rod constructs, proximal junctional kyphosis/failure prevention, navigation and robotics, artificial intelligence, and recovery pathways. Alignment targets have evolved beyond fixed SRS Schwab thresholds to age-adjusted and proportional concepts, with increasing attention to pelvic morphology, lumbar shape, segmental lordosis, and whole-body compensation. Bone health, frailty, sarcopenia, cognition, and psychosocial vulnerability are now treated as modifiable or decision-shaping variables. Circumferential minimally invasive surgery, anterior column realignment, prone lateral access, and staged or single-position workflows can reduce approach morbidity in selected deformities, although severe rigid deformity still requires open posterior reconstruction or three-column osteotomy. Junctional prevention is increasingly multimodal, combining appropriate correction, soft-tissue preservation, transition rods or hooks, ligament augmentation, cement when indicated, and osteoporosis treatment. Robotics, navigation, automated radiographic measurement, and machine-learning models are expanding planning and execution, but external validation, calibration, explainability, and workflow economics remain limiting. The contemporary objective is a durable, physiologically tolerable reconstruction tailored to the patient's goals and failure risk.***

Keywords: adult spinal deformity, sagittal alignment, minimally invasive surgery, proximal junctional failure, osteoporosis, frailty, robotics, machine learning

1. Introduction

ASD encompasses degenerative scoliosis, iatrogenic flatback, sagittal imbalance, post-traumatic or post infectious deformity, and residual idiopathic deformity. Operative treatment offers clinically important and durable improvement for appropriately selected symptomatic patients, but the benefit is purchased with substantial perioperative and long-term risk [1-3]. Contemporary innovation has consequently shifted from the question of whether a deformity can be corrected to whether a particular correction is biologically affordable, mechanically durable, and aligned with the patient's priorities.

This article is a targeted narrative review of developments most relevant to current surgical practice. PubMed-indexed literature and major multicenter or society-derived studies were prioritized, with emphasis on 2022-2026 publications. Because several newer strategies are supported mainly by retrospective cohorts, registry analyses, biomechanical work, or early technology series, the strength and maturity of evidence are explicitly distinguished.

2. Evolving evaluation and patient selection

Whole-patient phenotyping

Radiographic severity alone poorly captures operative risk or likely benefit. Modern evaluation integrates symptom drivers, neurologic compression, standing and dynamic alignment, hip and knee compensation, bone quality, frailty, sarcopenia, cognition, nutrition, smoking, diabetes, opioid exposure, and patient goals. Frailty indices consistently associate with complications, prolonged recovery, and non-home discharge, but recent work cautions against equating disability with biological frailty [15,16]. The practical implication is to use frailty as a continuous risk marker and a trigger for optimization and shared decision making, not as an automatic contraindication.

Sarcopenia is moving from a research label toward an actionable phenotype. Cross-sectional muscle area, psoas and paraspinal morphology, grip strength, gait speed, and chair-rise performance measure different constructs and are not interchangeable. A combined functional and imaging assessment is more defensible than a single CT-area threshold [17]. Cognitive impairment, catastrophizing, depression, and low self-efficacy can also affect recovery and satisfaction; preoperative identification enables expectation setting and targeted support [18].

Bone health as a core deformity variable

Dual-energy X-ray absorptiometry may be misleading in degenerative lumbar spines. Contemporary assessment supplements hip and forearm DXA with opportunistic CT Hounsfield units, vertebral fracture assessment, and laboratory evaluation for secondary causes. The 2026 AO Spine recommendations formalize osteoporosis evaluation and management in ASD and support an anabolic-first strategy for high risk reconstruction when feasible [19]. A randomized controlled trial reported that perioperative teriparatide reduced proximal junctional failure compared with denosumab in osteoporotic women undergoing ASD surgery, strengthening the evidence for preoperative anabolic treatment rather than postoperative rescue alone [20]. Exact timing and duration remain individualized, but many programs aim for several months before surgery and continued therapy during fusion maturation.

3. Personalized alignment: beyond fixed thresholds

The SRS-Schwab modifiers remain useful for communication, but fixed thresholds such as PI-LL mismatch <10 degrees, PT <25 degrees, and SVA <5 cm should not be treated as universal operative endpoints. Normal alignment changes with age, pelvic incidence, thoracic morphology, lower-extremity compensation, and functional demand. Age-adjusted targets and the Sagittal Age-Adjusted Score emphasize that aggressive normalization in older patients may increase PJK/PJF without adding proportional clinical benefit [4,5]. GAP and Roussouly-based planning add proportionality and lumbar shape concepts, yet external validation is inconsistent; no single score reliably predicts mechanical failure across populations [6,7].

The current planning paradigm is therefore multidimensional:

- Choose a global target that is age-appropriate and avoids both material undercorrection and overcorrection.
- Restore lumbar shape, not merely total lordosis: concentrate lordosis in L4-S1 when anatomy permits and avoid a hypolordotic distal foundation.
- Interpret PI-LL together with pelvic tilt, T1 pelvic angle, SVA, thoracic compensation, and hip/knee flexion.
- Plan the distribution and sequence of correction, including expected relaxation after decompression, interbody placement, positioning, and rod contouring.
- Reassess alignment dynamically after surgery because pelvic non-response or reciprocal changes can move a patient away from the intended target [8].

Coronal balance is receiving renewed attention. CMIS can achieve durable symptom improvement, but postoperative coronal malalignment remains clinically relevant and must be deliberately addressed through approach-side selection, asymmetric interbody placement, releases, and posterior translation rather than assumed to resolve with sagittal correction [24].

4. Risk- Adjusted Surgical Strategy

Clinical phenotype	Preferred contemporary strategy	Principal limitation
Flexible degenerative deformity	Decompression plus interbody-based correction; MIS or hybrid posterior fixation	Limited correction if facets/ALL remain resistant
Moderate sagittal deformity	Multilevel lateral/oblique or anterior interbodies, posterior column osteotomies, percutaneous or mini-open fixation	Staging, access complications, coronal planning
Rigid flatback / fused deformity	Open revision with PSO or selected three-column osteotomy; multi-rod lumbosacral construct	Blood loss, neurologic risk, pseudarthrosis, PJF
Frail or osteoporotic patient	Optimization, smaller goal-directed operation, staged strategy, or nonoperative care	Residual deformity may be preferable to physiologically excessive correction
High junctional-risk patient	Age-adjusted correction plus bone treatment, soft-tissue preservation, gradual transition, and selective tether/cement	No single prophylactic measure eliminates PJK/PJF

5. Minimally invasive, hybrid, and single-position reconstruction

Circumferential minimally invasive surgery (CMIS) combines multilevel interbody correction with percutaneous posterior fixation, often using lateral, oblique, or anterior access. Compared with traditional open reconstruction, selected series show lower blood loss, reduced soft-tissue injury, and potentially faster recovery, at the cost of radiation exposure, a learning curve, access-related complications, and less power for severe rigid deformity [21-24]. The most important conceptual advance is not incision size but using the interbody corridor to restore disc height, segmental lordosis, foraminal dimensions, and coronal alignment while reducing posterior muscle disruption.

Anterior column realignment through release of the anterior longitudinal ligament and placement of hyperlordotic cages can generate substantial segmental correction without a pedicle subtraction osteotomy. It is powerful but technically demanding; vascular, visceral, neural, and cage-related risks require careful level and patient selection. Prone transpsoas and other single-position workflows can eliminate repositioning, permit simultaneous posterior work, and exploit prone lordosis. Evidence currently supports feasibility and efficiency more strongly than superiority in long-term ASD outcomes.

Standalone anterolateral constructs and posterior-only MIS strategies may be reasonable in carefully selected, relatively flexible deformity, but broad generalization is premature. UIV selection remains consequential even in MIS; a 2025 analysis demonstrated that lower-thoracic versus upper-lumbar endpoints produce different tradeoffs rather than a universally superior choice [23]. Severe multiplanar deformity, major fixed sagittal imbalance, substantial coronal translation, poor bone, and complex revision anatomy continue to favor hybrid or open reconstruction.

6. Osteotomies and mechanical construct evolution

Pedicle subtraction osteotomy remains indispensable for rigid sagittal deformity, but the modern trend is to reserve it for patients whose correction cannot be safely distributed across discs and posterior elements. Multilevel posterior column osteotomies, interbody-based lordosis, and staged correction can reduce the need for a single high-stress apex. When a three-column osteotomy is necessary, preoperative CT-based planning, temporary rods, controlled closure, multi-rod support, and robust neuromonitoring are central.

Rod and fixation strategies increasingly address fatigue rather than only immediate strength. Multi-rod constructs across PSO and the lumbosacral junction, accessory rods, cobalt-chromium or hybrid metallurgy, and pelvic fixation with S2-alar-iliac screws can reduce rod fracture and pseudarthrosis in high stress regions. However, construct stiffness is a double-edged variable: very rigid constructs may transfer stress proximally. Patient-specific rods improve fidelity to the planned contour and may reduce intraoperative rod manipulation, but evidence that they independently improve long-term clinical outcomes remains limited. Expandable or porous interbody cages and sacropelvic fixation refinements are useful adjuncts; none compensates for poor biology or an inappropriate alignment target.

7. Proximal junctional kyphosis and failure: prevention as a bundle

PJK ranges from a radiographic finding to painful structural failure requiring revision. Contemporary prevention treats PJF as a systems failure arising from patient biology, alignment, soft-tissue injury, construct transition, and postoperative loading. Alignment alone is insufficient: a 2025 machine-learning study found that models combining alignment, bone quality, and soft tissue were more accurate than alignment-only models [29].

A practical prevention bundle includes:

- Correct to an age- and morphology-appropriate target and avoid abrupt, excessive lordosis or global overcorrection.
- Optimize osteoporosis, nutrition, vitamin D status, smoking, diabetes, and fall risk before surgery. • Preserve the UIV facet capsule, interspinous/supraspinous ligaments, and proximal paraspinal muscle attachments.
- Create a gradual stiffness transition using appropriate rod contour, selective hooks or less rigid proximal fixation, and avoidance of screw violation at the UIV.
- Consider posterior ligamentous augmentation in high-risk constructs. A 2025 meta-analysis of 1,333 patients associated augmentation with lower PJK and PJF, but included studies were predominantly nonrandomized [9,10].
- Use prophylactic vertebroplasty selectively in severe osteoporosis or high fracture risk; benefits must be balanced against cement leakage, adjacent fracture, and uncertain long-term effect. • Standardize early postoperative mobilization, fall prevention, and surveillance; reserve bracing for selected patients because evidence for routine use is inconsistent.

The key advance is disciplined risk matching: high-risk patients may warrant several complementary measures, whereas indiscriminate use increases cost and procedure burden without guaranteed benefit.

8. Neurologic safety, blood conservation, and recovery

Complex deformity correction requires a perfusion-centered neurologic strategy. Multimodal neuromonitoring, preoperative review of canal compromise and cord draping, careful osteotomy closure, staged correction when needed, and a rehearsed response to signal loss remain foundational. Contemporary protocols emphasize prompt reversal of recent maneuvers, restoration of mean arterial pressure and oxygen delivery, inspection for compression, and wake-up testing or imaging when appropriate. Navigation may reduce implant-related risk but does not prevent stretch, perfusion, or closure-related injury.

Patient blood management now combines preoperative anemia correction, tranexamic acid, cell salvage, meticulous hemostasis, temperature and coagulation management, and procedure staging when physiologic burden becomes excessive. Enhanced Recovery After Surgery pathways incorporate multimodal analgesia, opioid stewardship, early nutrition and mobilization, delirium prevention, and predefined discharge criteria. A 2025 propensity-matched study suggested that ERAS combined with preoperative anti-frailty intervention improved outcomes in frail ASD patients, but prospective multicenter validation is needed [14].

9. Robotics, navigation, augmented reality, and intraoperative imaging

Robotic and navigation platforms are increasingly used for percutaneous pedicle and pelvic screw placement, trajectory planning, and workflow integration in ASD [25]. Their most plausible benefits are accuracy in altered anatomy, consistency across numerous implants, reduced surgeon radiation exposure, and facilitation of MIS. Limitations include registration error, line-of-sight or array movement, skiving, cost, operating-room footprint, and the false reassurance of a digitally planned trajectory. Surgeons must preserve the ability to recognize inaccurate registration and convert to conventional techniques.

Augmented-reality navigation and intraoperative 3-dimensional imaging may shorten the distance between planning and execution. Patient-specific guides and rods similarly translate preoperative plans to the operating room. The next step is closed-loop surgery: automated measurement of the evolving construct, comparison with the planned alignment, and adjustment before final fixation. At present, most evidence concerns accuracy and workflow rather than patient-reported outcomes, mechanical failure, or cost effectiveness.

10. Artificial intelligence and predictive analytics

Artificial intelligence is being applied to automated

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measurement, image segmentation, phenotype discovery, outcome prediction, and complication modeling. Automated spinopelvic measurements can reduce repetitive work and improve reproducibility, although performance depends on image quality and external validation [26]. Unsupervised clustering has identified prognostic ASD phenotypes that may better reflect interacting age, disability, alignment, and comorbidity patterns than conventional categories [11,27]. Supervised models can estimate the probability of an ideal outcome or mechanical complication [12,28-30].

Clinical readiness should be judged by more than area under the receiver-operating curve. Models require external and temporal validation, calibration, decision-curve analysis, handling of missing data, fairness testing, and integration into a workflow where the output changes management. The strongest near-term role is decision support: highlighting modifiable risks, comparing plausible operations, and improving informed consent. AI should not yet be treated as an autonomous selector of surgical candidacy or alignment target.

11. What is genuinely practice-changing?

Development	Current evidence maturity	Practical interpretation
Age-/morphology adjusted alignment	Moderate; multicenter validation but no universal target	Use multiple frameworks and avoid overcorrection, especially in older patients
Bone health optimization / anabolic therapy	Moderate to high for high-risk osteoporosis; emerging ASD specific RCT evidence	Screen routinely; treat before large reconstruction when feasible
Frailty and sarcopenia assessment	Moderate prognostic evidence	Use for optimization and shared decisions, not categorical exclusion
CMIS / hybrid correction	Moderate in selected flexible deformity	Reduces approach morbidity but does not replace open surgery for every rigid deformity
Ligament augmentation	Moderate-low; favorable meta-analysis dominated by observational data	Consider as one component of a junctional-risk bundle
Robotics/navigation	High for screw accuracy; lower for ASD patient-level outcomes	Useful execution tool; cost and workflow remain center specific
AI prediction / automated measurement	Early to moderate; validation gap	Promising decision support, not autonomous decision making

12. Future directions

The next generation of ASD care will likely combine dynamic whole-body imaging, opportunistic bone and muscle biomarkers, patient-specific musculoskeletal modeling, and digital simulation of alternative constructs. Subject-specific modeling aims to estimate loads at the junction, osteotomy, rods, and sacropelvic fixation rather than infer risk from alignment alone [31]. Wearables may quantify real-world posture, gait, and recovery, while longitudinal registries can support adaptive prediction. Meaningful progress will require pragmatic multicenter trials comparing integrated care pathways, not only new devices. Core outcomes should include patient-defined goal attainment, time at home, opioid independence, return of function, mechanical durability, reoperation, and cost.

13. Conclusion

Recent progress in ASD is best understood as a transition from standardized deformity correction to personalized reconstruction. The durable operation is one that achieves enough correction, in the right distribution, for the right patient, with biology and construct transition deliberately protected. Current evidence supports comprehensive bone and frailty assessment, age- and morphology-adjusted alignment, selective use of less invasive circumferential techniques, multimodal PJF prevention, and disciplined recovery pathways. Robotics and AI are important enabling technologies, but their value depends on whether they improve patient-level outcomes rather than technical metrics alone. For the foreseeable future, high-quality ASD care will remain an exercise in judgment: balancing radiographic ambition against physiologic reserve, mechanical risk, and the patient's own definition of success.

Clinical takeaways

- Do not plan from PI-LL alone; integrate age, lumbar shape, global alignment, compensation, and patient goals.
- Treat osteoporosis and frailty as core reconstructive variables before choosing the magnitude of surgery.
- Use interbody-based and minimally invasive correction for flexible deformity; reserve three-column osteotomy for genuinely rigid pathology.
- Prevent PJF with a bundle- appropriate correction, preserved proximal tissues, optimized bone, and a graded construct transition.
- Adopt robotics and AI where they solve a defined clinical or workflow problem, and audit outcomes beyond accuracy.

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Note

This narrative review is intended for professional education and manuscript development. It is not a formal clinical guideline. Several emerging interventions are supported by observational or early-stage evidence, and local protocols, regulatory status, and patient-specific factors should guide use.