Osteotomies in the treatment of spinal deformities: Indications, classification, and surgical planning

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GENERAL REVIEW

Osteotomies in the treatment of spinal deformities: indications, classification, and surgical planning

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Abstract The surgical treatment of adult spinal deformity has been shown to offer superior clinical and radiographic outcomes compared with nonoperative approaches; furthermore, osteotomies are increasingly applied for treating spinal deformities. Establishing a plan for a patient suffering from marked spinal deformity is a matter of consideration of certain radiographic parameters which correlate with health-related quality of life scores, adherence to consistent principles of alignment and established formulas, and selecting the appropriate osteotomies. This is a review of the most recent work on vertebral osteotomies and includes a summary of a systematic and anatomically based osteotomy classification. A universal classification will facilitate communication, standardize outcomes research, and establish a framework upon which indications can be properly studied and described. Ongoing multicenter collaboration is certain to drive a more evidence-based approach to the complex clinical scenarios of patients suffering from spinal deformity.

Keywords Spinal osteotomy · Anatomical classification · Adult spinal deformity · Surgical planning

Indications for osteotomies

Many spinal pathologies warrant surgical intervention, especially complex three-dimensional deformities which can be disabling and require complex realignment through the use of spinal osteotomies. In this era of scientific advancement and increased attention to the nuances of disease manifestation in each individual, patient-specific planning and surgical intervention can profoundly drive improvements in quality of life.

Trending toward more deformity and more surgery

After infancy and adolescence, the prevalence of scoliosis peaks again after age 50 and is known as adult spinal deformity (ASD); this third peak was previously reported at varying from 1.4 to 32 % [1–4] in asymptomatic patients. In 1978, 20 % of all scoliosis operations performed by members of Scoliosis Research Society were in adults [5]. Twenty-seven years after the latter report, ASD was noted to be present in 68 % of asymptomatic volunteer population older than 60 years [6]. ASD encompasses sagittal and coronal spinal deformities secondary to either progressive adolescent idiopathic scoliosis (AIS) or de novo from degenerative lumbar disease, both of which are on the rise particularly due to the increasing prevalence noted with aging (Fig. 1).

It is important to note that the elderly population is expected to expand significantly due to demographic shifts. In the year 2003, the population at age 60 could expect to live about 22.2 more years [7]. The highest life expectancy was observed for white females (80.5 years) [7], possibly contributing to a higher prevalence of scoliosis, since women have been reported to have about twice the prevalence of scoliosis as men [8].

Regarding treatment and expectations for scoliosis, surgery is frequently a last resort for patients with spinal disease and patients often have high expectations of their surgical outcomes [9]. Many look at surgery as the cure to all their pain and disability; however, these expectations can become unrealistic and surgery should be viewed as a

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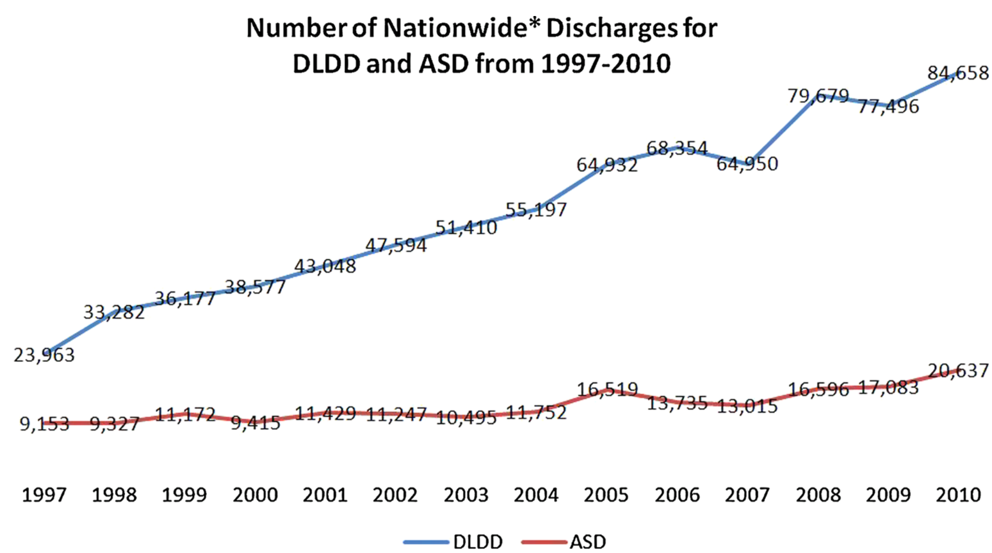

Fig. 1 Rise in AIS and DLD. *Data are weighted national estimates from Healthcare Cost and Utilization Project (HCUP) Nationwide Inpatient Sample (NIS), based on HCUP NIS = 39,434,956

temporizing measure of a chronic disease, not a cure. Saban et al. [10], in a study related to patient expectations after lumbar spine surgery, reported that half of the patients expected to become completely free of leg pain and more than three-fourth of the patients expected to gain complete recovery in their walking ability.

Patient expectations continue to rise at unprecedented levels due to significant developments in the medical arena; however, surgical outcomes have been incongruent with such expectations. Patients are expecting not only to live longer, but to maintain a productive and increased quality of life on par with young individuals, broadening the gap between expectations and surgical outcomes and generating potential disappointment. Enriching our knowledge to improve and maintain clinical outcomes after spinal surgeries will aid in narrowing this gap.

The surgical treatment of ASD has been shown to offer superior clinical and radiographic outcomes compared with nonoperative approaches [11, 12]; furthermore, osteotomies are increasingly applied for treating spinal deformities. National trends support these assertions. Statistics from the Agency for Healthcare Research and Quality (AHRQ) show a significant increase in the number of patients discharged with osteotomies, fusions, and ASD procedures within the last 15 years in the USA (Fig. 2).

With increased use of osteotomies as a treatment modality, there is also a concomitant rise in comfort and training in applying osteotomies. However, this rise in comfort and utilization coexists with high complication rates, failures, and revisions. Rates in the published literature for revision surgery after osteotomy procedures can be up 25.8 % [13]. Ironically, despite the increase in ASD and the demand for quality of life, surgery often leads to repeated needs for intervention.

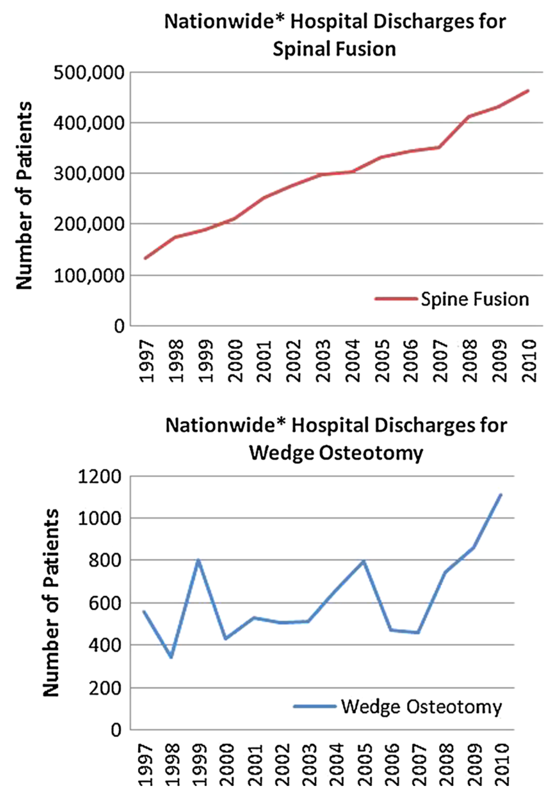

Fig. 2 Rise in Hospital Discharges for Osteotomies and Fusions. *Data are weighted national estimates from Healthcare Cost and Utilization Project (HCUP) Nationwide Inpatient Sample (NIS), based on HCUP NIS = 39,434,956

Radiographic evidence for surgery

Certain radiographic parameters, especially ones describing sagittal alignment, are correlated with poor health-related quality of life scores (HRQOLs). Sagittal malalignment such as loss of lumbar lordosis (LL) and thoracolumbar kyphosis is significantly associated with greater pain scores [14–16].

Moreover, radiographic pelvic parameters such as pelvic retroversion (measured by the pelvic tilt, PT), spinopelvic mismatch (measured by pelvic incidence minus lumbar lordosis, PI−LL), and global sagittal alignment (measured by sagittal vertical axis, SVA, or T1 pelvic angle, T1PA) reflect significant changes in patient-reported outcomes [17–20]. Recently, Schwab et al. [21] used the radiographic parameters as modifiers to provide a validated system to classify ASD. In addition, a significant coronal radiographic parameter that also is associated with pain scores is the obliquity of lumbar vertebrae; contrary to common thought, Cobb angle actually has less bearing on HRQOLs and pain [16].

Spinopelvic harmony, as quantified objectively utilizing radiographic parameters, is indicative of proper spinal alignment. Given that severity of symptoms increases in a linear fashion with progressive sagittal malalignment, even a mildly positive sagittal vertical axis offset (SVA) is somewhat detrimental [22].

While mild spinopelvic malalignment can be corrected with numerous kinds of spinal procedures, some adult patients present with severe, rigid curves, where the use of vertebral osteotomies may be necessary to achieve significant restoration of the sagittal and coronal alignment. Adequate correction of the deformity can produce considerable improvements in the patient's quality of life [23].

Although managing a symptomatic ASD patient typically involves an initial attempt at nonoperative approach [24], there are proposed indications for surgical intervention. Indications for 3 column (3CO) osteotomies have been described as pseudoarthrosis, sharp angular kyphosis, severe global positive sagittal malalignment, concomitant coronal deformity, or previous multilevel circumferential fusions [23, 25, 26]. However, despite aggressive attempts at surgical realignment, it is important to cite findings that up to 29 % of patients do not experience a clinically noticeable improvement following surgery [27, 28].

Considerations for spinal osteotomies

In addition to evaluating direct indications for osteotomies based on radiographic alignment, assessing the etiology of the deformity may factor into the decision of surgical strategy. De novo spinal deformities involve the sagittal plane to a more significant degree than the coronal plane. Therefore, realigning the sagittal plane is paramount, especially because of the sagittal plane impact on quality of life. Other minimally invasive or hybrid techniques may offer correction of the sagittal plane; however, there is a limitation to the amount of correction achievable and these techniques may not always be appropriate in rigid deformities [29]. In patients presenting with hypolordosis and pelvic retroversion, shortening the posterior column by either Smith-Peterson or pedicle subtraction osteotomies, allows for correction in the sagittal plane so that the patient can assume a more physiological alignment [30].

In AIS patients, deformities often afflict the coronal plane. Even though HRQOLs are not highly correlated with coronal radiographic parameters, osteotomies are still indicated in curves that may progress (Cobb angle >30° in patients that are still growing or >45° in patients that have completed their growth) or cause the patient significant cosmetic distress [31]. Maximum permanent correction of the deformity in three dimensions is often achieved by three-column thoracic osteotomy (TCTO) [32].

Along with the myriad of indications for osteotomies, there are also a variety of osteotomies. Further research and knowledge in matching appropriate indications to specific osteotomies necessitates an organizational framework, a classification scheme.

Anatomical classification of osteotomies

Background

The spectrum of surgical realignment techniques ranges from partial facetectomies to major resections such as corpectomies. Smith-Petersen, in 1945, described a superior facet osteotomy to intervene in the fused facets of rheumatoid arthritis [33, 34]. Decades later in 1984, Ponte took the Smith-Petersen osteotomy (SPO) one step further, resecting both superior and inferior facets, as well as the posterior ligaments to correct the rounding kyphosis that may characterize patients with Scheuermann's disease [35]. Though there is overlap, Ponte and SPO are often, and mistakenly used interchangeably in the spine literature creating confusion and further hampering the clarity of presented research.

In 1984, Heinig published his approach on a resection of the vertebral body which he called the "eggshell procedure," more commonly known today as a transpedicular decancellation [36]. Variations have lead to the techniques of closing wedge osteotomy or pedicle subtraction osteotomy (PSO); a procedure he concluded that was reserved for treating more complex reconstructive problems like sharp angled deformities, traumatic deformity, tumors, and infection [37–39].

These techniques are just a sample of the myriad of osteotomies utilized in spinal surgical practice. Until recently, there was no official classification categorizing these various types of osteotomies and group eponyms into a universal language.

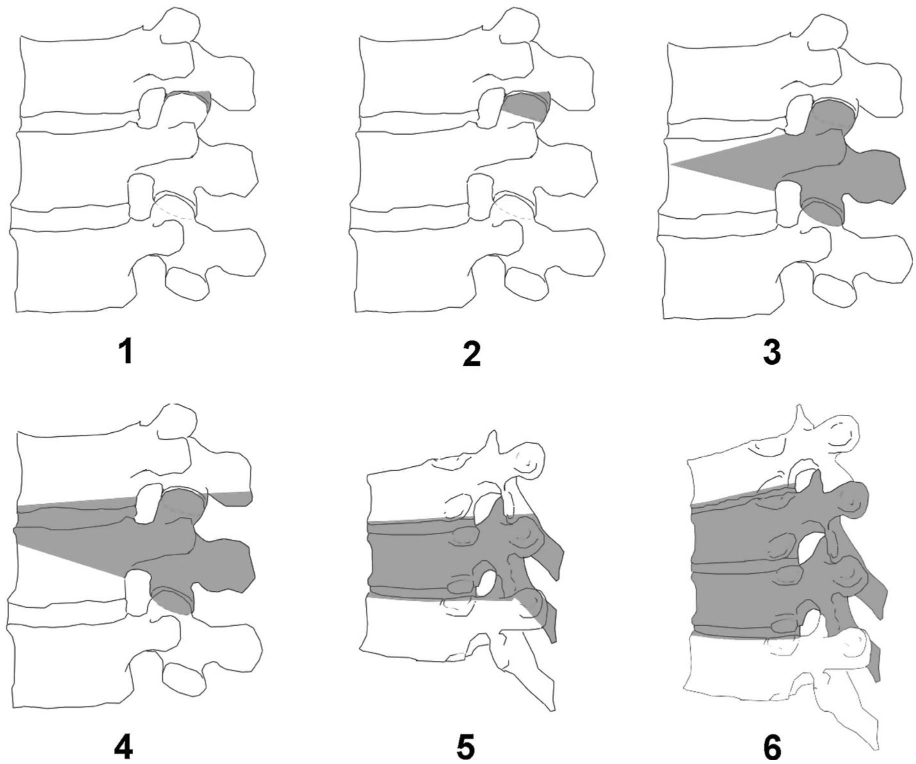

Fig. 3 Osteotomy classification: grades *1–6* according to the anatomical resection

Classifying vertebral osteotomies

A systematic and anatomically based approach toward spinal osteotomies that is reliable and simple to learn is needed to facilitate communication, standardize outcomes research, and establish a framework upon which indications can be properly studied and described. As noted in prior research [40], an osteotomy classification system, such as the Denis classification system [41], should be anatomically based. Schwab et al. [42] proposed an anatomical classification that offers 6 grades of resection that reflect increasing degrees of destabilization and thus potential angular correction ability (Fig. 3). Furthermore, to address the surgical approach, modifiers were added: P for posterior approach and A/P for combined anterior and posterior approach (Table 1).

Grade 1: Partial facet resection

A grade 1 osteotomy achieves the most modest deformity correction and encompasses techniques that resect the inferior facet and joint capsule like the Chevron osteotomy, extension osteotomy, and SPO. This is essentially a partial facetectomy without complete removal of the superior articular process and Smith-Petersen osteotomies fall into this category. About 5°–10° of correction can be gained at each level of the grade 1 osteotomy, which is approached from the posterior only (modifier P). If this osteotomy is utilized, the patient must have a nonfused anterior column due to the anterior lengthening that occurs.

Grade 2: Complete facet resection

Like the grade 1 osteotomy, the grade 2 osteotomy requires anterior column mobility and involves resection of the inferior facet. However, a grade 2 osteotomy extends the resection to include both the inferior facet and superior facet, along with their articulating processes, the ligamentum flavum, and potentially other posterior elements to include the lamina or spinous process. Osteotomies like the Ponte procedure are only approached from the posterior, but other grade 2 osteotomies like the one described by Burgos et al. [43] for pediatric thoracolumbar scoliosis involving an anterior soft tissue release with a posterior resection, would have a combined A/P modifier. Again, it is important to distinguish between the inferior facet resection of a grade 1 osteotomy and the inferior and superior facet resection and removal of the respective articulating processes of a grade 2 osteotomy; while both SPO and Ponte osteotomies involved facet resection, they differ in amount of bone removed and degrees of angulation achievable, and thus should be distinguished (Grade 1 vs. Grade 2).

Table 1 Spinal osteotomy classification

	Anatomical resection	Description	Surgical approach modifiers
Grade 1	Partial facet joint	Resection of the inferior facet and joint capsule at a given spinal level	P (posterior approach only)
Grade 2	Complete facet joint	Both superior and inferior facets at a given spinal segment are resected with complete ligamentum flavum removal; other posterior elements of the vertebra including the lamina, and the spinous processes may also be resected	P (posterior approach only) A/P (anterior soft tissue release combined with posterior resection)
Grade 3	Pedicle/partial body	Partial wedge resection of a segment of the posterior vertebral body and a portion of the posterior vertebral elements with pedicles	P (posterior approach only) A/P (both)
Grade 4	Pedicle/partial body/disk	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 intervertebral disk	P (posterior approach only) A/P (both)
Grade 5	Complete vertebra and disks	Complete removal of a vertebra and both adjacent disks (rib resection in the thoracic region)	P (posterior approach only) A/P (both)
Grade 6	Multiple vertebrae and disks	Resection of more than one entire vertebra and adjacent disks. Grade 5 resection and additional adjacent vertebral resection	P (posterior approach only) A/P (both)

Grade 3: Partial body and pedicle resection

The grade 3 osteotomy extends the resection into the vertebral body, specifically a wedge resection with the posterior elements, while leaving the disks and a portion of cortex above and below the resection intact. Depending on the technique, grade 3 osteotomies can be approached posteriorly (P) or combined (A/P). There exist many published procedures that fall into this grade including the PSO, circumferential wedge bone resection, multilevel vertebral osteotomy by Suh et al. [44, 45] closing opening wedge osteotomy, and Pascal-Moussellard's osteotomy are all grade 3 resections.

Grade 4: Partial body, pedicle, and disk resection

Disk removal characterizes a grade 4 osteotomy. This osteotomy resects slightly more than the grade 3 to include not only just the posterior vertebral body and posterior elements, but also an end plate and at least one adjacent disk; a grade 4 resection in the thoracic region would involve a concomitant rib resection. The approach modifier for grade 4 is also P or A/P. Examples in the published literature include a modified eggshell procedure [36], and a technique described by Scudese and Calabro which combines a modified SPO with removal of the superior disk and superior body to lessen stretching which could cause aortic or inferior vena cava obstruction [46].

Grade 5: Complete body and disks resection

Grade 5 osteotomy involves total removal of a vertebral body, posterior elements, pedicles, as well as the adjacent disks; in the thoracic region, a grade 5 osteotomy is accompanied with a rib resection. The approach is usually a posterior (P), but can actually be performed in a combined method as well (A/P). This osteotomy is also commonly known as a vertebral column resection (VCR) [30]. Another grade 5 osteotomy described by Brodner et al. utilizes an anterior approach and can also be labeled grade 5A/P [47].

Grade 6: Multiple vertebral and disks resection

A grade 6 osteotomy expands upon the resection of a grade 5 osteotomy to include several adjacent vertebrae, thus achieving the most coronal and sagittal plane correction of all the osteotomies; at the very least, this includes one complete vertebral body and a partial second vertebrae. Congenital malformations can lead to partially developed vertebrae that may warrant a grade 6 osteotomy. In addition, tumors and infectious processes can lead to destruction of multiple adjacent vertebrae, also necessitating surgical treatment with a grade 6 osteotomy. Like the other higher grade osteotomies, the approach modifier can be either P or combined A/P.

The reproducibility and reliability of this classification scheme have also been evaluated and found to be userfriendly and consistent. Specifically, the intra-rater reliability for the resection grade and modifier has been tested to find an average Fleiss kappa coefficient of 0.96 and 0.90, respectively, and an interrater reliability of 0.96 and 0.88 [40]. This anatomically based, graded scale classification system which also addresses the nuances of approach, attempts to include the majority of spinal osteotomy techniques, yet it is still simple enough to permit comparative analysis for future research in spinal deformity treatment.

Surgical planning

Why plan?

As mentioned above, there still remains a noteworthy percentage of patients who do not report a clinically significant change in health care-related quality of life after surgery. In addition, there is still a portion of patients who have poor sagittal realignment and radiographic outcomes, which are also tied to the patient-measured quality of life outcomes. Recently, Moal et al. [48] analyzed the radiographic parameters for 161 ASD patients at baseline and 1 year postoperatively. Only 23 % of the patients sustained a complete radiographic correction in coronal or sagittal plane at 1-year follow-up, while the rest of the patients had a deformity in the sagittal, coronal, and both planes (35, 14, and 27 %, respectively) [48]. Prior studies have also reported failed realignment rates of 23 % after PSO and 22 % after TCTO [49, 50]. This data suggest that threshold radiographic deformity can still be present after osteotomy, with sagittal deformities being the most persistent.

Optimal sagittal realignment centers the patient's head over his or her pelvis, restores level gaze, and recreates an ergonomic standing posture, resulting in improved function and reduced pain. Radiographic parameters specific to evaluating sagittal realignment include SVA, PT, and PI-LL [17, 51, 52]. The thresholds of deformity are defined by a SVA <50 mm, PT <20°, and PI-LL <10° [21].

Jackson and Hales set a goal for realigning mission which is SVA <50 mm [53]. Reaching this goal may require a different amount of correction for each patient and thus a patient-specific approach, with larger spinopelvic deformities receiving larger osteotomies, or additional corrective procedures beyond osteotomies to avoid undercorrection [49].

Realignment also involves accounting for PT and estimating subsequent changes in the unfused spine. There have been many mathematical models and formulas that attempt to account for PT and compensatory changes in order to predict postoperative sagittal alignment. Smith et al. [54, 55] evaluated 5 predictive models for predicting postoperative SVA after PSO and demonstrated that the Lafage formulas, developed from a multivariate linear regression of 219 adult patients treated for spinal deformity, showed the greatest accuracy in predicting postoperative SVA when PT and spinal compensatory changes are accounted for. Such formulas are essential in spinal reconstruction and must be considered during preoperative planning for PSO procedures.

Although osteotomies are associated with high complications and revision surgery rates, human error plays a significant role in this deterioration. In a multisite study, Maier et al. [56] reported that variations in surgical technique, composition of surgical team, and treatment center were parameters to predict rates of revision surgery; among the eight sites in the study, revision surgery rates varied between 6.3 and 31.9 %. Additionally, a combined (anterior and posterior) surgical approach was reported as the strongest predictor of revision surgery in retrospective study by Hart et al. [57].

Intriguingly, a 2-surgeon approach has been shown to improve outcomes and decrease complications [58, 59]. Previously, Blam et al. [58] found an increased odds ratio of postoperative infection for orthopaedic or neurosurgeons operating alone compared with a combined team. More recently, Ames et al. [59] demonstrated that over 0.5 l of blood and 2.5 h of operative time could be saved by using 2 experienced deformity surgeons. Several leading spine centers have started to adopt the team approach in spine surgery over the last few years, including 2 or more trained surgeons on complex deformity procedures [59].

In addition to a multisurgeon team, usage of Tranexamic acid (TXA) in the setting of spinal deformity surgery can markedly reduce estimated blood loss [60]. Blood loss remains one of the most common intraoperative complications, while not yet directly associated with realignment failure, every effort should be made to reduce intraoperative and postoperative complications. Also, minimally invasive surgery continues to be an area where studies are demonstrating benefit to patients, perhaps by minimizing blood loss as well. Ongoing education on these approaches is critical to optimize learner skills and patient care [61].

The next step in improving osteotomy outcomes is a root cause analysis to identify factors that are associated with successful and unsuccessful surgical outcomes. A recent study by Moal et al. [62] on 40 consecutive deformity patients suggests that undercorrection of LL occurs in patients that had no major change from the preoperative plan and those that had a major intraoperative deviation from the preoperative plan. These results illustrate the complexity of intraoperative decision making. Further work in this root cause analysis needs to be pursued, again demonstrating the need for a comprehensive, but simple osteotomy classification scheme.

How to plan surgical realignment of the spine

Establishing a plan for a patient suffering from marked spinal deformity is a matter of systematic analysis, adherence to consistent principles of alignment goals, and use of established formulas.

Drivers of deformity

Loss of LL is one of the common drivers for malalignment in ASD. This loss could be due to degenerative changes with age, iatrogenic causes, or progression of an idiopathic deformity. LL, as a sagittal plane parameter, is usually low or even negative in patients with ASD [63]. Restoring LL to normal values is a common method to re-establish the spinal alignment [64].

Normal LL has been studied and exists as a seemingly broad range of normative values, anywhere 30–80 [65], but this is a clinically insufficient guideline for surgical planning. However, when LL is linked to PI, this potentially broad range of normative LL, narrows. Schwab et al. [52] proposed a relationship between PI and LL, such that correcting the LL to match the PI was more patient specific than targeting a definite normative LL. This study defined a threshold value of PI-LL >10 for severe disability in ASD [66]. However, this applies only when the sagittal plane deformity is isolated to the lumbar spine and does not account for abnormal thoracic or thoracolumbar alignment [67].

In addition to the drivers of deformity in the sagittal plane, there exist additional factors in the coronal plane that surgeons must also consider in planning. Many studies have revealed that lumbar vertebrae obliquity, apical level of scoliotic deformity, and intervertebral subluxation are correlated with clinical outcome scores [16, 22, 68, 69]. A C7 coronal plumbline offset of 4–5 cm and rotatory subluxation <7 mm is generally well tolerated [68].

Compensatory mechanisms

Compensatory mechanisms are the patient's progressive response to their spinal deformity starting in the flexible parts of the spine moving distally to the hip and lower extremities [70].

When the center of both acoustic meatus (CAM) overhangs the vertical projection of the axis between the femoral heads by 2 cm, the whole spine is globally malaligned [71] and the patient starts recruiting mechanisms to compensate. Patients use these maneuvers to counter the forward or backward translation of center of mass (COM) [72]. Initially, patients utilize muscular tone to manipulate the spinal regions adjacent to the deformity, for instance, straightening the thoracic spine in a case of lumbar degenerative kyphosis [73]. This requires a muscular ability to maintain posture. With ASD patients, muscular compensation can only go so far as fatigue and lower back pain set in; as the pathology evolves, there is less reliance on the back musculature with the shift of compensation toward retrograding the pelvis along with flexing the knee and ankles [70, 74].

Quantifying the previous mechanisms by certain parameters exposes the amount of deformity the patient is trying to hide by compensating. PT quantifies pelvic retroversion, while the angle of femur obliquity (FOA, the inclination of the femoral shaft to the vertical) can quantify the amount of knee flexion [63]. Thus, a clinical evaluation of the lower extremities is needed.

While the drivers of deformity cause the malalignment, the compensators are the counterbalance and are not to be corrected, because restoring the alignment by correcting the deformers will automatically correct these clinical manifestations. Nonetheless, compensators should be considered in the planning, because they complete the picture of the patient's deformity.

Amount of correction, osteotomy selection, level and degree

The amount of correction the patient needs is not a theoretical fixed amount, but rather varies based on the patient morphological parameters, compensation capacity and harmony between the corrected curve and the other spinal curves, which will be reciprocally changed.

Several authors have proposed mathematical formulas to aid determining the amount of correction needed. Ondra et al. [75] used a trigonometric method to calculate the angle of correction to achieve neutral alignment for PSO procedures, but this failed to consider pelvic compensation. Full body integrated (FBI) proposed by Le Huec is another technique to calculate the theoretical correction needed [63]. In cases of Ankylosing Spondolystisis (AS) Van Royen et al. [76] proposed a way to calculate the correction needed based on chin-brow to vertical angle (CBVA) and sacral endplate angle (SEA) then developed a computational program called ASKyphoplan for the same purpose [77]. Regarding more recently utilized parameters, patients with high PI require a greater correction in LL compared with patients with a lower PI [76]. Surgeons have started to account for the relationship between PI and LL to determine how much LL needs to be corrected; this is the author's preferred method. Moreover, patients with high PI also have high theoretical PT [78]. Lafage et al. [54, 55] were the first to incorporate PT as a factor in predicting postoperative SVA and were found to be superior to prior formulas which did not account for spinopelvic harmony (Table 2).

Table 2 Smith et al. [54] accuracy of mathematical formulas to predict good and poor postoperative sagittal alignment after single-level PSO (with permission from Ref. [54])

Mathematical formula	Author	Accuracy prediction good postoperative SVA (% correct)	Accuracy prediction poor postoperative SVA (% correct)	Total prediction accuracy (good and poor postoperative SVA; % correct)	Prediction accuracy (good and poor postoperative SVA; spearman coefficient)	Mean error SVA prediction (mm)
LL $\geq$ TK + 20°	Kim et al.	51	87	63	0.37	NA
PSO angle = atan (y/z)	Ondra et al.	59	98	72	0.54	111
LL + PI + TK < 45°	Rose et al.	97	28	74	0.37	NA
LL $\geq$ PI − 10°	Schwab et al.	78	79	78	0.55	NA
SVA = −52.87 + 5.90 (PI) − 5.13 (LL_{max}) − 4.45 (PT) − 2.09 (TK_{max}) + 0.57 (age)	Lafage et al.	98	70	89*	0.75*	30

LL lumbar lordosis, *TK* thoracic kyphosis, *PI* pelvic incidence, LL_{max} maximum lumbar lordosis, TK_{max} maximum thoracic kyphosis, *TL* T10-L1 kyphosis, *NA* not applicable

* $P < 0.05$

The second step involves selecting the surgical technique, which depends on the deformity etiology and the state of anterior spinal column. PSO is preferable in patients who have had prior operations and present with a very large posterior bone callus, while SPO and TLIF are favorable if disk spaces seem to be mobile after posterior release [73].

Regarding level and degree, Lafage et al. [79] reported that the location of the osteotomy along the spine needs to be considered when attempting to normalize PT. PT reduction is greater when the osteotomy performed is more caudal; however, the level of osteotomy and degree of correction is correlated with change in PT [55, 80]. It is also important to consider that spinal segments not incorporated within the fusion may become more kyphotic after lumbar PSO [67]. This negative impact has been reported by Lafage et al. [81] to a reciprocal increase of 13° in TK within the unfused thoracic spine after lumbar PSO, and this phenomenon is more common in patients with a higher PI, a greater preoperative sagittal misalignment, and an older age.

Concluding thoughts

Over the past decades, spinal deformities warranting surgical intervention and vertebral osteotomies have continued to rise. Because osteotomies range from smaller facetectomies to major three-column resections, a new classification scheme that is anatomically based is necessary to standardize a common language for patient care and continued research. Surgical planning continues to evolve and plays an important role in preparing for the complex impact of osteotomies on the various spinal parameters which orthopaedic and neurosurgeons attempt to control. Using osteotomies for surgical correction involves skill not only in the operating setting, but a meticulous patient-specific plan prior to operative intervention. Ongoing multicenter collaboration is certain to drive a more evidence-based approach to the complex clinical scenarios of patients suffering from spinal deformity.

Conflict of interest None.

References

1. Biot B, Perdrix D (1982) Fréquence de la scoliose lombaire à l'âge adulte. Ann Med Phys 25:251–254
2. Francis RS (1988) Scoliosis screening of 3,000 college-aged women. The Utah Study–phase 2. Phys Ther 68:1513–1516
3. Robin GC, Span Y, Steinberg R et al (1982) Scoliosis in the elderly: a follow-up study. Spine 7:355–359
4. Grevitt M, Khazim R, Webb J et al (1997) The short form-36 health survey questionnaire in spine surgery. J Bone Joint Surg Br 79:48–52
5. Kostuik JP, Bentivoglio J (1981) The incidence of low-back pain in adult scoliosis. Spine 6:268–273
6. Schwab F, Dubey A, Gamez L et al (2005) Adult scoliosis: prevalence, SF-36, and nutritional parameters in an elderly volunteer population. Spine 30:1082–1085
7. Shrestha LB (2006) CRS Report for Congress
8. Carter OD, Haynes SG (1987) Prevalence rates for scoliosis in US adults: results from the first National Health and Nutrition Examination Survey. Int J Epidemiol 16:537–544
9. Saban KL, Penckofer SM (2007) Patient expectations of quality of life following lumbar spinal surgery. J Neurosci Nurs 39:180–189
10. Saban KL, Penckofer SM (2007) Patient expectations of quality of life following lumbar spinal surgery. J Neurosci Nurs 39(3):180–189
11. Bridwell KH, Glassman S, Horton W et al (2009) Does treatment (nonoperative and operative) improve the two-year quality of life in patients with adult symptomatic lumbar scoliosis: a prospective multicenter evidence-based medicine study. Spine 34:2171–2178. doi:10.1097/BRS.0b013e3181a8fdc8
12. Smith JS, Shaffrey CI, Berven S et al (2009) Improvement of back pain with operative and nonoperative treatment in adults with scoliosis. Neurosurgery 65:86–93. doi:10.1227/01.NEU.0000347005.35282.6C discussion 93–4
13. Mok JM, Cloyd JM, Bradford DS et al (2009) Reoperation after primary fusion for adult spinal deformity. Spine 34:832–839

14. Schwab F, Dubey A, Pagala M et al (2003) Adult scoliosis: a health assessment analysis by SF-36. Spine 28:602–606. doi:10.1097/01.BRS.0000049924.94414.BB
15. Schwab F, El-Fegoun AB, Gamez L et al (2005) A lumbar classification of scoliosis in the adult patient: preliminary approach. Spine 30:1670–1673
16. Schwab FJ, Smith VA, Biserni M et al (2002) Adult scoliosis: a quantitative radiographic and clinical analysis. Spine 27:387–392
17. Lafage V, Schwab F, Patel A et al (2009) Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine 34:E599–E606. doi:10.1097/BRS.0b013e3181aad219
18. Smith JS, Klineberg E, Schwab F et al (2013) Change in classification grade by the SRS-Schwab adult spinal deformity classification predicts impact on health-related quality of life measures: prospective analysis of operative and non-operative treatment. Spine 38:1663–1671. doi:10.1097/BRS.0b013e31829ec563
19. Terran J, Schwab F, Shaffrey CI et al (2013) The SRS-Schwab adult spinal deformity classification: assessment and clinical correlations based on a prospective operative and nonoperative cohort. Neurosurgery 73:559–568. doi:10.1227/NEU.0000000000000012
20. Protopsaltis TS, Schwab FJ, Smith JS et al (2013) The T1 Pelvic Angle (TPA), a novel radiographic parameter of sagittal deformity, correlates strongly with clinical measures of disability. Spine J 13:S61. doi:10.1016/j.spinee.2013.07.173
21. Schwab F, Ungar B, Blondel B et al (2012) Scoliosis research society-Schwab adult spinal deformity classification: a validation study. Spine 37:1077–1082. doi:10.1097/BRS.0b013e31823e15e2
22. Glassman SD, Bridwell K, Dimar JR et al (2005) The impact of positive sagittal balance in adult spinal deformity. Spine 30:2024–2029
23. Hassanzadeh H, Jain A, El Dafrawy MH et al (2012) Three-column osteotomies in the treatment of spinal deformity in adult patients 60 years old and older: outcome and complications. Spine. doi:10.1097/BRS.0b013e31827c2415
24. Smith JS, Shaffrey CI, Glassman SD et al (2013) Clinical and radiographic parameters that distinguish between the best and worst outcomes of scoliosis surgery for adults. Eur Spine J 22:402–410. doi:10.1007/s00586-012-2547-x
25. Voos K, Boachie-Adjei O, Rawlins BA (2001) Multiple vertebral osteotomies in the treatment of rigid adult spine deformities. Spine 26:526–533
26. Wang MY, Berven SH (2007) Lumbar pedicle subtraction osteotomy. Neurosurgery 60:ONS140–ONS146. doi:10.1227/01.NEU.0000249240.35731.8F discussion ONS146
27. Moal B, Lafage V, Smith JS et al (2012) Clinical improvement through surgery for adult spinal deformity (ASD): what can be expected and who is likely to benefit most? In: Proceedings of the NASS 27th Annual Meeting. Spine J, pp 99S–165S
28. Liu S, Schwab F, Smith JS et al (2014) Likelihood of reaching minimal clinically important difference in adult spinal deformity : a comparison of operative and nonoperative treatment. Ochsner J 14:1–12
29. Li G, Passias P, Kozanek M et al (2009) Adult scoliosis in patients over sixty-five years of age: outcomes of operative versus nonoperative treatment at a minimum two-year follow-up. Spine 34:2165–2170. doi:10.1097/BRS.0b013e3181b3ff0c
30. Bridwell KH (2006) Decision making regarding Smith-Petersen vs. pedicle subtraction osteotomy vs. vertebral column resection for spinal deformity. Spine 31:S171–S178. doi:10.1097/01.brs.0000231963.72810.38
31. Weinstein SL, Ponseti IV (1983) Curve progression in idiopathic scoliosis. J Bone Joint Surg Am 65:447–455
32. Bakaloudis G, Lolli F, Di Silvestre M et al (2011) Thoracic pedicle subtraction osteotomy in the treatment of severe pediatric deformities. Eur Spine J 20(Suppl 1):S95–S104. doi:10.1007/s00586-011-1749-y
33. Smith-Petersen MN, Larson CB, Aufranc OE (1969) Osteotomy of the spine for correction of flexion deformity in rheumatoid arthritis. Clin Orthop Relat Res 66:6–9
34. Smith-Petersen MN, Larson CB, Aufranc OE (1945) Osteotomy of the spine for correction of flexion deformity in rheumatoid arthritis. J Bone Joint Surg Am 27:1–11
35. Ponte A, Vero B, Siccardi G (1984) Surgical treatment of scheuermann's hyperkyphosis. In: 19th Annual Meeting of the Scoliosis Research Society
36. Heinig C (1984) Eggshell procedure. Segmental spinal instrumentation, pp 221–234
37. Bridwell KH, Lewis SJ, Lenke LG et al (2003) Pedicle subtraction osteotomy for the treatment of fixed sagittal imbalance. J Bone Joint Surg Am 85-A:454–463
38. Murrey DB, Brigham CD, Kiebzak GM et al (2002) Transpedicular decompression and pedicle subtraction osteotomy (eggshell procedure): a retrospective review of 59 patients. Spine 27:2338–2345. doi:10.1097/01.BRS.0000030853.62990.BC
39. Berven S, Deviren V, Smith JA et al (2001) Management of fixed sagittal plane deformity: results of the transpedicular wedge resection osteotomy. Spine 26:2036–2043
40. Schwab F, Blondel B, Chay E et al (2013) The comprehensive anatomical spinal osteotomy classification. Neurosurgery. doi:10.1227/NEU.0000000000000182
41. Denis F (1983) The three column spine and its significance in the classification of acute thoracolumbar spinal injuries. Spine 8:817–831
42. Schwab F, Blondel B, Chay E et al (2014) The comprehensive anatomical spinal osteotomy classification. Neurosurgery 74:112–120. doi:10.1227/NEU.0000000000000182o
43. Burgos J, Rapariz J, Gonzalez-Herranz P (1998) Anterior endoscopic approach to the thoracolumbar spine. Spine 23:2427–2431
44. Suh SW, Modi HN, Yang J et al (2009) Posterior multilevel vertebral osteotomy for correction of severe and rigid neuromuscular scoliosis: a preliminary study. Spine 34:1315–1320. doi:10.1097/BRS.0b013e3181a028bc
45. Pascal-Moussellard H, Klein J, Schwab F, Farcy J (1999) Simultaneous anterior and posterior approaches to the spine for revision surgery: current indications and techniques. J Spinal Disord Tech 12:206–213
46. Scudese V, Calabro J (1963) Vertebral wedge osteotomy. Correction of rheumatoid (ankylosing) spondylitis. JAMA 186:627–631
47. Brodner W, Mun Yue W, Moller H et al (2003) Short segment bone-on-bone instrumentation for single curve idiopathic scoliosis. Spine 28:S224–S233
48. Moal B, Schwab FJ, Ames CP et al (2012) Radiographic outcomes of adult spinal deformity correction: a critical analysis of variability and failures across deformity patterns. Congress of Neurological Surgeons, 2012 Annual Meeting, Chicago, Illionis, 6–10 October 2012
49. Schwab F, Patel A, Shaffrey CI et al (2012) Sagittal realignment failures following pedicle subtraction osteotomy surgery: are we doing enough? J Neurosurg Spine 16:539–546. doi:10.3171/2012.2.SPINE11120
50. Lafage V, Smith JS, Bess S et al (2012) Sagittal spino-pelvic alignment failures following three column thoracic osteotomy for adult spinal deformity. Eur Spine J 21:698–704. doi:10.1007/s00586-011-1967-3
51. Jackson RP, McManus AC (1994) Radiographic analysis of sagittal plane alignment and balance in standing volunteers and patients with low back pain matched for age, sex, and size. A prospective controlled clinical study. Spine 19:1611–1618
52. Schwab F, Lafage V, Patel A, Farcy J-P (2009) Sagittal plane considerations and the pelvis in the adult patient. Spine 34:1828–1833. doi:10.1097/BRS.0b013e3181a13c08

53. Jackson RP, Hales C (2000) Congruent spinopelvic alignment on standing lateral radiographs of adult volunteers. Spine 25:2808–2815
54. Smith JS, Bess S, Shaffrey CI et al (2012) Dynamic changes of the pelvis and spine are key to predicting postoperative sagittal alignment after pedicle subtraction osteotomy: a critical analysis of preoperative planning techniques. Spine 37:845–853. doi:10.1097/BRS.0b013e31823b0892
55. Lafage V, Schwab F, Vira S et al (2011) Spino-pelvic parameters after surgery can be predicted: a preliminary formula and validation of standing alignment. Spine 36:1037–1045. doi:10.1097/BRS.0b013e3181eb9469
56. Maier S, Smith JS, Schwab F et al (2014) Revision surgery after three-column osteotomy in 335 adult spinal deformity patients: inter-center variability and risk factors. Spine. doi:10.1097/BRS.0000000000000304
57. Hart R, McCarthy I, O'brien M et al (2013) Identification of decision criteria for revision surgery among patients with proximal junctional failure following surgical treatment for spinal deformity. Spine 38:1223–1227. doi:10.1097/BRS.0b013e31829fedde
58. Blam OG, Vaccaro AR, Vanichkachorn JS et al (2003) Risk factors for surgical site infection in the patient with spinal injury. Spine 28:1475–1480. doi:10.1097/01.BRS.0000067109.23914.0A
59. Ames CP, Barry JJ, Keshavarzi S et al (2013) Perioperative outcomes and complications of pedicle subtraction osteotomy in cases with single versus two attending surgeons. Spine Deform 1:51–58. doi:10.1016/j.jspd.2012.10.004
60. Goz V, Slobodyanyuk K, Cheriyan T et al (2013) Antifibrinolytics reduce blood loss in adult spinal deformity surgery: a prospective randomized controlled trial. Spine J 13:S1. doi:10.1016/j.spinee.2013.07.032
61. Mummaneni PV, Tu T-H, Ziewacz JE et al (2013) The role of minimally invasive techniques in the treatment of adult spinal deformity. Neurosurg Clin N Am 24:231–248. doi:10.1016/j.nec.2012.12.004
62. Moal B, Lafage VC, Maier SP et al (2014) Discrepancies in preoperative planning and operative execution in the correction of sagittal spinal deformities. In: North American Spine Society 29th Annual Meeting (San Francisco)
63. Le Huec JC, Leijssen P, Duarte M, Aunoble S (2011) Thoracolumbar imbalance analysis for osteotomy planification using a new method: FBI technique. Eur Spine J 20(Suppl 5):669–680. doi:10.1007/s00586-011-1935-y
64. Debarge R, Demey G (2010) Radiological analysis of ankylosing spondylitis patients with severe kyphosis before and after pedicle subtraction osteotomy. Eur Spine J 19:65–70. doi:10.1007/s00586-009-1158-7
65. Vialle R, Levassor N, Rillardon L et al (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. J Bone Joint Surg Am 87:260–267. doi:10.2106/JBJS.D.02043
66. Schwab F, Bess RS, Blondel B et al (2011) Combined assessment of pelvic tilt, lumbar lordosis/pelvic incidence mismatch and sagittal vertical axis predicts disability in adult spinal deformity: a prospective analysis. Spine J 11:S158–S159. doi:10.1016/j.spinee.2011.08.380
67. Akbar M, Terran J, Ames CP et al (2013) Use of Surgimap Spine in sagittal plane analysis, osteotomy planning, and correction calculation. Neurosurg Clin N Am 24:163–172. doi:10.1016/j.nec.2012.12.007
68. Schwab F, Farcy J, Bridwell K et al (2006) A clinical impact classification of scoliosis in the adult. Spine 31:2109–2114. doi:10.1097/01.brs.0000231725.38943.ab
69. Glassman SD, Berven S, Bridwell K et al (2005) Correlation of radiographic parameters and clinical symptoms in adult scoliosis. Spine 30:682–688
70. Obeid I, Hauger O, Aunoble S et al (2011) Global analysis of sagittal spinal alignment in major deformities: correlation between lack of lumbar lordosis and flexion of the knee. Eur Spine J 20(Suppl 5):681–685. doi:10.1007/s00586-011-1936-x
71. Gangnet N, Pomero V, Dumas R et al (2003) Variability of the spine and pelvis location with respect to the gravity line: a three-dimensional stereoradiographic study using a force platform. Surg Radiol Anat 25:424–433. doi:10.1007/s00276-003-0154-6
72. Lafage V, Schwab F, Skalli W et al (2008) Standing balance and sagittal plane spinal deformity: analysis of spinopelvic and gravity line parameters. Spine 33:1572–1578. doi:10.1097/BRS.0b013e31817886a2
73. Aurouer N, Obeid I, Gille O et al (2009) Computerized preoperative planning for correction of sagittal deformity of the spine. Surg Radiol Anat 31:781–792. doi:10.1007/s00276-009-0524-9
74. Barrey C, Roussouly P, Le Huec J-C et al (2013) Compensatory mechanisms contributing to keep the sagittal balance of the spine. Eur Spine J 22(Suppl 6):S834–S841. doi:10.1007/s00586-013-3030-z
75. Ondra SL, Marzouk S, Koski T et al (2006) Mathematical calculation of pedicle subtraction osteotomy size to allow precision correction of fixed sagittal deformity. Spine 31:E973–E979. doi:10.1097/01.brs.0000247950.02886.e5
76. Van Royen BJ, De Gast A, Smit TH (2000) Deformity planning for sagittal plane corrective osteotomies of the spine in ankylosing spondylitis. Eur Spine J 9:492–498
77. Van Royen BJ, Scheerder FJ, Jansen E, Smit TH (2007) ASKyphoplan: a program for deformity planning in ankylosing spondylitis. Eur Spine J 16:1445–1449. doi:10.1007/s00586-007-0371-5
78. Vialle R, Levassor N, Rillardon L et al (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. J Bone Joint Surg Am 87:260–267. doi:10.2106/JBJS.D.02043
79. Lafage V, Schwab F, Vira S et al (2011) Does vertebral level of pedicle subtraction osteotomy correlate with degree of spinopelvic parameter correction? J Neurosurg Spine 14:184–191. doi:10.3171/2010.9.SPINE10129
80. Ames CP, Smith JS, Scheer JK et al (2012) Impact of spinopelvic alignment on decision making in deformity surgery in adults: a review. J Neurosurg Spine 16:547–564. doi:10.3171/2012.2.SPINE11320
81. Lafage V, Ames C, Schwab F et al (2012) Changes in thoracic kyphosis negatively impact sagittal alignment after lumbar pedicle subtraction osteotomy: a comprehensive radiographic analysis. Spine 37:E180–E187. doi:10.1097/BRS.0b013e318225b926