Degenerative Spinal Deformity

Tamir Ailon, MD, MPH*
Justin S. Smith, MD, PhD*
Christopher I. Shaffrey, MD, FACS*
Lawrence G. Lenke, MD‡
Darrel Brodke, MD§
James S. Harrop, MD¶
Michael Fehlings, MD, PhD‖
Christopher P. Ames, MD#

*Department of Neurosurgery, University of Virginia Health System, Charlottesville, Virginia; ‡Department of Orthopedic Surgery, Washington University School of Medicine, St. Louis, Missouri; §Department of Orthopedics, University of Utah, Salt Lake City, Utah; ¶Department of Neurosurgery, Thomas Jefferson University, Philadelphia, Pennsylvania; ‖Division of Neurosurgery and Spinal Program, University of Toronto, Toronto, Ontario, Canada; #Department of Neurosurgery, University of California San Francisco, San Francisco, California

Correspondence:
Justin S. Smith, MD, PhD, Department of Neurosurgery, University of Virginia Health Sciences Center, PO Box 800212, Charlottesville, VA 22908.
E-mail: jss7f@virginia.edu

Degenerative spinal deformity afflicts a significant portion of the elderly and is increasing in prevalence. Recent evidence has revealed sagittal plane malalignment to be a key driver of pain and disability in this population and has led to a significant shift toward a more evidence-based management paradigm. In this narrative review, we review the recent literature on the epidemiology, evaluation, management, and outcomes of degenerative adult spinal deformity (ASD). ASD is increasing in prevalence in North America due to an aging population and demographic shifts. It results from cumulative degenerative changes focused in the intervertebral discs and facet joints that occur asymmetrically to produce deformity. Deformity correction focuses on restoration of global alignment, especially in the sagittal plane, and decompression of the neural elements. General realignment goals have been established, including sagittal vertical axis $<$50 mm, pelvic tilt $<$22°, and lumbopelvic mismatch $<\pm$9°; however, these should be tailored to the patient. Operative management, in carefully selected patients, yields satisfactory outcomes that appear to be superior to nonoperative strategies. ASD is characterized by malalignment in the sagittal and/or coronal plane and, in adults, presents with pain and disability. Nonoperative management is recommended for patients with mild, nonprogressive symptoms; however, evidence of its efficacy is limited. Surgery aims to restore global spinal alignment, decompress neural elements, and achieve fusion with minimal complications. The surgical approach should balance the desired correction with the increased risk of more aggressive maneuvers. In well-selected patients, surgery yields excellent outcomes.

KEY WORDS: Adult spinal deformity, Deformity correction, Degenerative spinal deformity, Kyphoscoliosis, Scoliosis

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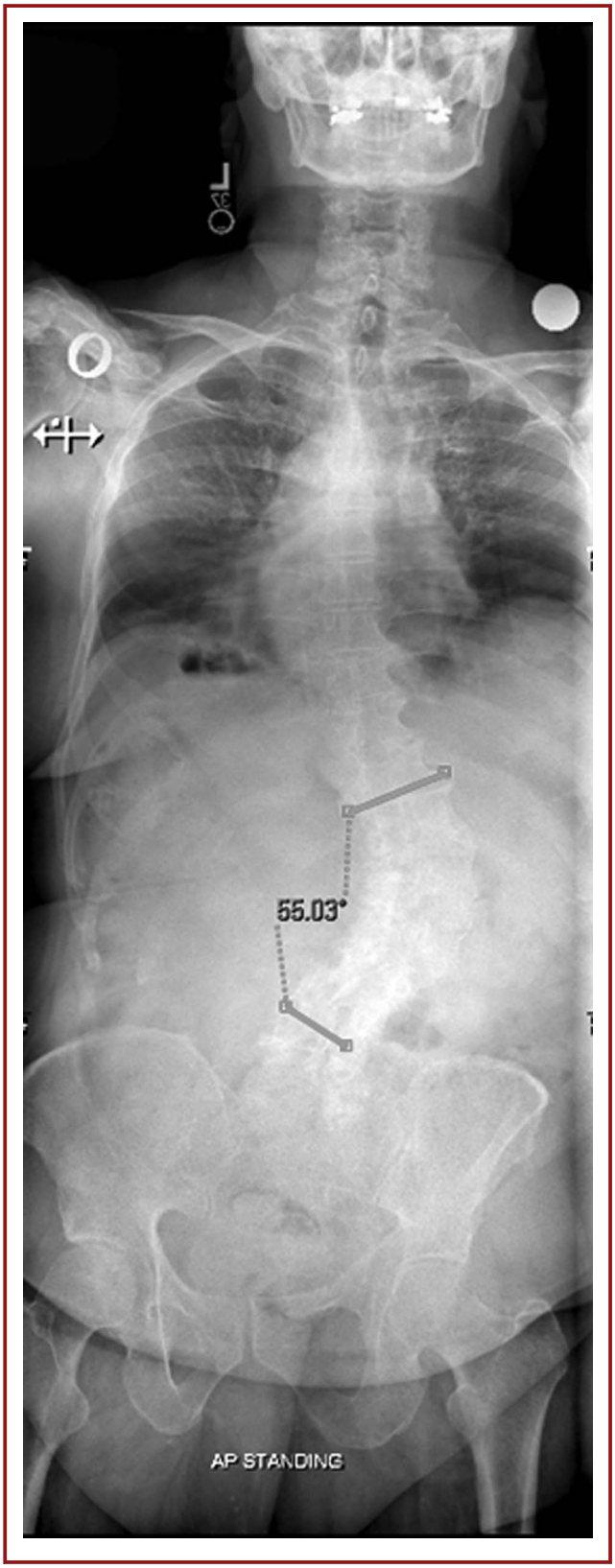
Spinal deformity can be defined as an abnormality in alignment, formation, or curvature of 1 or more portions of the spine. Adult spinal deformity (ASD) describes a wide range of conditions that result in abnormal spinal alignment and may result in pain, disability, neurological impairment, and/or loss of function. Such deformities can involve any combination of the axial, coronal, and sagittal planes.[1] Scoliosis is defined as a lateral spinal curvature $>$10° seen on coronal imaging. There is typically concomitant rotational (axial plane) deformity, and there may also be associated kyphotic or lordotic (sagittal plane) deformity. Recent data have shown the critical importance of sagittal plane deformity, either as a component of scoliosis (kyphoscoliosis) or in isolation (hyperkyphosis/hyperlordosis), in the generation of pain and disability. Isolated sagittal plane deformity, most commonly in the form of uncompensated hyperkyphosis, typically affects older persons and results in an inability to maintain normal upright posture with the head over the pelvis and feet.[1]

Multiple disease processes, individually or in combination, may result in ASD. In younger adults, the most common spinal deformity is

ABBREVIATIONS: ASD, adult spinal deformity; **C7PL,** plumb line dropped from the C7 centroid; **CSVL,** line drawn vertically through the center of the sacrum; **HRQOL,** health-related quality of life; **LL,** lumbar lordosis; **MIS,** minimally invasive surgery; **PA,** posteroanterior; **PI,** pelvic incidence; **PI − LL,** lumbopelvic mismatch; **PJF,** proximal junction failure; **PJK,** proximal junction kyphosis; **PSO,** pedicle subtraction osteotomy; **PT,** pelvic tilt; **SRS,** Scoliosis Research Society; **SS,** sacral slope; **SVA,** sagittal vertical axis; **TK,** thoracic kyphosis; **TLIF,** transforaminal lumbar interbody fusion; **VCR,** vertebral column resection



persistent idiopathic scoliosis, whereas in middle-aged and older adults, degenerative (de novo) scoliosis, degenerative kyphosis, and iatrogenic deformities are more prevalent.[1,2] ASD may also arise from neuromuscular conditions (eg, spinal cord injury, cerebral palsy, syringomyelia, and spinal dysraphism), congenital anomalies (eg, failure of segmentation), trauma, infection, and neoplastic disease. Degenerative spinal deformity arises in individuals without preexisting deformity as a result of cumulative degenerative changes that occur with aging, and is the focus of this review.

EPIDEMIOLOGY AND NATURAL HISTORY

The prevalence of ASD is increasing in North America due to an aging population, demographic shifts, increased life expectancy,[3] and, likely, increased recognition of the disorder. In particular, the number and proportion of Americans older than 65 years of age (in whom degenerative deformity is most prevalent) has increased from 12.5 million (10%) in 1990 to 47.7 million (15%) in 2015 and is projected to increase to 91.5 million (23%) by 2060.[4] The reported prevalence of adult scoliosis ranges from 1% to 30%.[2,5-10] In elderly adults, higher rates have been reported, including 30% of 554 patients between 50 and 84 years old[10] and 68% of 75 asymptomatic volunteers older than 60 years of age.[9] Degenerative scoliosis presents at a mean age of 70.5 years[11] and often occurs in the lumbar spine with coronal curves >10°, an apex at L3, and an associated distal fractional curve between L4 and S1 (Figure 1).[2] Due to the lumbar curve, compensatory (but not structural) thoracic/thoracolumbar curves are common. More severe structural deformities are characterized by lateral listhesis and rotatory subluxation, often at L3-4.[12] The magnitude of these curves is inversely proportional to their prevalence: 10°, 10° to 20°, and >20° curves occur with a prevalence of 63%, 44%, and 24%, respectively.[11] The mean age at presentation is 70.5 years, and the male:female ratio is approximately 1:1.[2] Lumbar degenerative scoliotic curves with a Cobb angle >30°, apical rotation greater than grade II, lateral listhesis >6 mm and/or an intercrest line through L5 are thought to be more likely to progress.[13] Neither patient age nor sex appears to affect curve progression in this group.[2]

Estimates of the prevalence of degenerative hyperkyphosis in elderly patients range from 20% to 40%.[14] However, unlike degenerative scoliosis, there is currently no uniformly accepted threshold to define the cutoff between "normal" thoracic spine alignment and hyperkyphosis. Thoracic kyphosis has been reported to increase an average of 3° per decade,[15] with more dramatic increases occurring in older age groups.[16] Thus, the definition of hyperkyphosis may depend on the patient's age.

FIGURE 1. *Typical appearance of a lumbar degenerative curve with apex at L2/3 disc space and associated distal fractional curve from L4 to S1. Lumbar dextroscoliosis measures at 55° from T12 to L4 using the Cobb method. AP, anteroposterior.*

Risk factors for the development and progression of degenerative hyperkyphosis have not been well described. Vertebral compression fractures, the most commonly cited cause of hyperkyphosis, are present in <40% of older persons with the greatest degree of kyphosis. This suggests an important role for other factors including postural changes, degenerative disc disease, muscular weakness, and genetic influences.[14]

PATHOGENESIS

ASD often results from accumulated degenerative changes that occur with age. Specifically, asymmetrical disc degeneration, dehydration, and collapse in combination with facet degeneration and ligamentous laxity lead to laxity in the spinal column.[2,17] These processes occur in tandem and may have synergistic effects, such as disc height loss promoting increased facet loading. Vertebral compression fractures, for which osteoporosis is the major risk factor, contribute to sagittal plane deformity. Together, these changes may result in instability of the spinal column with resultant rotation, spondylolisthesis, lateral listhesis, and kyphosis. Asymmetrical degenerative processes also contribute to the development and progression of scoliosis.[17] Iatrogenic spinal deformity, often in the form of flatback syndrome, may occur after simple decompression (laminectomy) or lumbar fusion procedures and is characterized by loss of physiological lumbar lordosis. This is a common and significant factor contributing to sagittal malalignment in ASD patients.

CLINICAL PRESENTATION AND EVALUATION

History

The typical presentation of adults with spinal deformity differs from that of adolescents: whereas adolescents most commonly present with cosmetic concerns or deformity progression, adults characteristically report pain and disability.[1,18-20] Patients typically have a combination of axial back and leg pain.[18,19,21] When taking a history, these should each be characterized with respect to severity, quality, exact location, and aggravating and alleviating factors. When both are present, the relative severity and contribution to overall disability should be quantified. Leg pain that is radicular in nature should be differentiated from that attributable to neurogenic claudication. It is useful to determine which conservative measures have been used (physical therapy, aquatics therapy, medications, steroid injections) and their efficacy. For some patients with mild symptoms, the initial visit may focus on education, optimizing nonoperative care, and establishing follow-up, whereas others may have already exhausted such measures and be considering surgery.

The presence of neurological deficits should be elicited by asking about weakness, decreased/altered sensation, bowel or bladder dysfunction, gait disturbance, and incoordination. Tandem cervical stenosis has been reported in up to 28% of patients with lumbar disease,[22] necessitating an evaluation for myelopathic symptoms.

Many patients with symptomatic spinal deformity have had previous spine surgery, which may include simple decompressions and short-segment or long-segment fusions for deformity correction.[23] Such procedures should be documented including when they were performed, whether they were successful in ameliorating the patient's symptoms, the duration of efficacy, and any complications that occurred (eg, infection and dural tears). This information provides a context for understanding the patient's current symptoms and deformity and should be considered in planning further care.

In addition to the above focused history, one should carefully document the general health condition of the patient, including comorbidities. Of particular interest when considering operative management are osteopenia/osteoporosis, cardiovascular disease, pulmonary compromise, and smoking history. Comorbidities do not necessarily preclude surgical treatment; however, they may individually or collectively affect the risk/benefit ratio such that operative strategies are deemed less favorable. Major ASD procedures constitute a significant physiological stress to the patient and have inherent risks.[20,24] Patients should be counseled appropriately to ensure that the process of shared decision making is optimized.

Physical Examination

Examination should begin with an assessment of the deformity in supine, sitting, standing, and ambulatory positions. Standing examination yields the most accurate assessment of sagittal and coronal plane deformity. ASD patients will often be "pitched forward" with positive sagittal imbalance and may have associated trunk shift in the coronal plane. Positive sagittal malalignment is associated with compensatory pelvic retroversion to bring the head over the pelvis and is identified by noting flattening of the buttocks. In more severe deformity, this may be accompanied by hip and knee flexion (crouched posture) while standing or walking. In the long term, this posture may lead to the development of hip flexion contractures, which can be assessed using the Thomas leg raise test.[25] This test is performed with the patient supine on the examination table while 1 leg is flexed at the hip by bringing the knee to the chest while the contralateral leg remains extended. It is said to be positive for hip flexion contracture if the contralateral hip inadvertently flexes without knee extension. Hip flexion contractures may complicate postoperative recovery and outcome after attempted realignment surgery, and these patients may benefit from preoperative physical therapy. Although less common in ASD than in adolescent spinal deformity, rib humps may be present and are accentuated with forward bending at the waist. Pelvic obliquity, if identified, should be evaluated using shoe lifts to appreciate the impact on the patient's coronal balance.[25]

The sitting posture allows for assessment of deformity in the absence of potentially confounding leg length discrepancy or hip flexion contractures. Supine examination is particularly important in differentiating between rigid and flexible deformity, as the latter will typically, at least partially, correct from standing to supine

position. Comparison of supine and standing positions can also aid in the detection of positional deformities such as camptocormia that may develop as a result of Parkinson disease, dystonia, or thoracolumbar disc herniation. Gait assessment may reveal spasticity due to cervical myelopathy, neuromuscular disease (eg, shuffling gait in Parkinson disease), antalgic gait due to nerve root impingement, or imbalance secondary to global malalignment.

All ASD patients should have a detailed neurological examination including assessment of motor strength, sensation, tone, reflexes, and coordination.[1] Signs of myelopathy, including hyperreflexia, pathological reflexes, clonus, and gait disturbance, should be sought. If present, this may necessitate magnetic resonance imaging of the cervical and/or thoracic spine and could change the urgency of intervention.

IMAGING EVALUATION

Imaging of a patient with suspected spinal deformity begins with posteroanterior (PA) and lateral full-length (36-inch) radiographs of the entire spinopelvic axis.[25,26] Radiographs are taken with the patient standing with elbows flexed, fingertips on the clavicles, and hips and knees extended. They should extend from the occipital condyles cranially to the femoral heads caudally. These radiographs provide an assessment of global and regional spinopelvic alignment and permit the necessary measurements. This allows for determination of deformity severity and assessment of progression (by comparison with previous imaging), as well as quantification of the amount of correction needed to restore spinopelvic alignment.

By convention, PA radiographs are viewed with the heart on the left side (true left). Coronal alignment is measured as the horizontal distance between a line drawn vertically through the center of the sacrum (CSVL) and a plumb line dropped from the C7 centroid (C7PL). A C7PL that falls to the left, on, or to the right of the CSVL corresponds to negative, neutral, and positive coronal alignment, respectively (Figure 2A). Pelvic obliquity and leg-length discrepancy is assessed as illustrated in Figure 2B. Pelvic obliquity may be primary, due to leg-length discrepancy or pelvic deformity, or secondary, ie, arising from compensatory changes in the setting of lumbar scoliosis. Failure to appreciate the relationship between pelvic obliquity and scoliotic deformity may result in suboptimal coronal realignment. These patients should, therefore, be evaluated for leg-length discrepancy with a scanogram and re-evaluated with a shoe lift if a discrepancy is found.

Coronal curvature (scoliosis) is also assessed on PA radiographs. The apex, defined as the disc or vertebra maximally displaced from midline and minimally angulated, determines the location of the curve. Thoracic, thoracolumbar, and lumbar curves have their apex between the T2 and the T11-12 discs, between the T12 and L1 vertebra, and inferior to the L1-2 disc, respectively. Dextroscoliosis is defined as a convex right curve, whereas a convex left curve is termed levoscoliosis. The largest curve, as measured with the Cobb technique from the maximally angulated (end) vertebra above and below the apex, is considered the major curve. Additionally, adjacent curves are termed minor and may be compensatory or structural. Supine side-bending radiographs obtained with the patient in the supine position distinguish between the former (reduce to $<25°$) and the latter (remain $>25°$ on side-bending radiographs). This distinction is important because surgical correction of the major curve will typically result in spontaneous correction of compensatory but not structural minor curves. Therefore, structural curves should be incorporated into the surgical construct.

Global and regional spinal alignment is assessed on lateral 36-inch radiographs oriented with the patient facing to the right. Regional sagittal alignment measures of interest include thoracic kyphosis (TK) and lumbar lordosis. TK is measured between the cephalad end plate of T2 or T5 and the caudal end plate of T12 and is designated, by convention, with a positive value. Lumbar lordosis is the angle between the caudal end plate of T12 or L1 and the cephalad end plate of S1 (Figure 2C). The sagittal vertical axis (SVA), a measure of global sagittal alignment, is the horizontal distance from the C7PL to the posterior superior corner of the sacrum (Figure 2D). By convention, a C7PL that falls anterior or posterior to the posterior superior sacrum is designated as positive or negative, respectively. The T1 and T9 spinopelvic inclinations (T1SPI and T9SPI, respectively) constitute alternative measures of global sagittal alignment that carry the advantage of not being dependent on image scale (Figure 2D). Protopsaltis et al[27] recently introduced a novel measure of global sagittal deformity, the T1 pelvic angle (TPA). The TPA is defined as the angle between lines connecting the femoral head axis to the T1 centroid and the midpoint of the superior S1 endplates. It is the sum of the T1SPI and the pelvic tilt (PT; see below). TPA is advantageous because it does not vary based on pelvic retroversion or other postural compensatory mechanisms and, as an angular measure, does not need to be calibrated to the scale of the radiograph. The T1 pelvic angle correlates strongly with pain and disability, with an angle of 20° corresponding to severe disability (Oswestry Disability Index [ODI] >40).[27]

Sagittal spinal alignment is greatly influenced by pelvic morphology and alignment.[25,28-33] Three key pelvic parameters of interest have emerged: pelvic incidence (PI), PT, and sacral slope (SS). The techniques for measuring these parameters are illustrated in Figure 3. The PI is a fixed morphological parameter that does not change after skeletal maturity and is independent of pelvic position. It is measured as the angle between the femoral heads (or a line connecting their centers when not superimposed) and a line drawn perpendicular to the midpoint of the sacral end plate (Figure 3A). Determination of the PI allows for calculation of lumbopelvic mismatch or the difference between PI and lumbar lordosis (LL) (PI − LL). Generally, the PI − LL can be thought of as the deficit in lumbar curvature that should be restored during surgical correction.

The PT is a measure of pelvic retroversion, which occurs in compensation for positive sagittal malalignment such that increased retroversion corresponds to increased PT. The PT is

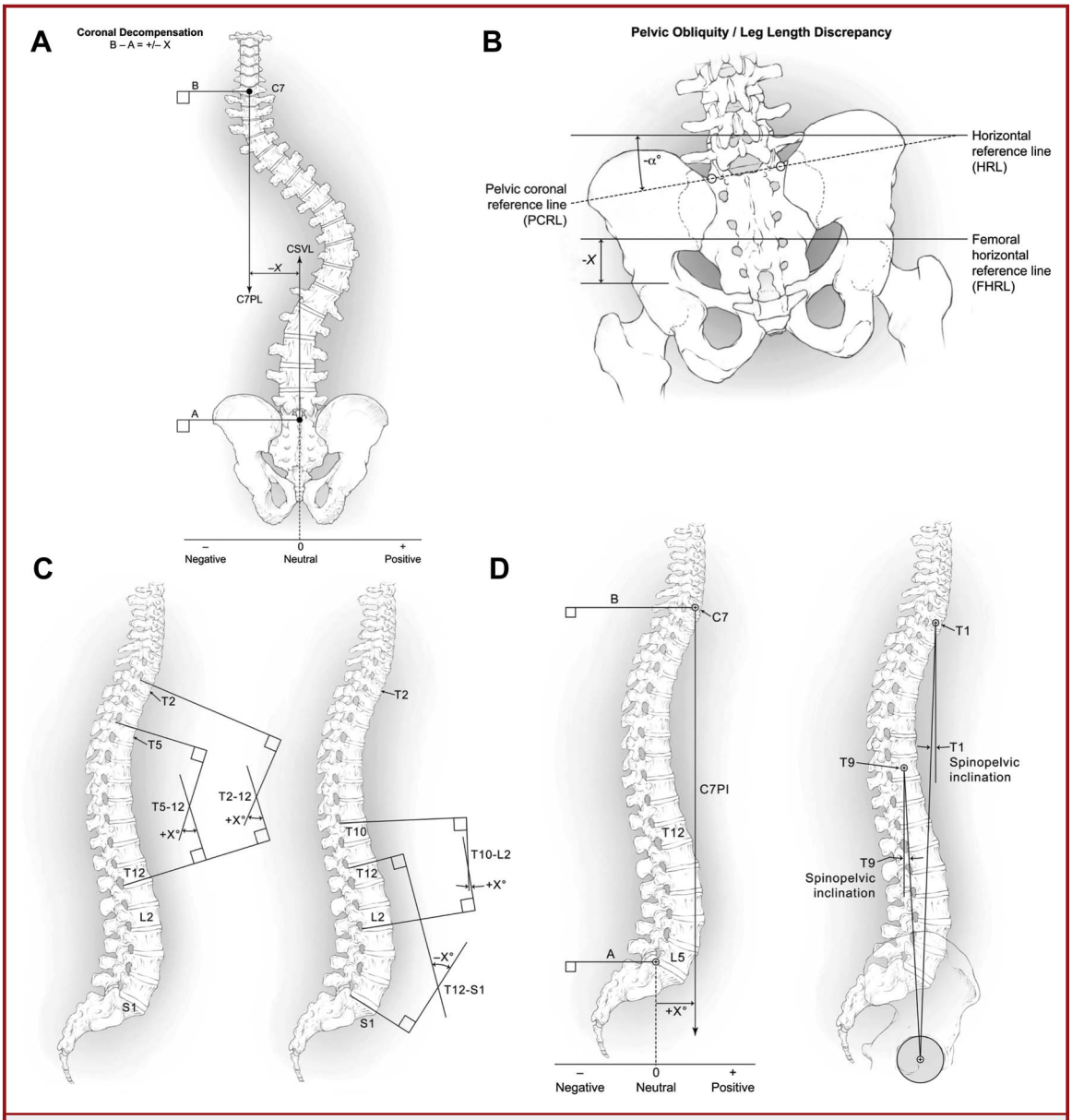


FIGURE 2. *Measurements commonly used to quantify spinal deformity.* **A**, *coronal balance is measured as the distance between the C7 plumb line and the central sacral vertical line (−x).* **B**, *measurement of pelvic obliquity and leg-length discrepancy.* **C**, *measurement of regional alignment. Thoracic kyphosis is typically measured, using the Cobb method, from T2 or T5 to T12 depending on the visibility of the T2 endplate (***left***). Thoracolumbar alignment is measured from T10 to L2 (***right***). Lumbar lordosis is measured from T12 to S1 (***right***).* **D**, *the sagittal vertical axis is measured as the distance from a vertical plumb line dropped from the C7 centroid to the posterior superior corner of the sacrum, shown here as +x (***left***). Spinopelvic inclination is the angle formed by a line connecting the femoral heads to the T-1 or T-9 centroid and their vertical plumb line (***right***).*

the angle between a line drawn from the center of the femoral heads to the midpoint of the sacral endpoint and a vertical reference line extending upward from the femoral head axis (Figure 3B). The SS is the angle between the sacral end plate and a horizontal reference line (Figure 3C) and is related to the other parameters by the formula: PI = PT + SS.

Additional radiographs that provide important supplemental information in assessing spinal deformity include standing dynamic radiographs to determine the presence and degree of instability associated with spondylolisthesis, supine side-bending radiographs as discussed previously, and supine films over a bolster to assess rigidity of the deformity. Additional views that may be

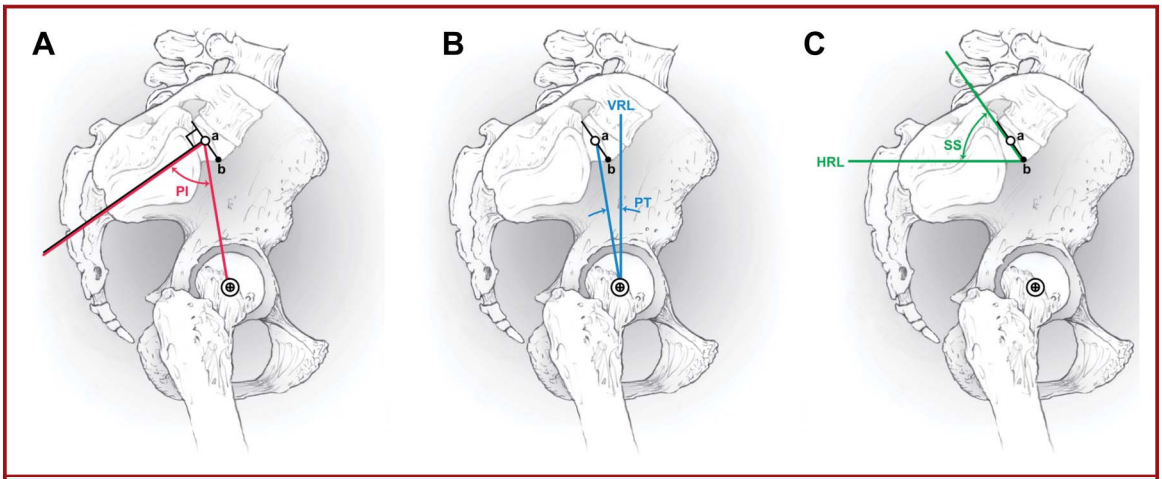


FIGURE 3. *Measurement of typical pelvic parameters used to quantify spinal deformity.* **A**, *pelvic incidence (PI) is the angle formed from lines connecting the center of the bicoxofemoral axis to the perpendicular intersecting the midpoint of the cranial sacral endplate.* **B**, *pelvic tilt (PT) is the angle formed by a vertical line passing through the center of the bicoxofemoral axis (VRL) and a line intersecting the midpoint of the superior sacral endplate.* **C**, *sacral slope (SS) is the angle formed between a line drawn parallel to the sacral endplate and a horizontal reference line (HRL). Images used with the permission of K.X. Probst/Xavier Studio, 2012.*

helpful include the Ferguson view to visualize the sacral region and oblique views to visualize the pars interarticularis. Although axial rotation can be assessed and graded using the Nash-Moe method on conventional radiographs, computed tomography imaging likely facilitates more comprehensive and accurate assessment of axial plane deformity.[34]

Advanced imaging has become standard in the assessment of ASD patients. Magnetic resonance imaging provides exceptional soft-tissue detail and is therefore useful in assessing disc disease, nerve and spinal cord impingement, and intraspinal abnormalities. Computed tomography imaging reveals bony detail and is important for surgical planning, especially with regard to placement of instrumentation. Computed tomography myelography combines excellent visualization of intraspinal disease and neural compression with high-resolution of bony detail. It is particularly useful in the setting of previous instrumentation in which it is less subject to artifact than magnetic resonance imaging. Improvements in imaging software allow multiplanar rendering and 3-dimensional reconstructions, both of which are tremendously helpful in understanding complex deformities and in operative planning.

Older patients being considered for surgery, especially female patients, should undergo a dual-energy x-ray absorptiometry scan to assess for osteoporosis. A femoral neck T score of less than −2.5 is classified as osteoporosis.[35] Lumbar spinal T scores should be interpreted with caution, as they may be artificially elevated in patients with sclerosis secondary to scoliosis.

SPINAL BALANCE

Central to our current understanding of spinal deformity and its management is the concept of spinal balance. Global spinal alignment serves to maintain an upright posture and horizontal gaze while minimizing energy expenditure and is dependent on the interaction between regional spinal and pelvic alignment.[25,28,30-33,36,37] Dubousset[38] introduced the concept of the "cone of economy," a hypothetical cone that extends upward from the feet (Figure 4). Within the cone, the individual is able to sustain painless upright posture with minimal energy expenditure. Increasing deviation from the center of the cone, as occurs with spinal deformity, requires greater energy expenditure to maintain a standing posture through compensatory mechanisms. Deviation outside the limits of the cone, in the setting of more severe deformity, results in failure of these mechanisms and may result in an inability to stand upright or may necessitate assistive devices to do so.[30]

The normal adult spine comprises 4 curves in the sagittal plane: lordosis in the cervical and lumbar areas and kyphosis in the thoracic and sacral regions. The spine is normally straight in the coronal plane but may have a slight right thoracic curve. These regional curves, in combination with balanced spinopelvic alignment, facilitate comfortable erect posture while standing and walking.[37,39] Traditionally, great emphasis has been placed on coronal alignment; however, recent literature has demonstrated that sagittal spinopelvic alignment is a much greater determinant of health-related quality of life (HRQOL) and pain in ASD patients.[28,32,37,40-43]

Although coronal imbalance >4 cm is associated with increased pain and worse function in ASD patients,[40] positive sagittal balance has repeatedly been shown to be the most robust and reliable predictor of symptoms in this group.[29,37,40-42] In particular, an SVA >50 mm is correlated with moderate disability (ODI >40).[3] Sagittal balance, in turn, is dependent

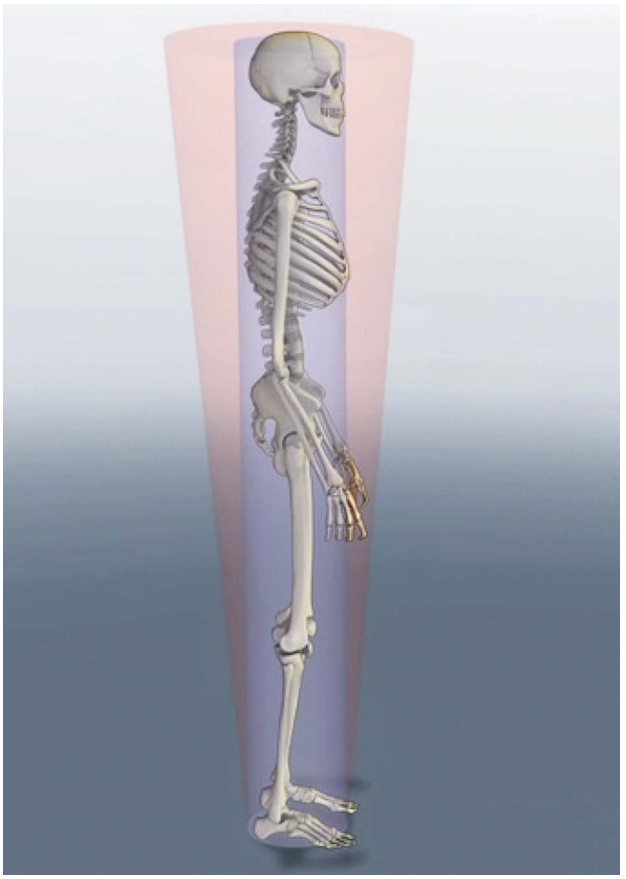


FIGURE 4. *Cone of economy. Normal standing alignment places the head over the pelvis and feet, minimizing energy expenditure. Deviation from the cone results in increased use of postural muscles and compensatory mechanisms in an attempt to restore global alignment at the cost of increased energy expenditure. Image used with the permission of K.X. Probst/Xavier Studio, 2014.*

on the morphology and alignment of the pelvis. The PI defines the amount of LL required to maintain a balanced spine.[25,30,33] Indeed, in patients with spinopelvic mismatch (PI − LL >10°), similar postoperative HRQOL improvements have been demonstrated in those with and without positive sagittal imbalance.[44] The PT is also of critical importance to understanding spinopelvic balance. Because pelvic retroversion serves as a compensatory mechanism, it can potentially mask sagittal imbalance. Patients may have a normal or near-normal SVA but only achieve this through maximally retroverting their pelvis (increased PT and decreased SS). Failure to appreciate this interaction may lead to undercorrection of sagittal malalignment. Based on several studies correlating radiographic parameters with HRQOL and disability scores in ASD patients, realignment goals have been established that include SVA <50 mm, PT <22°, and PI − LL <±9°.[1,25,28,29,33,37,40,41,45] Values outside these ranges are correlated with deterioration in HRQOL measures. Conversely, values within these ranges after realignment surgery are correlated with improved outcomes. Recent evidence suggests that disability thresholds may vary by patient age.[46] Table 1 lists thresholds for severe disability (ODI >40) stratified by age for SVA, PT, and PI − LL. These results suggest that preoperative planning should take into account patient age to optimize the planned degree of correction.

CLASSIFICATION

A classification scheme for ASD should be clinically relevant, parsimonious, and specific. A system of classification allows comparison of different treatments and their outcomes across institutions. The Scoliosis Research Society (SRS)–Schwab[47] classification system is a highly reliable and well validated system for ASD. It includes 4 coronal curve types and 3 sagittal modifiers, as seen in Figure 5. The first sagittal modifier, PI − LL, constitutes the difference between PI and LL and is of critical importance in surgical planning, as discussed previously. The second sagittal modifier is SVA and represents the global sagittal spinal alignment. PT, the third modifier, must be considered because, as discussed previously, increased PT is a compensatory mechanism that can mask the degree of sagittal malalignment. Even in patients with similar SVAs, those with higher PT have greater pain and disability scores and an increased risk of postoperative failure.[28] Cutoffs for the sagittal modifiers are based on an analysis correlating these parameters with HRQOL thresholds in a multicenter database of adult deformity patients.[48] This further strengthens the clinical relevance of the SRS-Schwab classification. Other advantages include its high intra- and interrater reliability scores,[49] which underscore its ease of use and consistency.

MANAGEMENT

Nonoperative Treatment

In the absence of significant or progressive neurological deficits concerning instability or rapidly progressive curves, nonoperative management is a reasonable option for patients with ASD.[2,11,50,51] Patients are typically referred for physical therapy that focuses on low-impact core strengthening and endurance.[17] Aquatics-based

TABLE 1. Age-Based Thresholds of Sagittal Spinopelvic Parameters for Severe Disability[a]

Age Group, y	SVA, mm	PT, Degrees	PI − LL, Degrees
≤45	33	15	2
46-64	71	23	13
65-74	90	26	18
≥75	105	29	22

[a]SVA, sagittal vertical axis; PT, pelvic tilt; PI, pelvic incidence; LL, lumbar lordosis; PI − LL, lumbopelvic mismatch.[46] Severe disability defined as Oswestry Disability Index >40.

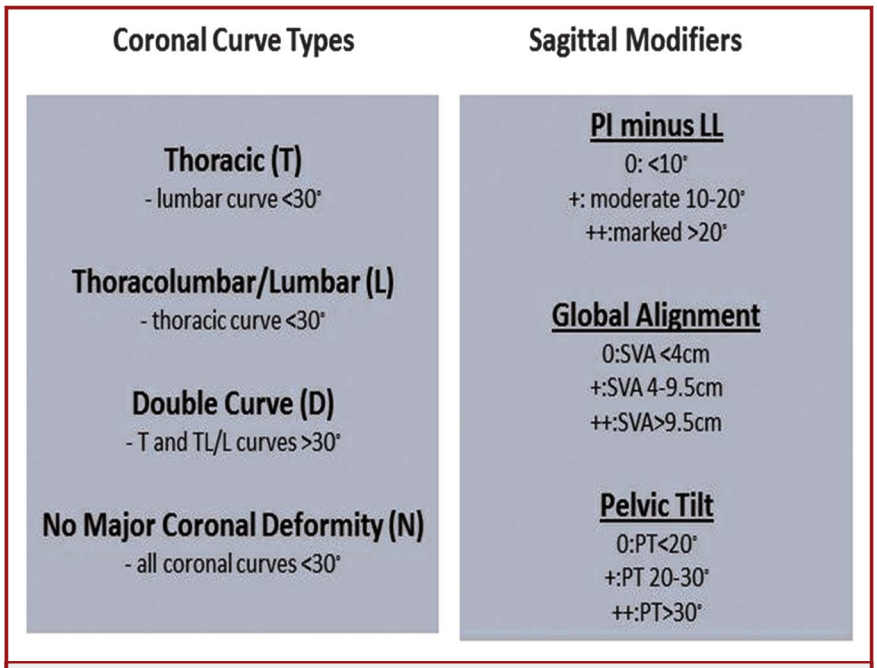


FIGURE 5. *Scoliosis Research Society–Schwab classification of adult spinal deformity. There are 4 curve types and 3 sagittal modifiers. PI, pelvic incidence; LL, lumbar lordosis; PT, pelvic tilt; SVA, sagittal vertical axis. Adapted from Schwab et al.*[49]

programs may be better suited for ASD patients who often find it difficult to exercise effectively on land. Analgesics, including nonsteroidal anti-inflammatory drugs and nerve stabilizers (eg, gabapentin, pregabalin), may be beneficial; however, these should be used judiciously due to their potential respective side-effect profiles. For acute exacerbations of symptoms, narcotics can be considered, but their long-term use is not routinely recommended due to short- and long-term side effects including overdose, tolerance, and addiction. Patients can also be referred for epidural steroid injections, selective nerve root blocks, facet blocks, and/or trigger point injections based on a careful consideration of their imaging and likely pain generators. Bracing is not routinely recommended in ASD patients, as it does not halt curve progression, and any pain relief provided is offset by associated deconditioning.[2,17]

Unfortunately, there is a paucity of evidence supporting the above-mentioned nonoperative modalities in the treatment of patients with degenerative spinal deformity. Everett and Patel[51] conducted a systematic review of nonsurgical treatment of adult scoliosis and found indeterminate level III/IV evidence only. They identified level IV evidence for physical therapy, chiropractic care, and bracing and level III evidence for steroid injections. More recently, Glassman et al[52] assessed the cost associated with nonoperative treatment of ASD and found that despite the substantial mean cost of $10 815 per patient, there was no improvement in any HRQOL measure over 2-year follow-up. Despite the lack of evidence for nonoperative treatment, some patients do experience a benefit, and the need for surgery may be delayed or obviated by successful employment of such strategies. Future studies are needed to better differentiate which patients are likely to be managed successfully with vs without surgery.

Operative Treatment

Patients in whom conservative measures have failed are considered for surgical treatment. Rarely, the presence of progressive neurological deficits will mandate urgent intervention. More commonly, a patient is followed over time clinically and with serial imaging studies to evaluate for progression of symptoms and deformity. The decision to transition to operative care is based on several considerations, including the patient's symptoms and their impact on the patient's function and quality of life. The surgeon's role is to educate the patient regarding the expectations, potential benefits, and risks of surgery in the context of their deformity and general health condition. Specific indications for surgery in ASD include refractory back and/or leg pain, documented curve progression, severe and/or progressive neurological deficit, cardiopulmonary compromise, and deterioration in sagittal and/or coronal balance with associated decompensation.[2,17,50] Relative contraindications include significant cardiopulmonary disease, severe osteoporosis, organ failure, and any physical/mental condition that would preclude participation in appropriate preoperative evaluation and optimization for surgery and/or postoperative rehabilitation.[17]

The main goals of surgery are to decompress involved neural elements, realign the spine in the coronal and sagittal planes to attain harmonious balance, and minimize operative and perioperative risks.[2,17,50] Whereas increased coronal plane deformity is commonly the justification for surgical treatment in younger adults, pain and disability guide selection of treatment modality in older ASD patients.[53] Accordingly, correction of sagittal plane deformity, the primary driver of pain and disability in this population, generally should be prioritized before that of coronal deformity. Given our current understanding of the relationship between key spinopelvic parameters (SVA, PT, PI − LL) and HRQOL, these parameters must be incorporated in the development of the surgical strategy. Specific realignment goals include an SVA <50 mm, PT <22°, and spinopelvic mismatch within 9°. Based on recent evidence suggesting that disability thresholds for these parameters vary by patient age (Table 1), realignment goals may have to be tailored accordingly.[46]

Mathematical formulas have been proposed to aid in estimating the amount of correction needed to restore sagittal balance in ASD patients. The most comprehensive and reliable of these incorporated spinopelvic parameters, including PI, maximum LL, PT, maximum TK, and age. This formula had the highest prediction accuracy of postoperative SVA (89%) in a recent review.[32,54] Additional adjuncts include surgical planning software that allows for simulation of planned operative strategies, including the use of osteotomies, to predict postoperative spinopelvic alignment.[36]

Surgical interventions for ASD patients can range from simple decompression to combined anterior and posterior fusions with decompression. Decompression alone is an option for the minority of ASD patients with small curves and no clinical or radiographic evidence of instability. It may also be considered in patients with severe pain who are not candidates for major fusion procedures due to poor health and significant comorbidities. Although decompression can relieve claudication or radiculopathy, the risk of iatrogenic postoperative instability is higher in patients with deformity.[17,55-57] Some authors have suggested that the use of minimally invasive techniques to decompress the spine while preserving the posterior elements minimizes this risk.[56] However, Transfeldt et al[55] reported superior functional outcomes in ASD patients who underwent decompression and fusion compared with those who had decompression alone, and Kelleher et al[57] demonstrated a significantly higher revision rate in the latter. The presence of lateral listhesis makes decompression alone less favorable because it increases the risk of needing a revision.[57] Caution is warranted in selecting patients with ASD for decompression alone, and care should be taken to preserve the posterior elements to minimize the risk of instability.

Selection of fusion levels should take several factors into account. First, the proximal fusion should be a neutral (no axial rotation relative to the most cephalad and caudal vertebrae that are not rotated in a curve[58]) and stable (thoracic/lumbar vertebra cephalad to a scoliosis that is bisected by the CSVL[58]) vertebra.[2,12] Stopping at the physiological apex of thoracic kyphosis (T5-6) should be avoided due to the increased risk of proximal junctional kyphosis (PJK).[2,59] Hence, constructs typically end either at or below T10 or between T2 and T4. Selection of distal fusion level follows similar principles with identification of a neutral and stable vertebra. Fusion to the sacrum is necessary if there is an oblique takeoff of L5 from the sacrum, fractional curve >15°, advanced L5-S1 disc degeneration, poor bone quality, and/or spondylolisthesis.[2] The additional risks of pseudarthrosis, instrumentation failure, and sacral insufficiency fractures[60,61] associated with extension to S1 can be mitigated by performing an interbody fusion at L5-S1 and/or through the use of sacropelvic fixation. The latter involves placement of supplemental iliac or S2 alar iliac screws and serves to stress-shield the L5-S1 level during fusion. Sacropelvic fixation should be considered for any fusion that extends proximally to T12 or above.[2,50] In addition to the principles outlined above for selection of fusion levels, extension of the construct may be required to allow for adequate neural decompression at a suspected symptomatic level.

Posterior Approaches

Posterior approaches have become the mainstay of surgical treatment of degenerative thoracolumbar deformity due to their versatility, familiarity, and high rates of success. Such approaches typically entail segmental pedicle screw instrumentation from the thoracic spine to the sacrum with placement of iliac or sacroiliac screws. The use of transforaminal lumbar interbody fusion (TLIF) at the lowermost levels (L4-5 and L5-S1) facilitates correction of the fractional curve, restoration of segmental lordosis, and both direct and indirect decompression of the neural elements. Li et al[62] demonstrated improved mean Cobb angles, LL, and mean segmental lordosis in 46 patients who underwent TLIF for degenerative scoliosis. Other authors have reported similar improvements in radiographic[63-65] as well as HRQOL[65] measures.

Posterior approaches may also include osteotomies, when required, to achieve realignment goals. An important principle of deformity surgery is to sufficiently release bone and soft-tissue elements to permit realignment of the spine without the use of undue force and in a way that promotes fusion. Osteotomies comprise a spectrum from partial facet joint resection to 3-column osteotomies including pedicle subtraction osteotomy (PSO) and vertebral column resection (VCR). Table 2 lists these osteotomies from least to most aggressive and delineates the specific structures that are removed in each.[66] Selection of osteotomies requires careful consideration of the balance between the need for more aggressive procedures to achieve realignment goals and their necessarily increased risk. The choice of osteotomy further depends on the flexibility of the deformity, the degree of desired sagittal/coronal correction, and the number of segments over which this correction will occur.[2,17,39,67]

The Smith-Petersen osteotomy involves removal of bilateral facets, the spinous process, the inferior lamina, and the interspinous ligament at a given segment. Resection of these posterior elements is followed by closure of the osteotomy defect with extension through the disc space, which shortens the posterior

TABLE 2. Osteotomy Classification Grades[a]

Spinal Osteotomy Classification			
	Anatomic Resection	**Description**	**Surgical Approach Modifiers**
Grade 1	Partial facet joint	Resection of the inferior facet and joint capsule at a given spinal level	P
Grade 2	Complete facet joint	Resection of superior and inferior facets at a given spinal segment with complete ligamentum flavum removal; other posterior elements of the vertebra including the lamina and spinous processes may also be resected	P, A/P
Grade 3	Pedicle/partial body	Partial wedge resection of a segment of the posterior vertebral body and portion of the posterior vertebral elements with pedicles	P, A/P
Grade 4	Pedicle/partial body/disc	Wider wedge resection through the vertebral body; includes a substantial portion of the posterior vertebral body, posterior elements with pedicles, and includes resection of at least a portion of 1 endplate with the adjacent disc	P, A/P
Grade 5	Complete vertebra and discs	Complete removal of a vertebra and both adjacent discs (plus rib resection in the thoracic region)	P, A/P
Grade 6	Multiple vertebrae and discs	Resection of >1 entire vertebra and adjacent discs	P, A/P

[a]P, posterior approach only; A/P, anterior soft-tissue release combined with posterior resection. Modifiers denote the surgical approach options to perform each osteotomy. Adapted from Schwab et al.[66]

column and increases segmental lordosis by 5° to 10°.[67] A flexible (unfused) disc space is a prerequisite for this osteotomy. A Smith-Petersen osteotomy can be performed at multiple segments and is best suited for moderate sagittal imbalance (SVA <10 cm) such as that associated with flatback deformity and/or smooth thoracic hyperkyphosis (Figure 6).[39] Conversely, sharp angular deformities with more severe sagittal malalignment (SVA >10 cm) may require a PSO (Figure 7). This is a technically demanding procedure involving removal of all posterior elements as well as the pedicle and a wedge of bone with apex anteriorly with subsequent closure of the osteotomy defect. It carries an increased risk of significant blood loss and/or neurological injury.[68] It is typically performed below the level of the conus but can be applied to the cervical or thoracic spine. A PSO can provide up to 30° of segmental correction and can be performed asymmetrically to effect simultaneous correction of coronal plane deformity.[39] For example, Lafage et al[69] reported between 22° and 25° of correction after lumbar PSO. Interestingly, in contrast to the current view that lower placement of a PSO has more impact on translational correction of the SVA, Lafage et al[69] found no such correlation. They did, however, have greater reduction in PT with a more caudal lumbar PSO. As discussed previously, consideration of preoperative PT is critical in optimizing correction because failure to incorporate PT into surgical planning may result in insufficient angular correction and residual postoperative sagittal imbalance.[39,70]

The VCR entails complete resection of the posterior elements as with a PSO, in addition to removal of the entire vertebral body. It is reserved for severe focal coronal/sagittal deformities that cannot be satisfactorily treated with the more conservative osteotomies. VCR permits up to 45° of sagittal plane correction and allows considerable coronal realignment. It is the most technically challenging osteotomy and carries the highest risk of complications.[67,71-73] Suk et al[71] evaluated 16 patients who underwent VCR from a posterior approach for scoliosis >80° with <25% flexibility. They reported a mean 59% deformity correction; however, 4 patients experienced complications, including 1 patient with permanent paralysis.

Anterior and Lateral Approaches

Advantages to anterior approaches include preservation of additional motion segments, enhanced fusion due to a larger fusion surface area, the ability to use large interbody grafts to facilitate sagittal and coronal correction, indirect decompression of neural elements, and preservation of the posterior spinal muscles.[74] This comes at the cost of potential complications related to the anterior approach including ileus, vascular injury, ilioinguinal or iliohypogastric nerve injury, graft subsidence or displacement, abdominal wall hernia, and, in males, retrograde ejaculation.[75,76] Anterior spinal instrumented arthrodesis has been shown to have excellent correction of deformity and is associated with high levels of patient satisfaction in carefully selected patients.[17] In a retrospective review of 62 patients who underwent anterior thoracolumbar fusion for deformity, 82% of patients were satisfied with their result. However, several patients were dissatisfied with their degree of incisional pain

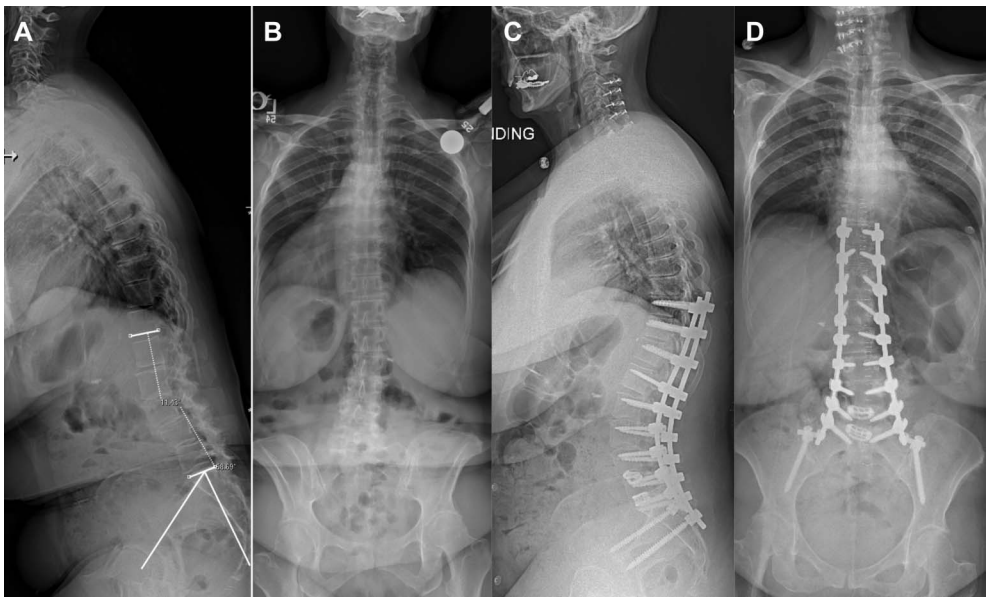


FIGURE 6. *Lateral (**A**) and posteroanterior (**B**) radiographs of 62-year-old woman with severe lower back and bilateral lower extremity pain and inability to stand upright. Images show nearly complete loss of lumbar lordosis resulting in positive sagittal alignment. Spinopelvic parameters: SVA, 180 mm; C7PL, 18 mm; PI, 58°; PT, 33°; LL, 11°; PI − LL, 47°; TK, 30°. The patient was treated with T10-S1 instrumented arthrodesis with placement of bilateral iliac screws, L4/5 and L5/S1 TLIF, and T12/L1 to L5/S1 Smith-Petersen osteotomies. **C** and **D**, postoperative radiographs demonstrating restoration of regional (lumbopelvic) and global alignment. Postoperative spinopelvic parameters: SVA, 44 mm; C7PL, 10 mm; PI, 58°, PT, 22°; LL, 58°; PI − LL, 0°; TK, 30°. C7PL, plumb line dropped from the C7 centroid; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis; TLIF, transforaminal lumbar interbody fusion.*

(32%), a bulging appearance (44%), and functional disturbance with their daily activities that they attributed to the anterior incision (24%).

The lateral transpsoas approach has been proposed as an alternative to traditional anterior approaches to reduce the surgical footprint and avoid the need for mobilization of the iliac vessels.[17,77-82] Proponents of this approach cite reduction in blood loss, shorter hospital stays, high fusion rates, and satisfactory correction of coronal and sagittal plane deformity as its advantages. Mundis et al[83] reviewed the literature on the lateral approach and found significant improvements in visual analog scale and ODI scores with variable complication rates. The rates of major complications were relatively low overall, and the majority of studies cited transient motor deficit in the initial postoperative period that subsequently resolved.[83] One of the current anatomic limitations of the lateral transpsoas approach is the difficulty in accessing L5-S1 and, in some cases L4-5, due to the position of the iliac crest.[84] Stand-alone lateral interbody fusion may be considered for a select group of patients with a low risk of cage subsidence, no significant instability, and less severe deformity.[17] Otherwise, concurrent posterior instrumentation is indicated.

Combined Approaches

Combined approaches for the treatment of ASD offer the greatest potential correction but are associated with an increase in physiological stress to the patient, increased total operative time, and a higher rate of complications.[17,60,83] They are, therefore, typically reserved for more severe deformity with significant coronal and/or sagittal imbalance. High rates of success in terms of fusion rates, degree of deformity correction, and HRQOL have been reported in the literature with combined anteroposterior fusion.[17,85] Some authors have advocated "hybrid" techniques which combine lateral interbody fusion with posterolateral open or percutaneous instrumentation to capitalize on the benefits of both approaches. Proponents argue that such combined approaches minimize the complications associated with traditional open anterior or posterior approaches[78,82,86]; however, long-term follow-up data are currently limited.

Surgical Adjuncts

Neurophysiological monitoring has become an important component of spinal deformity surgery. Such monitoring provides the surgeon with real-time data on the functional integrity of the spinal cord and nerve roots. This can alert the surgeon, anesthesiologist, and neurophysiology team to ominous changes so that appropriate adjustments can be made in surgical technique,

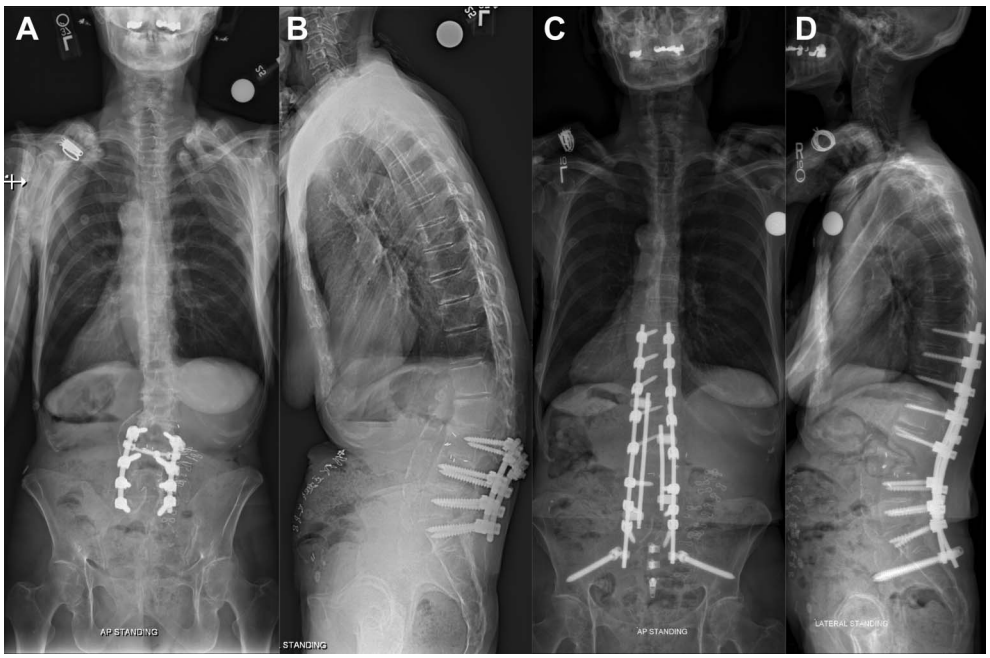


FIGURE 7. *Posteroanterior (A) and lateral (B) radiographs of a 77-year-old woman with previous L3-S1 posterior instrumented fusion in whom proximal junctional kyphosis developed, manifesting as fixed lumbar kyphosis. This has resulted in severe sagittal imbalance with an SVA of 110 mm. Other spinopelvic parameters include C7PL, 22 mm; PI, 44°; PT, 40°; LL, 9° (kyphosis); PI − LL, 53°; TK, 34°. C and D, postoperative radiographs after T10 to S1 instrumented arthrodesis with placement of bilateral iliac screws and L3 pedicle subtraction osteotomy demonstrating restoration of sagittal alignment. Postoperative parameters: SVA, 35 mm; C7PL, 9 mm; PI, 44°; PT, 20°; LL, 40°; PI − LL, 4°; TK, 38°. C7PL, plumb line dropped from the C7 centroid; LL, lumbar lordosis; PI, pelvic incidence; PT, pelvic tilt; SVA, sagittal vertical axis; TK, thoracic kyphosis.*

anesthesia delivery, and/or patient physiology to avoid permanent neurological deficits. Use of multiple modalities, typically including somatosensory evoked potentials, electromyography, and motor evoked potentials, capitalizes on the individual strengths of each to maximize sensitivity and specificity. In a recent review of 1162 patients undergoing deformity surgery, the sensitivity, specificity, and positive predictive value of motor evoked potentials for significant neurological deficit were 100%, 99.7%, and 83%, respectively.[87] Similarly, Bhagat et al[88] reported an overall combined sensitivity of multimodal monitoring (somatosensory evoked potentials and motor evoked potentials) of 100% and a specificity of 99.3%. They concluded that multimodal monitoring permits early detection of impending neurological injury that is superior to any single modality.

Significant blood loss and transfusion requirements are associated with ASD surgery. As such, medical treatments and surgical techniques to reduce intraoperative and postoperative blood loss is an active area of research. Elgafy et al[89] conducted a review of the literature on reduction of blood loss in major spine surgery and found a high level of evidence supporting the use of antifibrinolytics (such as tranexamic acid, aprotinin, and ε-aminocaproic acid). Conversely, there was low level evidence for the use of recombinant factor VIIa, normovolemic hemodilution, and cell saver. Yuan et al[90] reviewed the safety and efficacy of antifibrinolytics in spine surgery and found decreased blood loss and need for transfusion with no increase in the risk of deep vein thrombosis.

Patients with concurrent spinal deformity and osteoporosis represent a significant management challenge. Osteoporosis compromises the interface between bone and instrumentation, which may lead to pedicle screw loosening and graft subsidence.[50] Such patients for whom surgery is being considered should be referred to a bone endocrinologist for evaluation and treatment preoperatively to optimize their bone quality. In general, medical management can include bisphosphonates and nonbisphosphonate antiresorptive agents and parathyroid hormone analogs. For patients who elect surgery, several important principles should be followed, including the use of multiple sites of fixation, meticulous preparation of end plates for interbody graft placement, use of bicortical screw fixation where safe, and acceptance of lesser degrees of deformity correction.[17,50] Adjuncts to improve fixation include the use of specialized pedicle screws, cement augmentation of pedicles with polymethylmethacrylate, and the use of anterior column support to reduce the stress on posterior instrumentation.

Additionally, particular attention should be paid to achieving a rapid and solid fusion to offload the instrumentation and its relatively poor bone interface.

Current Controversies in the Surgical Management of ASD

The operative management of ASD has evolved considerably in recent years due to improved understanding of its pathophysiology and the importance of sagittal alignment, the emergence of new surgical techniques including the application of minimally invasive surgery (MIS) systems, and greater appreciation of the potential complications. In conjunction with this evolution, several controversies have emerged in the deformity literature. One such controversy is the appropriate application of MIS techniques to deformity correction. In an effort to mitigate the significant morbidity and high risk of complications (see the following) associated with open deformity surgery, MIS approaches have been proposed.[91-93] These include percutaneous pedicle screw fixation, mini-open TLIF, and lateral interbody fusion, among others, and can be applied alone or in combination with open techniques to the correction of spinal deformity. Although several authors have reported promising results, high-quality studies on the clinical and radiographic outcomes of MIS techniques for ASD are lacking. In a recent systematic review,[91] only 2 of 13 studies that met inclusion criteria were considered high quality. Deformity correction was inconsistent (only 4 of 10 studies with radiographic outcomes reported effective deformity correction), complication rates were high (46% including 14% with neurological complications), and fusion was incompletely assessed in most studies. HRQOL results were generally favorable; however, mean follow-up was only 12.1 months.[91] Haque et al[94] retrospectively compared clinical and radiographic outcomes of MIS, hybrid, and open ASD surgery. The hybrid group had the greatest lumbar curve correction and change in PI − LL followed by the open, then the MIS group. Conversely, the greatest SVA correction (25 mm) was achieved in the open group compared with ≤1 mm of average SVA correction in the MIS group. The MIS group had significantly less intraoperative blood loss than either the hybrid or open group. Clinical outcomes (ODI, back and leg pain) at 1 year were comparable across the groups, suggesting that, in well-selected patients, similar results can be obtained. To aid in patient selection, the MIS spinal deformity surgery algorithm was introduced. This divides ASD patients into 3 classes based on the degree of radiographic malalignment, the presence of lateral listhesis, and the flexibility of the curve. Open surgery is recommended for class III patients, whereas those in class I or II can be managed with MIS. Further studies are required to evaluate the long-term outcome of MIS techniques applied to ASD and their comparative efficacy to open techniques.

Another challenge in the surgical management of ASD is determining the degree of planned correction, particularly in patients with severe preoperative malalignment. The establishment of radiographic thresholds to guide surgical planning in this respect has led to great enthusiasm for achieving fairly dramatic corrections. Although reaching such radiographic targets is associated with superior HRQOL outcomes,[40] in some cases, this may occur at too great a cost in terms of perioperative and postoperative risk. In particular, greater sagittal realignment is associated with a higher risk of PJK and proximal junction failure (PJF).[95-97] ASD patients experiencing PJF have greater SVA and PI − LL correction and more PSOs.[96] The majority of studies report an incidence of PJK between 20% and 40%.[98] Although PJF will develop in only a small subset of these patients, there is mounting evidence that their clinical course is negatively affected and that they have higher rates of revision surgery.[96] Several of the established risk factors for PJK/PJF, including older age and greater preoperative SVA, PI − LL, and TK, cannot be modified by the surgeon. In certain instances in which the risk of PJK is thought to be high (eg, an elderly patient with severe sagittal malalignment and poor bone quality), a less aggressive correction may constitute a reasonable compromise between radiographic alignment goals and operative risk. The use of radiographic thresholds based on age[46] may allow surgeons to better tailor their operative plans.

Several techniques have been proposed to reduce the risk of PJK and PJF. These include strategies to reduce the stiffness of the instrumentation such as selecting rods of smaller diameter, transitional rods, and/or less stiff composite metals, and using hooks[99] or sublaminar wires in place of pedicle screws at the upper instrumented vertebra (UIV). Other authors have advocated the use of cement to augment the UIV and potentially UIV + 1.[100,101] Enhancement of the posterior tension band through placement of an interspinous mersilene tape has been proposed. Percutaneous placement of pedicle screws in the upper 1 or 2 levels of the construct to minimize injury to the facet complex and supporting soft-tissue structures is currently being evaluated. The best strategy to prevent PJK is the subject of much debate and an area of active research.[102]

Surgery for ASD entails significant costs and, as mentioned, is increasing in frequency. From 2000 to 2010, there has been a 400% and 70% increase in spine deformity surgeries for Medicare and managed care patients, respectively. The average inpatient stay cost 230% more for Medicare patients in 2010 than it did in 2000. Taken together, the increased frequency and cost over the past decade has resulted in a 16-fold increase in total charges for Medicare patients undergoing ASD surgery from $56 million to $958 million.[103] Although the increased use and cost of deformity surgery is recognized, the underlying factors driving these changes are not well described. Such factors could include insurance status, physician numbers and training, advertising, geography, patient demographics, and disease severity.[103] McCarthy et al[104] retrospectively compared postoperative quality-adjusted life years with predicted quality-adjusted life years without surgery to determine the incremental cost-effectiveness ratio of 120 consecutive ASD patients. They projected an incremental cost-effectiveness ratio for surgical treatment (compared with nonoperative) of $80 000 at 10-year follow-up, well below the World Health Organization's suggested upper threshold

for cost-effectiveness of $140 000 ($2010).[104] Thus, preliminary data suggest that ASD surgery is cost-effective. Nevertheless, the trends in prevalence and cost of such procedures necessitate that they be done more efficiently to be sustainable in the face of ever-increasing economic pressures.

OUTCOME

Determination of the best management strategy for ASD requires an understanding of expected outcomes with operative vs nonoperative therapy in addition to an appreciation of its natural history. Yadla et al[105] conducted a systematic review of studies on surgical outcomes for ASD. In 49 articles with 3299 total patients, they identified a 26.6° mean major curve reduction (corresponding to 40.7% decrease), a mean 15.7 point decrease in ODI score, and a reduction in SRS-30 equivalent score of 23.1. They also reported an overall complication rate of 41.2% and a 12.9% rate of pseudarthrosis. They concluded that ASD surgery is associated with improvement in clinical and radiographic outcomes at ≥2 years postoperatively.

Recently, several studies comparing operative with nonoperative treatment have demonstrated superior results for the former.[18,106-108] Smith et al[18] demonstrated significant improvement in Numeric Rating Scale scores for back pain, ODI scores, and SRS-22 scores in 147 of 317 patients who underwent surgical treatment for scoliosis. Furthermore, despite having significantly higher baseline back pain and disability than the nonoperative group, the operative cohort had less back pain and disability and superior health status at 2 years. Similarly, Scheer et al[107] found that patients with ASD were 6 and 3 times more likely to experience improvement in back and leg pain, respectively, compared with those who were managed nonoperatively. Patients with the most severe preoperative back and leg pain improved to the greatest degree, and this change was most likely to reach minimal clinically important difference and substantial clinical benefit thresholds.

Bridwell et al[106] investigated whether operative and nonoperative treatment of ASD improved 2-year HRQOL. Both unmatched (160 patients) and propensity-matched (82 patients) comparisons demonstrated that operative treatment was associated with superior outcomes for all HRQOL measures (ODI, SRS domain scores, and Numeric Rating Scale back and leg pain scores) at 2-year follow-up. The nonoperative group did not change or experienced nonsignificant decline in HRQOL measures across the study duration. Smith et al[108] conducted a similar analysis in 689 ASD patients, of which 286 were managed operatively and 403 nonoperatively. At baseline, the operative group had worse deformity based on pelvic tilt, PI − LL, and SVA and worse HRQOL based on ODI, SRS-22, Short Form-36 and leg and back pain Numeric Rating Scale. After controlling for baseline differences through propensity matching, operative patients improved in all HRQOL measures except Short Form-36 Mental Component Summary score. In contrast, the nonoperative cohort did not, on average, experience improvement in any HRQOL measure with the exception of a small improvement in SRS-22r pain subscore.

COMPLICATIONS

ASD surgery is associated with high complication rates.[2,17,20,73,109] Complications reported in the literature include surgical site infection, cerebrospinal fluid leak, nerve root or spinal cord injury, implant failure, junctional kyphosis and adjacent segment degeneration, and pseudarthrosis. Patients may also experience systemic complications including venous thromboembolism, myocardial infarction, pneumonia, urinary tract infections, and postoperative ileus.[2,17] Sansur et al[110] reported a complication rate associated with adult scoliosis surgery of 13.4%. They also cited osteotomy revision procedures and combined approaches as risk factors. In a retrospective review of 453 ASD patients stratified by age, Smith et al[20] found overall complication rates of 17%, 42%, and 71% in patients of ages 25 to 45, 45 to 64, and 65 to 85, respectively. Interestingly, the increased complication rate in the older groups was offset by great improvement in pain, disability, and health status. Taken together, these data suggest that elderly individuals may experience a disproportionately greater benefit from ASD surgery than younger patients at the cost of an increased risk of complications.

Looking specifically at 3-column osteotomies, Bianco et al[111] reported an incidence of major intraoperative, postoperative, and overall complications of 7%, 39%, and 42%, respectively. Risk factors included age older than 60, 2 osteotomies (vs 1), thoracic level (vs lumbar or sacral), and major blood loss (>4 L). They also identified significant variability in complication rates across the 8 involved centers.

CONCLUSION

Degenerative spinal deformity is characterized by malalignment in the sagittal and/or coronal planes and, in adults, presents with pain and disability. Evaluation involves a thorough history, physical exam, and radiographic evaluation with a particular focus on spinal balance. Nonoperative management is recommended for patients with mild, nonprogressive symptoms; however, evidence of its efficacy is limited. Operative management seeks to restore global spinal alignment, decompress neural elements as indicated, achieve fusion, and minimize complications. A variety of surgical approaches and techniques are available to achieve these goals and should be implemented in a fashion that balances the desired correction with the increased risk of more aggressive maneuvers. In well-selected patients, surgery yields excellent outcomes in terms of reduction in pain and disability as well as improvement in HRQOL.

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