Pieters *et al. BMC Musculoskeletal Disorders (2025) 26:272*
https://doi.org/10.1186/s12891-025-08497-z

BMC Musculoskeletal Disorders

REVIEW **Open Access**

An update on improvement and innovation in the management of adult thoracolumbar spinal deformity

Thomas Pieters[1,2*], Gabrielle Santangelo[3], Taylor Furst[3] and Daniel M. Sciubba[1]

Abstract

Adult spinal deformity (ASD) is a spectrum of abnormalities of the thoracic and lumbar spine and has an increasing prevalence. It is associated with significant physical and mental disability in symptomatic patients. Given the increased rates and the morbidity associated with this disease, novel innovation in the diagnosis and treatment of such deformity is required. The SRS-Schwab classification system described coronal scoliotic deformity with sagittal modifiers. Other parameters, such as the sagittal vertical axis, pelvic tilt, T1 pelvic angle, pelvic incidence and lumbar lordosis attempted to quantify global sagittal balance. More recently, a focus on more patient specific parameters has been targeted to improve patient outcomes. The Roussouly classification system attempted to predict sagittal alignment parameters based on fixed parameters of the pelvis. Others determined the parameters based on patient age. Technological advances have also enhanced our understanding of ASD. Long cassette films and automated analyses have allowed standardization of these measurements across physicians. 3D printing has been used as an adjunct for both surgical planning and implants, both generic and patient specific, to improve outcomes. With these, advances in minimally invasive approaches have allowed ASD correction with lower complications and blood loss. Intraoperative navigation and the use of robotics has allowed improved accuracy in the care of these patients. Development of complex osteotomies have allowed for correction of advanced deformity. Fusion, however, is the ultimate goal of surgical ASD correction. Advances in biologics such as the use of recombinant Human Bone Morphogenetic Protein-2 have been used to improve fusion rates and combat pseudoarthrosis. Finally, post-operative advances in ASD patient care with emphasis on enhanced recovery after surgery has allowed improvements in hospital length of stay and pain scores. ASD is becoming a more ubiquitous diagnosis for spine surgeons with an increasing aging population. Improvement in the understanding of the diagnosis, spinopelvic parameters, imaging techniques, and post operative care are all aimed toward helping patients in whom care can be extremely difficult. Further study in ASD patient care will target advanced innovation to provide optimal treatment to these patients and allow for best possible outcomes.

Keywords Adult spinal deformity, Sagittal balance, Deformity correction, Spine surgery

*Correspondence:
Thomas Pieters
Thomas.Pieters@umassmemorial.org
[1] Department of Neurosurgery, Zucker School of Medicine at Hofstra/Northwell, Great Neck, NY, USA
[2] Department of Neurosurgery, University of Massachusetts, 55 N Lake Ave, Worcester, MA 01655, USA
[3] Department of Neurosurgery, University of Rochester, 601 Elmwood Avenue, Rochester, NY, USA

Overview of adult spinal deformity

Adult spinal deformity (ASD) is a blanket term encompassing a spectrum of abnormalities of the thoracic and lumbar spine in patients who have completed their growth [1, 2]. ASD may be from de-novo onset, worsening of previous deformity, or iatrogenic from prior spine surgery [3, 4]. At present, global population trends are increasing, with the proportion of people over 60 years projected to increase from 10.0% in 2000 to 21.8% in 2050 to 32.2% in 2100 [5]. This trend is reflected in rates of surgery performed for ASD for Medicare patients which showed a fourfold increase from 2000 to 2010, a 70% increase for managed care patients across that same period and a 273% increase in the overall rates of fusions for ASD since 2001 [2, 6]. Though the costs of ASD surgeries have increased over the last two decades largely due to inflation and implant costs, the one-time median cost of ~ $30,000–60,000 is offset by an estimated annual cost of ~ $10,000 per patient managed non-operatively making surgical intervention not only beneficial to the patient, but also cost effective [4, 7].

The aging population has increasing incidence of osteoporosis and decreased bone mineral density [8]. A recent study showed that 32.8% of patients undergoing surgical correction for ASD carried the diagnosis of osteoporosis. Of these, only 34.4% were undergoing treatment for their osteoporosis [9]. In addition to other causative factors in this population, increasing spinal degeneration and deformity can lead to imbalance and falls [8]. A recent retrospective review of emergency department admissions over 10 years showed that 18% of adults over the age of 65 who were admitted after falling from a low level (< 3 feet) sustained a spinal fracture [10]. Such fractures can frequently be associated with progressive deformity requiring surgical correction [11].

ASD is associated with significant physical and mental disability in symptomatic patients. A study using the Standard Form (SF) 36 showed that the mean physical component score for these patients was worse than that of unaffected U.S. total population. If the ASD is associated with severe sagittal malalignment, then physical component scores are lower than patients with limited use of their arms and legs [12]. Using the Scoliosis Research Society (SRS) instrument, compared to a control population, those with surgical deformity showed lower scores in almost all subgroups including pain, self-image, function and mental health [13]. Similarly, Schwab et al. showed significantly lower scores in all eight SF-36 subgroup scores when compared to the US population norm [14]. Notably, this study demonstrated not only physical debilitation but also a significant diminution in their mental health scores [14]. Given the increased rates of patients with ASD and the morbidity associated with this progressive disease, novel innovation in the diagnosis and treatment of such deformity will be required to keep pace.

Diagnosis of adult spinal deformity

With the improvement in understanding of the etiology and effects of ASD has come a more rigorous definition of the diagnosis and thus more specific treatment goals for surgery. In 2006, Schwab et al. created the SRS-Schwab classification system of ASD. This system described coronal scoliotic deformity with modifiers for the amounts of lumbar lordosis and intervertebral subluxation [15]. This system was expanded in 2012 to the coronal curve and global alignment using the sagittal vertical axis and pelvic parameters including the pelvic tilt and the relationship between the pelvic incidence and lumbar lordosis [16].

Sagittal vertical axis

The sagittal vertical axis (SVA) is defined as the measured offset between a mid-body C7 plumbline and the posterosuperior corner of S1 [17, 18] (Fig. 1D). SVA less than 50 mm has generally been considered within normal and is targeted during corrective surgery [17–19]. An increase in SVA is associated with a linear increase in pain and decrease in function as measured by SRS, Owestry Disability Index (ODI) and SF-12 [17]. In fact, Glassman et al. considers sagittal balance and its restoration to be the primary objective of deformity surgery [20].

Pelvic tilt

Pelvic tilt (PT) is defined as the angle between a line drawn from the femoral heads to the midpoint of the S1 endplate and a vertical line [21] (Fig. 1C). Elevated PT has been correlated with impairment of walking tolerance [19] as it is frequently a compensatory mechanism to maintain upright posture relative to poor sagittal alignment [17]. It has been proposed that increased pelvic tilt (> 20 degrees) in the setting of corrected SVA (< 5 mm) indicates that the patient has residual spinal deformity [19].

(See figure on next page.)

Fig. 1 Advanced spinopelvic parameter measurements. **A**: Pelvic incidence is the angle between the line perpendicular to the S1 endplate at its midpoint and the line connecting this point to the axis of the femoral head. **B**: Lumbar lordosis is the angle measured from the superior endplate of L1 to the superior endplate of S1. C: Pelvic tilt is defined as the angle between a line drawn from the femoral heads to the midpoint of the S1 endplate and a vertical line. **D**: The sagittal vertical axis is defined as the measured offset between a mid-body C7 plumbline and the posterosuperior corner of S1. **E**: T1 pelvic angle is defined as the angle between a line drawn from the center of the T1 vertebral body to the femoral heads and a line from the femoral heads to the center of the S1 endplate. **F**: The cobb angle is measured between the upper border of the upper vertebra and the lower borders of the lowest vertebra in a scoliotic curve in the coronal plane

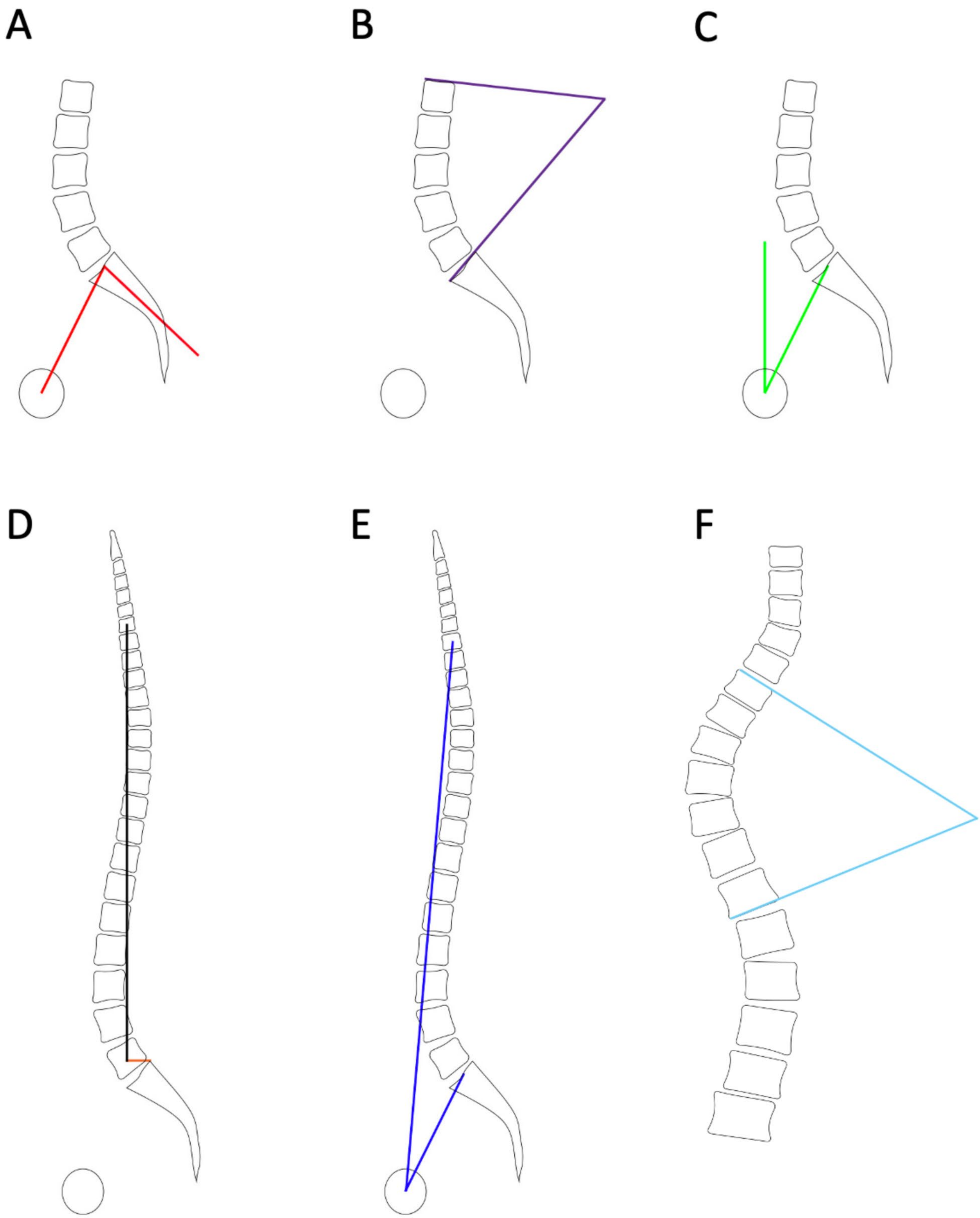

Fig. 1 (See legend on previous page.)

T1 pelvic angle

PT can be compensatory for an increased SVA with these values being closely interrelated. As such, T1 pelvic angle (TPA) has been identified as a measurement that can account for both PT and SVA and is unaffected by compensation [22]. TPA is defined as the angle between a line drawn from the center of the T1 vertebral body to the femoral heads and a line from the femoral heads to the center of the S1 endplate [22, 23] (Fig. 1E). Severe deformity threshold for TPA is considered 20 degrees which corresponds with an ODI > 40. Notably, a change of 4.1 degrees corresponded to a concordant 15 point change in ODI [23]. Increasing TPA has been shown to parallel significant and progressive worsening in health-related quality of life [22]. Ryan et al. suggest a target TPA of 10 degrees such that if any post-operative deterioration occurs, a buffer is well established prior to the severe deformity level of 20 degrees [23].

Pelvic incidence and lumbar lordosis

Pelvic incidence (PI) is defined as the angle between the line perpendicular to the S1 endplate at its midpoint and the line connecting this point to the axis of the femoral head [21] (Fig. 1A). Lumbar lordosis is the angle measured from the superior endplate of L1 to the superior endplate of S1 [21] (Fig. 1B). The difference between the two is known as the PI-LL mismatch and is part of the expanded 2012 Schwab classification. When the mismatch is less than 10 degrees, the modifier is "0", when it is between 10 and 20, the modifier is "+" and greater than 20, the modifier is "+ +" [16]. This parameter correlates with health related quality of life scores [17] and authors note that matching these parameters with osteotomies during surgery can result in harmonious correction in ASD [15].

Roussouly classification system

More recently, it has been proposed that these parameters interact more than previously appreciated. In 2005, the Roussouly classification was introduced [24] and argued that characteristics of the lumbar lordosis are most dependent on the orientation of the sacral slope and the pelvis. Originally, four subgroups were identified, type 1 and 2 with a low PI, and type 3 and 4 with a high PI. Type 1 has a low sacral slope, low lordotic apex and higher compensatory kyphosis. Type 2 also has a low sacral slope but with a slightly higher lordotic apex and thoracic hypokyphosis. Type 3 patients have a moderate sacral slope and higher lordotic apex and tend to be relatively balanced. Finally, type 4 are patients with high sacral slope and a resulting high lordotic apex [24]. In 2018, this classification was amended to include a group of patients (group 3, anteverted) with low PI but high sacral slope [25]. In 2020, Sebaaly et al. showed that restoring the shape of the spine according to this classification decreased the combined rate of proximal junctional kyphosis fracture of the rods, loosening of the instrumentation or clear nonunion on imaging by threefold [26]. This relatively innovative thinking focuses on the shape of the entire spine according to PI and represents a significant advancement in the diagnosis and understanding of ASD.

Global coronal alignment

While sagittal imbalance has been the focus of correction in ASD, global coronal malignment (GCM) is gaining traction as being a significant predictor of poor outcomes in ASD [27]. Zuckerman et al. proposed a coronal vertical axis (CVA) of > 3 cm as the definition of GCM with the Qiu classification to describe curve directionality [28]. Disturbance of the global coronal alignment can be attributed to a progressive baseline deformity or, often, as an iatrogenic complication of prior surgery [27, 28]. The International Spine Study Group performed a multicenter prospective study showing an 25.7% incidence of coronal imbalance after ASD surgery and in patients undergoing upper thoracic fusion was associated with worse clinical outcomes than after lower thoracic fusions [27]. The same group demonstrated that a residual GCM of > / = 3 cm was associated with worse patient reported outcomes which is a finding recapitulated in other studies [29–31]. Coronal deformity was interestingly removed from the Scoliosis Research Society (SRS)-Schwab ASD classification after the 2006 iteration but is regaining recognition as an important measurement in ASD [32].

Age specific parameters

Lafage, et al. classified the spinopelvic parameters listed above into age related categories [33]. Using age specific US normative ODI values, the authors established age-specific spinopelvic parameters. In general, the ideal spino-pelvic alignment parameters increased with age, indicating that these patients tolerate a higher baseline deformity [33]. With increasing efforts to deliver patient specific care, these values allow the spine surgeon to target ideals for surgical correction of ASD on an individual patient basis.

Imaging

Importantly, all the parameters that comprise bony spinopelvic alignment are measured on x-ray with the patient in the standing position. Long cassette standing films allow the surgeon to evaluate global spinopelvic alignment to better plan for surgery [34]. Multiple studies have shown that patients while standing show significantly different parameters when compared to any variant of seated position [35]. Innovation in this field has centered around optimizing both image capture and post processing/analysis. Recently, there has been development of a simultaneous anterior–posterior and lateral plane x-ray to image the full body of the patient [36]. This accession allows for the measurement of the stated parameters as well as a 3D analysis to improve the overall understanding of the patient's anatomy [36]. Innovative software analysis simplifies user and physician calculations of spinopelvic parameters using validated tools such a Surgimap Spine Software (Nemaris Inc, New York, NY) [37]. Understanding and advancements in assessing bony spinopelvic parameters are paramount, however, there is growing evidence regarding the impact of paraspinal muscle sarcopenia on surgical outcomes in ASD. Sarcopenia is defined as muscle atrophy with replacement by fatty infiltrates, findings that can be identified on pre-operative magnetic resonance imaging and quantified by muscle cross sectional area [38, 39]. Specifically, paraspinal sarcopenia has been associated with not only the development of ASD, but also surgical outcomes such as increased rates of proximal junctional kyphosis and failure [38, 39]. Further study into the association of paraspinal sarcopenia with ASD outcomes and pre-operative strategies to optimize paraspinal musculature health is needed.

Advances in 3-Dimensional (3D) printing in adult spinal deformity

A recent advancement in medicine has been the use of 3D printing to influence multiple aspects of care. In spine surgery, 3D models have been used for pre-operative surgical planning and surgical guides [40]. These 3D models have been shown to decrease time in the operating room with an average reduction of 45.5 min. They can also reduce the use of fluoroscopy thus reducing surgeon and patient exposure to ionizing radiation [40]. Surgical guides have the potential to improve outcomes as they serve as both a tactile and visual aid that can be placed on the patient's bone to confirm landmarks and improve accuracy of implant insertion [41, 42].

3D printed surgical implants have also been developed and can optimize surgical outcomes both in terms of increased rates of osteogenesis and decreased rates of hardware failure. In comparison to polyetheretherketone and titanium alloy cages, 3D printed biomimetic titanium showed 2.6 and 8.9 times the amount of bony ongrowth at 12 weeks, respectively [43]. In the same study, though eventually comparable at 12 weeks, the boney ingrowth was faster in the 3d printed implant and was significantly higher at 6 weeks than the other two implant types [43]. Furthermore, 3D printing has allowed customizable implants in the setting of gross deformity from pathologies such as tumor [44] or osteoporotic fracture [45].

Intraoperative advances in adult spinal deformity

Minimally invasive deformity surgery

Increasing efforts to ameliorate the surgical burden of spine surgery on the patient have been undertaken in recent years using minimally invasive surgery (MIS). Specifically, the goal is to decrease iatrogenic tissue damage and improve clinical outcomes with a favorable socioeconomic balance [46]. The use of MIS technology for ASD is being further defined in the literature. Authors advocate for strict patient selection criteria such as a cobb angle greater than 90 (Fig. 1F), an SVA greater than 10 cm, the presence of a fixed deformity, and/or osteoporotic patients [47]. As with open surgical approaches, preoperative standing x-rays to assess these spinal parameters are essential to patient selection and pre-operative planning. Careful patient selection allows for the application of single stage MIS, combined MIS anterior/lateral and MIS posterior approaches, known as circumferential MIS (cMIS), or hybrid MIS and open cases [48]. In a comparison of hybrid MIS and cMIS, the hybrid group had a higher complication rate of 55% vs 33% in the cMIS group [49]. More recently, Uribe et al. published overall complication rates of cMIS, hybrid MIS and open surgery, and showed no significant difference amongst the groups. There was, however, significantly less intraoperative complications in the cMIS group which may be related to reportedly lower blood loss [50]. Most notably, studies show that outcomes as measured by ODI and Visual Analog Score (VAS) were not significantly different postoperatively [49, 50]. Regardless of MIS approach, intra-operative x-rays are necessary for real-time localization, and post-operative standing x-rays provide the surgeon the ability to critically assess their correction and should be utilized similar to the post-operative care in an open approach.

Intraoperative full body films

Spine surgeons have difficulty in accurately predicting postoperative radiographic parameters based on the preoperative films and proposed plan [35]. This difficulty tends to extend to the operating room given that traditionally, spinopelvic parameters are measured on x-rays that are taken while a patient is standing. Intraoperative films while a patient is recumbent do not provide the same load bearing changes in the spine as a person that is standing. Salem et al. determined that though segmental lumbar lordosis improved on intraoperative x-rays, this improvement was lost at 6 month postoperative follow up x-rays [51]. As such, a modern innovation in spine surgery is the development of intraoperative long films and algorithms to correlate this to postoperative radiographic outcomes [52]. For instance, it has been postulated that L4-S1 intraoperative lordosis is, on average, 4 degrees greater than postoperative measurements [53]. Other studies have suggested that measuring global alignment parameters such as the TPA with intraoperative long films has much greater ability to predict postoperative alignment when compared to regional values such as the lumbar lordosis [54]. Ultimately, furthering this understanding and technology of intraoperative imaging will allow spine surgeons to more accurately target specific intraoperative goals to improve postoperative alignment and outcomes.

Intraoperative navigation and robotics

Correction of ASD is achieved through pedicle screw placement and subsequent correction to normal values described above. Patients with 3D rotations or abnormal pedicles present a significant difficulty when considering standard "free-hand" or fluoroscopic techniques [55]. As such, advances in intraoperative navigation have improved technical outcomes in these patients. Pedicle breach in pediatric deformity has been shown to be significantly decreased when navigation was used – from 23% in the fluoroscopy group to 2% in the navigation group [56].

More recently, robotic assistance, especially in combination with navigation has come into favor when treating deformity, especially when doing so using minimally invasive techniques [57, 58]. Roser et al. proposed that the ideal robot is semi-autonomous with the surgeon guiding the robot, but maintaining control of the surgery to diminish the safety risks associated with inadvertent motion causing registration to the patient to be inaccurate leading to misplaced instrumentation and possible neurological injury or need for reoperation [58, 59]. Robotic pedicle screw placement has been found to be more accurate with decreased revision rates and less radiation exposure to the surgeon and patient when compared to conventional techniques [58–61]. It can also allow for safe placement of larger screws [62]. That being said, robotic technology has not been adequately studied in the ASD population [55], and it is not clear if the relatively small improvement in accuracy offsets the financial cost, the learning curve or the potential safety risks with inaccurate patient registration [58, 60]. For example, the learning curve of using robotic systems is surpassed at approximately 20–30 cases; therefore, the most experienced surgeons will suffer from setbacks in their day-to-day practice when adopting this technology. Additionally, less experienced surgeons that begin to use robotics are compromising their surgical learning as well as their ability to teach traditional "free hand" or fluoroscopic techniques to trainees [63]. The need for continued traditional training is necessary, as not all residents graduating their program will practice in an area that has or can afford to purchase robotic technology. Though well versed in pedicle screw placement, at their current state, spinal robots cannot assist with rod placement or creation, decortication, or decompression [64]. It is likely that spinal robots will expand their capabilities tremendously in the coming years and "the future is bright" for this technology improving outcomes in spine surgery [64, 65].

Osteotomies

In the surgical treatment of ASD, surgeons typically employ advanced osteotomies to obtain improved sagittal and coronal balance. In 2014, Schwab et al. proposed a classification system for these osteotomies to codify understanding and discussion amongst surgeons [66]. Graded from 1 to 6, these osteotomies become increasingly technically complex with an increased risk, but also offer a greater degree of correction [67]. Grades 1 and 2 osteotomies are performed from a posterior approach and involve the facet only. As such, they require anterior column mobility to be truly effective [1]. Grade 3 osteotomy involves resection of the bilateral pedicles and a wedge of vertebral body while grade 4 extends this into the disc space above [66]. Finally, grades 5 and 6 involve resection of an entire vertebral level and multiple levels, respectively [66]. With increasing grade of osteotomy, particularly when involving all three columns of the spine, blood loss can be significant. Previous studies have shown increased blood loss to be associated with longer intensive care and overall length of stays [68]. With increased experience and the use of antifibrinolytics such as tranexamic acid (TXA), however, intraoperative blood loss can be lessened with the presumed benefit of decreased morbidity [69].

Patient specific instrumentation

Instrumentation fit to a patient's specific anatomy is being developed in tandem with improvements in preoperative planning software [70]. Pre-bent rods (MEDICREA Group, New York, USA) is an example of such a technology which holds promise of maintaining the maximum deformity correction initially planned without the need to bend a rod manually in the operating room. Small retrospective studies have shown a decrease in rod breakage and a significant correlation between planned and postoperative spinopelvic parameters with prefabricated rods [70–72]. Recently, four-rod, or quad-rod, constructs have begun to be used more frequently across sites of notable instability, such as an osteotomy, unique to the individual patient. Data thus far has shown that quad rod constructs reduce motion and construct stress thereby promoting enhanced rates of arthrodesis and lower rates of revision [73–75]. Additionally, the advent of trans-psoas and anterior-to-psoas approaches to the lumbar spine's intervertebral discs has led to increased ability to instrument the lumbar spine's anterior and middle columns. This technology bolsters significant power to restore lumbar lordosis, as interbody placement necessitates release of the anterior longitudinal ligament and annulus fibrosis during discectomy. They also carry similar reoperation rates while avoiding the higher rates of morbidity when compared to higher grade posterior approach osteotomies. Taken together, the success of the lumbar interbody fusion has resulted in a steady increase in their utilization with a corresponding decrease in pedicle subtraction osteotomy rates since 2010 [76, 77]. Despite promising technology, long-term, prospective studies are needed to better understand the benefits and potential pitfalls of patient-specific instrumentation.

Fusion generation

High rates of pseudoarthrosis have plagued long term stability of correction in ASD, being reported between 17 and 24% of cases [78, 79]. Recent advances in biologics have begun to correct this issue. Recombinant Human Bone Morphogenetic Protein-2 (BMP) was developed and shown to promote anterior interbody fusion in a nonhuman primate model leading to Federal Drug Administration (FDA) approval for the use in anterior lumbar interbody fusions [80]. BMP is now frequently used off-label in the surgical treatment of ASD with 24 month radiographic fusion rates of 100% being reported [81, 82]. Data has raised concerns over the early off-label use of BMP, specifically due to instances of dysphasia and airway compromise from bony growth in anterior cervical fusions, heterotopic ossification, osteolysis, seroma formation, soft tissue swelling and pain [83]. Newer data reported by Bess et al., however, has shown that it does not increase acute major, neurological, or wound complications [84]. In addition, a recent meta-analysis by Poorman et al. has shown BMP use to be associated with higher rates of arthrodesis without a significant relationship to tumorigenesis, infections, seroma formation, or osteolysis and in fact, spine surgeons may be underdosing BMP based on manufacturer recommendations [85].

Tethers

Another area of emerging technology to combat PJK is the inclusion of posterior polyethylene junctional tethers in fusion constructs. The reason for this decrease in PJK may be attributed to a more favorable biomechanical profile; reducing proximal intradiscal pressures, transmitting the force to the posterior ligament complex and increased pedicle screw loading. This technique involves the spinous process at and above the upper instrumented vertebrae, connecting them using polyethylene tape using maximal tension [78, 86]. Buell et al. presented the largest clinical study demonstrating a decrease in PJK rates after using both tape-only and cross-linking tethers in multi-level spinal instrumentation [86]. Further study is needed in this area, but it holds promise to potential reduce rates of PJK and PJF in this population.

Postoperative advances in adult spinal deformity

Recently, emphasis has been placed upon enhanced recovery after surgery (ERAS) programs to examine the delivery of quality care and improve outcomes with lower costs [87]. In a recent systematic review, early postoperative mobilization, postoperative analgesia, early urinary catheter and drain removal, and early diet advancement were associated with shorter hospitalizations, lower postoperative complication rates, and lower postoperative pain scores [87]. Use of ultrasound guided erector spinae and thoracolumbar interfascial plane blocks have been shown to improve postoperative pain control and reduced opioid usage [88, 89]. These improvements may result in early mobilization and shorter hospital stays. Overall, ERAS programs have been designed to improve patient outcomes, however, there are intrinsically high complication rates in ASD surgery ranging from ~ 8–70% in current literature [90]. Despite high complication rates, efforts such as ERAS have led to surgical outcomes outperforming non-operative care in ASD [4].

Conclusion

Adult spinal deformity, defined as abnormal alignment of the thoracic and lumbar spine in those who have finished growth is becoming a more ubiquitous diagnosis for spine surgeons with an increasing aging population. This progressive disease process is associated with significant physical and mental debility in symptomatic patients. Multiple measurements are helpful in determining the diagnosis of ASD, including SVA, PT, PI, LL and TPA, but a focus on harmonic, age-appropriate correction should be pursued. 3D printing and modelling have created patient specific implants to improve final correction. Intraoperative advancements in minimally invasive surgery, imaging, robotics, navigation, surgical techniques and biologics have allowed surgeons to achieve correction in even the most difficult cases. Finally, postoperative protocols and optimized pain management strategies have allowed patients to mobilize earlier and begin on the road of recovery in an expedited fashion.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08497-z.

Supplementary Material 1.

Acknowledgements
Not applicable.

Authors' contributions
All authors—all authors wrote and reviewed the manuscript in entirety.

Funding
Not applicable.

Data availability
Not applicable.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 18 August 2023 Accepted: 4 March 2025
Published online: 18 March 2025

References

1. Diebo B, Liu S, Lafage V, Schwab F. Osteotomies in the treatment of spinal deformities: indications, classification, and surgical planning. Eur J Orthop Surg Traumatol. 2014;24(Suppl 1):S11-20. https://doi.org/10.1007/s00590-014-1471-7.
2. McCarthy I, Hostin R, O'Brien M, Saigal R, Ames CP. Health economic analysis of adult deformity surgery. Neurosurg Clin N Am. 2013;24(2):293–304. https://doi.org/10.1016/j.nec.2012.12.005.
3. Diebo BG, Shah NV, Boachie-Adjei O, et al. Adult spinal deformity. Lancet. 2019;394(10193):160–72. https://doi.org/10.1016/S0140-6736(19)31125-0.
4. Safaee MM, Ames CP, Smith JS. Epidemiology and Socioeconomic Trends in Adult Spinal Deformity Care. Neurosurgery. 2020;87(1):25–32. https://doi.org/10.1093/neuros/nyz454.
5. Lutz W, Sanderson W, Scherbov S. The coming acceleration of global population ageing. Nature. 2008;451(7179):716–9. https://doi.org/10.1038/nature06516.
6. Zygourakis CC, Liu CY, Keefe M, et al. Analysis of National Rates, Cost, and Sources of Cost Variation in Adult Spinal Deformity. Neurosurgery. 2018;82(3):378–87. https://doi.org/10.1093/neuros/nyx218.
7. Wadhwa H, Leung C, Sklar M, et al. Utilization Trends, Cost, and Payments for Adult Spinal Deformity Surgery in Commercial and Medicare-Insured Populations. Neurosurgery. 2022;91(6):961–8. https://doi.org/10.1227/neu.0000000000002140.
8. Fehlings MG, Tetreault L, Nater A, et al. The Aging of the Global Population: The Changing Epidemiology of Disease and Spinal Disorders. Neurosurgery. 2015;77(Suppl 4):S1-5. https://doi.org/10.1227/NEU.0000000000000953.
9. Gupta A, Cha T, Schwab J, et al. Osteoporosis is under recognized and undertreated in adult spinal deformity patients. J Spine Surg. 2021;7(1):1–7. https://doi.org/10.21037/jss-20-668.
10. Jawa RS, Singer AJ, Rutigliano DN, et al. Spinal Fractures in Older Adult Patients Admitted After Low-Level Falls: 10-Year Incidence and Outcomes. J Am Geriatr Soc. 2017;65(5):909–15. https://doi.org/10.1111/jgs.14669.
11. Kim DH, Vaccaro AR. Osteoporotic compression fractures of the spine; current options and considerations for treatment. Spine J Sep-Oct. 2006;6(5):479–87. https://doi.org/10.1016/j.spinee.2006.04.013.
12. Bess S, Line B, Fu KM, et al. The Health Impact of Symptomatic Adult Spinal Deformity: Comparison of Deformity Types to United States Population Norms and Chronic Diseases. Spine (Phila Pa 1976). 2016;41(3):224–33. https://doi.org/10.1097/BRS.0000000000001202.
13. Baldus C, Bridwell KH, Harrast J, et al. Age-gender matched comparison of SRS instrument scores between adult deformity and normal adults: are all SRS domains disease specific? Spine (Phila Pa 1976). 2008;33(20):2214–8. https://doi.org/10.1097/BRS.0b013e31817c0466.
14. Schwab F, Dubey A, Pagala M, Gamez L, Farcy JP. Adult scoliosis: a health assessment analysis by SF-36. Spine (Phila Pa 1976). 2003;28(6):602–6. https://doi.org/10.1097/01.BRS.0000049924.94414.BB.
15. Schwab F, Farcy JP, Bridwell K, et al. A clinical impact classification of scoliosis in the adult. Spine (Phila Pa 1976). 2006;31(18):2109–14. https://doi.org/10.1097/01.brs.0000231725.38943.ab.
16. Schwab F, Ungar B, Blondel B, et al. Scoliosis Research Society-Schwab adult spinal deformity classification: a validation study. Spine (Phila Pa 1976). 2012;37(12):1077–82. https://doi.org/10.1097/BRS.0b013e31823e15e2.
17. Lafage V, Schwab F, Patel A, Hawkinson N, Farcy JP. Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine (Phila Pa 1976). 2009;34(17):E599-606. https://doi.org/10.1097/BRS.0b013e3181aad219.
18. Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR. Correlation of radiographic parameters and clinical symptoms in adult scoliosis. Spine (Phila Pa 1976). 2005;30(6):682–8. https://doi.org/10.1097/01.brs.0000155425.04536.f7.
19. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976). 2010;35(25):2224–31. https://doi.org/10.1097/BRS.0b013e3181ee6bd4.
20. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. Spine (Phila Pa 1976). 2005;30(18):2024–9. https://doi.org/10.1097/01.brs.0000179086.30449.96.
21. Legaye J, Duval-Beaupere G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J. 1998;7(2):99–103. https://doi.org/10.1007/s005860050038.
22. Protopsaltis T, Schwab F, Bronsard N, et al. TheT1 pelvic angle, a novel radiographic measure of global sagittal deformity, accounts for both spinal inclination and pelvic tilt and correlates with health-related quality of life. J Bone Joint Surg Am. 2014;96(19):1631–40. https://doi.org/10.2106/JBJS.M.01459.
23. Ryan DJ, Protopsaltis TS, Ames CP, et al. T1 pelvic angle (TPA) effectively evaluates sagittal deformity and assesses radiographical surgical outcomes longitudinally. Spine (Phila Pa 1976). 2014;39(15):1203–10. https://doi.org/10.1097/BRS.0000000000000382.
24. Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. Spine (Phila Pa 1976). 2005;30(3):346–53. https://doi.org/10.1097/01.brs.0000152379.54463.65.
25. Laouissat F, Sebaaly A, Gehrchen M, Roussouly P. Classification of normal sagittal spine alignment: refounding the Roussouly classification. Eur Spine J. 2018;27(8):2002–11. https://doi.org/10.1007/s00586-017-5111-x.
26. Sebaaly A, Gehrchen M, Silvestre C, et al. Mechanical complications in adult spinal deformity and the effect of restoring the spinal shapes according to the Roussouly classification: a multicentric study. Eur Spine J. 2020;29(4):904–13. https://doi.org/10.1007/s00586-019-06253-1.
27. Buell TJ, Shaffrey CI, Kim HJ, et al. Global coronal decompensation and adult spinal deformity surgery: comparison of upper-thoracic versus lower-thoracic proximal fixation for long fusions. J Neurosurg Spine. 2021;35(6):761–73. https://doi.org/10.3171/2021.2.SPINE201938.
28. Zuckerman SL, Cerpa M, Lai CS, Lenke LG. Coronal Alignment in Adult Spinal Deformity Surgery: Definitions, Measurements, Treatment Algorithms, and Impact on Clinical Outcomes. Clin Spine Surg. 2022;35(5):196–203. https://doi.org/10.1097/BSD.0000000000001175.

29. Buell TJ, Smith JS, Shaffrey CI, et al. Multicenter assessment of surgical outcomes in adult spinal deformity patients with severe global coronal malalignment: determination of target coronal realignment threshold. J Neurosurg Spine. 2021;34(3):399–412. https://doi.org/10.3171/2020.7.SPINE20606.
30. Lewis SJ, Keshen SG, Kato S, Dear TE, Gazendam AM. Risk Factors for Postoperative Coronal Balance in Adult Spinal Deformity Surgery. Global Spine J. 2018;8(7):690–7. https://doi.org/10.1177/2192568218764904.
31. Smith JS, Lafage V, Shaffrey CI, et al. Outcomes of Operative and Nonoperative Treatment for Adult Spinal Deformity: A Prospective, Multicenter, Propensity-Matched Cohort Assessment With Minimum 2-Year Follow-up. Neurosurgery. 2016;78(6):851–61. https://doi.org/10.1227/NEU.0000000000001116.
32. Lowe T, Berven SH, Schwab FJ, Bridwell KH. The SRS classification for adult spinal deformity: building on the King/Moe and Lenke classification systems. Spine (Phila Pa 1976). 2006;31(19 Suppl):S119-25. https://doi.org/10.1097/01.brs.0000232709.48446.be.
33. Lafage R, Schwab F, Challier V, et al. Defining Spino-Pelvic Alignment Thresholds: Should Operative Goals in Adult Spinal Deformity Surgery Account for Age? Spine (Phila Pa 1976). 2016;41(1):62–8. https://doi.org/10.1097/BRS.0000000000001171.
34. Ramchandran S, Smith JS, Ailon T, et al. Assessment of Impact of Long-Cassette Standing X-Rays on Surgical Planning for Cervical Pathology: An International Survey of Spine Surgeons. Neurosurgery. 2016;78(5):717–24. https://doi.org/10.1227/NEU.0000000000001128.
35. Alamin TF, Agarwal V, Zagel A, Qeli A. The effect of standing vs. variants of the seated position on lumbar intersegmental angulation and spacing: a radiographic study of 20 asymptomatic subjects. J Spine Surg. 2018;4(3):509–15. https://doi.org/10.21037/jss.2018.08.03.
36. Illes T, Somoskeoy S. The EOS imaging system and its uses in daily orthopaedic practice. Int Orthop. 2012;36(7):1325–31. https://doi.org/10.1007/s00264-012-1512-y.
37. Lafage R, Ferrero E, Henry JK, et al. Validation of a new computer-assisted tool to measure spino-pelvic parameters. Spine J. 2015;15(12):2493–502. https://doi.org/10.1016/j.spinee.2015.08.067.
38. Kim WJ, Shin HM, Lee JS, et al. Sarcopenia and Back Muscle Degeneration as Risk Factors for Degenerative Adult Spinal Deformity with Sagittal Imbalance and Degenerative Spinal Disease: A Comparative Study. World Neurosurg. 2021;148:e547–55. https://doi.org/10.1016/j.wneu.2021.01.053.
39. Park JS, Cho KJ, Kim JS, Park SJ, Baek H. Sarcopenia in paraspinal muscle as a risk factor of proximal junctional kyphosis and proximal junctional failure after adult spinal deformity surgery. J Neurosurg Spine. 2024;40(3):324–30. https://doi.org/10.3171/2023.9.SPINE23531.
40. Tack P, Victor J, Gemmel P, Annemans L. 3D-printing techniques in a medical setting: a systematic literature review. Biomed Eng Online. 2016;15(1):115. https://doi.org/10.1186/s12938-016-0236-4.
41. D'Urso PS, Williamson OD, Thompson RG. Biomodeling as an aid to spinal instrumentation. Spine (Phila Pa 1976). 2005;30(24):2841–5. https://doi.org/10.1097/01.brs.0000190886.56895.3d.
42. Mao K, Wang Y, Xiao S, et al. Clinical application of computer-designed polystyrene models in complex severe spinal deformities: a pilot study. Eur Spine J. 2010;19(5):797–802. https://doi.org/10.1007/s00586-010-1359-0.
43. Van Horn MR, Beard R, Wang W, et al. Comparison of 3D-printed titanium-alloy, standard titanium-alloy, and PEEK interbody spacers in an ovine model. Spine J. 2021;21(12):2097–103. https://doi.org/10.1016/j.spinee.2021.05.018.
44. Mobbs RJCM, Thompson R, Sutterlin CE. Phan K The utility of 3D printing for surgical planning and patient-specific implant design for complex spinal pathologies: case report. J Neurosurg Spine. 2017;26(4):513–8. https://doi.org/10.3171/2016.9.SPINE16371.
45. Siu TL, Rogers JM, Lin K, Thompson R, Owbridge M. Custom-Made Titanium 3-Dimensional Printed Interbody Cages for Treatment of Osteoporotic Fracture-Related Spinal Deformity. World Neurosurg. 2018;111:1–5. https://doi.org/10.1016/j.wneu.2017.11.160.
46. McAfee PC, Phillips FM, Andersson G, et al. Minimally invasive spine surgery. Spine (Phila Pa 1976). 2010;35(26 Suppl):S271-3. https://doi.org/10.1097/BRS.0b013e31820250a2.
47. Anand N, Baron EM. Minimally invasive approaches for the correction of adult spinal deformity. Eur Spine J. 2013;22 Suppl 2(Suppl 2):S232-41. https://doi.org/10.1007/s00586-012-2344-6.
48. Kanter AS, Tempel ZJ, Ozpinar A, Okonkwo DO. A Review of Minimally Invasive Procedures for the Treatment of Adult Spinal Deformity. Spine (Phila Pa 1976). 2016;41(Suppl 8):S59-65. https://doi.org/10.1097/BRS.0000000000001481.
49. Park P, Wang MY, Lafage V, et al. Comparison of two minimally invasive surgery strategies to treat adult spinal deformity. J Neurosurg Spine. 2015;22(4):374–80. https://doi.org/10.3171/2014.9.SPINE131004.
50. Uribe JS, Deukmedjian AR, Mummaneni PV, et al. Complications in adult spinal deformity surgery: an analysis of minimally invasive, hybrid, and open surgical techniques. Neurosurg Focus. 2014;36(5):E15. https://doi.org/10.3171/2014.3.FOCUS13534.
51. Salem KMI, Eranki AP, Paquette S, et al. Do intraoperative radiographs predict final lumbar sagittal alignment following single-level transforaminal lumbar interbody fusion? J Neurosurg Spine. 2018;28(5):486–91. https://doi.org/10.3171/2017.8.SPINE161231.
52. Praeger AJ, Wang YYI, Goldschlager T. Intraoperatively predicting postoperative sagittal balance using intraoperative X-rays. J Clin Neurosci. 2019;63:48–54. https://doi.org/10.1016/j.jocn.2019.02.008.
53. Greimel F, Wolkerstorfer S, Sporrer JF, et al. Radiological outcome of postoperative sagittal balance on standing radiographs in comparison to intraoperative radiographs in prone position when performing lumbar spinal fusion. Arch Orthop Trauma Surg. 2017;137(10):1319–25. https://doi.org/10.1007/s00402-017-2755-2.
54. Vaynrub M, Hirsch BP, Tishelman J, et al. Validation of prone intraoperative measurements of global spinal alignment. J Neurosurg Spine. 2018;29(2):187–92. https://doi.org/10.3171/2018.1.SPINE17808.
55. Boddapati V, Lombardi JM, Urakawa H, Lehman RA. Intraoperative image guidance for the surgical treatment of adult spinal deformity. Ann Transl Med. 2021;9(1):91. https://doi.org/10.21037/atm-20-2765.
56. Rajasekaran S, Vidyadhara S, Ramesh P, Shetty AP. Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. Spine (Phila Pa 1976). 2007;32(2):E56-64. https://doi.org/10.1097/01.brs.0000252094.64857.ab.
57. Mattei TA, Rodriguez AH, Sambhara D, Mendel E. Current state-of-the-art and future perspectives of robotic technology in neurosurgery. Neurosurg Rev. 2014;37(3):357–66; discussion 366. https://doi.org/10.1007/s10143-014-0540-z.
58. Roser F, Tatagiba M, Maier G. Spinal robotics: current applications and future perspectives. Neurosurgery. 2013;72(Suppl 1):12–8. https://doi.org/10.1227/NEU.0b013e318270d02c.
59. Soliman MAR, Pollina J, Poelstra K, Chaudhary S, Foley K. Can a Spine Robot Be More Efficient and Less Expensive While Maintaining Accuracy? Int J Spine Surg. 2022;16(S2):S50–4. https://doi.org/10.14444/8277.
60. Farber SH, Pacult MA, Godzik J, et al. Robotics in Spine Surgery: A Technical Overview and Review of Key Concepts. Front Surg. 2021;8:578674. https://doi.org/10.3389/fsurg.2021.578674.
61. Li C, Li W, Gao S, et al. Comparison of accuracy and safety between robot-assisted and conventional fluoroscope assisted placement of pedicle screws in thoracolumbar spine: A meta-analysis. Medicine (Baltimore). 2021;100(38):e27282. https://doi.org/10.1097/MD.0000000000027282.
62. Shafi KA, Pompeu YA, Vaishnav AS, et al. Does robot-assisted navigation influence pedicle screw selection and accuracy in minimally invasive spine surgery? Neurosurg Focus. 2022;52(1):E4. https://doi.org/10.3171/2021.10.FOCUS21526.
63. Khalifeh K, Brown NJ, Pennington Z, Pham MH. Spinal Robotics in Adult Spinal Deformity Surgery: A Systematic Review. Neurospine. 2024;21(1):20–9. https://doi.org/10.14245/ns.2347138.569.
64. Liounakos JI, Chenin L, Theodore N, Wang MY. Robotics in Spine Surgery and Spine Surgery Training. Oper Neurosurg (Hagerstown). 2021;21(2):35–40. https://doi.org/10.1093/ons/opaa449.
65. Lubelski D, Theodore N. Editorial. Benefits of robotic spine surgery: the future is bright. Neurosurg Focus. 2022;52(1):E5. https://doi.org/10.3171/2021.10.FOCUS21635.
66. Schwab F, Blondel B, Chay E, et al. The comprehensive anatomical spinal osteotomy classification. Neurosurg. 2014;74(1):112–20; discussion 120. https://doi.org/10.1227/NEU.0000000000000182o.
67. Bianco K, Norton R, Schwab F, et al. Complications and intercenter variability of three-column osteotomies for spinal deformity surgery: a retrospective review of 423 patients. Neurosurg Focus. 2014;36(5):E18. https://doi.org/10.3171/2014.2.FOCUS1422.

68. Wathen C, Dagli MM, Santangelo G, et al. Blood loss during three column osteotomies: influence on outcomes and mitigation strategies. J Spine Surg. 2024;10(3):395–402. https://doi.org/10.21037/jss-23-143.
69. Peters A, Verma K, Slobodyanyuk K, et al. Antifibrinolytics reduce blood loss in adult spinal deformity surgery: a prospective, randomized controlled trial. Spine (Phila Pa 1976). 2015;40(8):E443-9. https://doi.org/10.1097/BRS.0000000000000799.
70. Sadrameli SS, Boghani Z, Steele Iii WJ, Holman PJ. Utility of Patient-Specific Rod Instrumentation in Deformity Correction: Single Institution Experience. Spine Surg Relat Res. 2020;4(3):256–60. https://doi.org/10.22603/ssrr.2019-0101.
71. Barton C, Noshchenko A, Patel V, Kleck C, Burger E. Early Experience and Initial Outcomes With Patient-Specific Spine Rods for Adult Spinal Deformity. Orthopedics Mar-Apr. 2016;39(2):79–86. https://doi.org/10.3928/01477447-20160304-04.
72. Picton B, Stone LE, Liang J, et al. Patient-specific rods in adult spinal deformity: a systematic review. Spine Deform. 2024;12(3):577–85. https://doi.org/10.1007/s43390-023-00805-8.
73. Panico M, Chande RD, Lindsey DP, et al. High-Demand Spinal Deformity With Multi-Rod Constructs and Porous Fusion/Fixation Implants: A Finite Element Study. Global Spine J. 2024;14(4):1328–36. https://doi.org/10.1177/21925682221141874.
74. Sherif S, Arlet V. Revision surgery for non-union in adult spinal deformity. Eur Spine J. 2020;29(Suppl 1):103–15. https://doi.org/10.1007/s00586-020-06331-9.
75. Sherif S, Ling J, Zapolsky I, et al. Pelvic Fixation With a Quad-Rod Technique Using S2 Alar Iliac and Medialized Entry Iliac Screws for Long Fusion Constructs. J Am Acad Orthop Surg Glob Res Rev. 2023;7(8):e22.00251. https://doi.org/10.5435/JAAOSGlobal-D-22-00251.
76. Chan AK, Mummaneni PV, Shaffrey CI. Approach Selection: Multiple Anterior Lumbar Interbody Fusion to Recreate Lumbar Lordosis Versus Pedicle Subtraction Osteotomy: When, Why, How? Neurosurg Clin N Am. 2018;29(3):341–54. https://doi.org/10.1016/j.nec.2018.03.004.
77. Chi J, Zhang Y, Fontaine A, et al. Pedicle Subtraction Osteotomy Versus Multilevel Anterior Lumbar Interbody Fusion and Lateral Lumbar Interbody Fusion in the Treatment of Adult Spinal Deformity: Trends, Outcomes, and Cost. Clin Spine Surg. 2024;37(5):E192–200. https://doi.org/10.1097/BSD.0000000000001566.
78. Bess S, Harris JE, Turner AW, et al. The effect of posterior polyester tethers on the biomechanics of proximal junctional kyphosis: a finite element analysis. J Neurosurg Spine. 2017;26(1):125–33. https://doi.org/10.3171/2016.6.SPINE151477.
79. Weistroffer JK, Perra JH, Lonstein JE, et al. Complications in long fusions to the sacrum for adult scoliosis: minimum five-year analysis of fifty patients. Spine (Phila Pa 1976). 2008;33(13):1478–83. https://doi.org/10.1097/BRS.0b013e3181753c53.
80. Hecht BP, Fischgrund JS, Herkowitz HN, Penman L, Toth JM, Shirkhoda A. The use of recombinant human bone morphogenetic protein 2 (rhBMP-2) to promote spinal fusion in a nonhuman primate anterior interbody fusion model. Spine (Phila Pa 1976). 1999;24(7):629–36. https://doi.org/10.1097/00007632-199904010-00004.
81. Burkus JK, Dorchak JD, Sanders DL. Radiographic assessment of interbody fusion using recombinant human bone morphogenetic protein type 2. Spine (Phila Pa 1976). 2003;28(4):372–7. https://doi.org/10.1097/01.BRS.0000048469.45035.B9.
82. Burkus JK, Transfeldt EE, Kitchel SH, Watkins RG, Balderston RA. Clinical and radiographic outcomes of anterior lumbar interbody fusion using recombinant human bone morphogenetic protein-2. Spine Spine (Phila Pa 1976). 2002;27(21):2396–408. https://doi.org/10.1097/00007632-200211010-00015.
83. Epstein NE. Complications due to the use of BMP/INFUSE in spine surgery: The evidence continues to mount. Surg Neurol Int. 2013;4(Suppl 5):S343–52. https://doi.org/10.4103/2152-7806.114813.
84. Bess S, Line BG, Lafage V, et al. Does recombinant human bone morphogenetic protein-2 use in adult spinal deformity increase complications and are complications associated with location of rhBMP-2 use? A prospective, multicenter study of 279 consecutive patients. Spine (Phila Pa 1976). 2014;39(3):233–42. https://doi.org/10.1097/BRS.0000000000000104.
85. Poorman GW, Jalai CM, Boniello A, Worley N, McClelland S 3rd, Passias PG. Bone morphogenetic protein in adult spinal deformity surgery: a meta-analysis. Eur Spine J. 2017;26(8):2094–102. https://doi.org/10.1007/s00586-016-4841-5.
86. Buell TJ, Buchholz AL, Quinn JC, et al. A Pilot Study on Posterior Polyethylene Tethers to Prevent Proximal Junctional Kyphosis After Multilevel Spinal Instrumentation for Adult Spinal Deformity. Oper Neurosurg (Hagerstown). 2019;16(2):256–66. https://doi.org/10.1093/ons/opy065.
87. Pennington Z, Cottrill E, Lubelski D, Ehresman J, Theodore N, Sciubba DM. Systematic review and meta-analysis of the clinical utility of Enhanced Recovery After Surgery pathways in adult spine surgery. J Neurosurg Spine. 2021;34(2):325–47. https://doi.org/10.3171/2020.6.SPINE20795.
88. Yayik AM, Cesur S, Ozturk F, et al. Postoperative Analgesic Efficacy of the Ultrasound-Guided Erector Spinae Plane Block in Patients Undergoing Lumbar Spinal Decompression Surgery: A Randomized Controlled Study. World Neurosurg. 2019;126:e779–85. https://doi.org/10.1016/j.wneu.2019.02.149.
89. Ye Y, Bi Y, Ma J, Liu B. Thoracolumbar interfascial plane block for postoperative analgesia in spine surgery: A systematic review and meta-analysis. PLoS ONE. 2021;16(5):e0251980. https://doi.org/10.1371/journal.pone.0251980.
90. Soroceanu A, Burton DC, Oren JH, et al. Medical Complications After Adult Spinal Deformity Surgery: Incidence, Risk Factors, and Clinical Impact. Spine (Phila Pa 1976). 2016;41(22):1718–23. https://doi.org/10.1097/BRS.0000000000001636.

Publisher's Note