Current Concepts Review

Sagittal Alignment in the Degenerative Lumbar Spine

Surgical Planning

Bassel G. Diebo, MD, Mariah Balmaceno-Criss, BS, Renaud Lafage, MS, Christopher L. McDonald, MD, Daniel Alsoof, MBBS, Sereen Halayqeh, MD, Kevin J. DiSilvestro, MD, Eren O. Kuris, MD, Virginie Lafage, PhD, and Alan H. Daniels, MD

Investigation performed at Brown Spine Research Laboratory, Department of Orthopaedic Surgery, Warren Alpert Medical School, Brown University, Providence, Rhode Island

- Sagittal alignment of the spine has gained attention in the field of spinal deformity surgery for decades. However, emerging data support the importance of restoring segmental lumbar lordosis and lumbar spinal shape according to the pelvic morphology when surgically addressing degenerative lumbar pathologies such as degenerative disc disease and spondylolisthesis.
- The distribution of caudal lordosis (L4-S1) and cranial lordosis (L1-L4) as a percentage of global lordosis varies by pelvic incidence (PI), with cephalad lordosis increasing its contribution to total lordosis as PI increases.
- Spinal fusion may lead to iatrogenic deformity if performed without attention to lordosis magnitude and location in the lumbar spine.
- A solid foundation of knowledge with regard to optimal spinal sagittal alignment is beneficial when performing lumbar spinal surgery, and thoughtful planning and execution of lumbar fusions with a focus on alignment may improve patient outcomes.

The concept of spinopelvic alignment was described by Jean Dubousset as a "cone of economy" where the axial skeleton balances in line above the pelvis, lower limbs, and feet[1]. From this idea, an understanding of multiple important sagittal alignment parameters (Fig. 1) emerged in the spinal deformity literature over the past few decades, and the importance of a harmonious spine is now well established[2]. However, in the degenerative spine realm, careful consideration of the sagittal plane was not widely considered when planning operations for degenerative pathology. Recently, this paradigm has begun to shift, and the importance of sagittal alignment in assessment and treatment of patients with degenerative spinal conditions is becoming increasingly recognized. With the increased volume of lumbar fusions, and the need for better short-term and long-term patient outcomes, alignment concepts are emerging to possibly provide solutions to improve the outcomes and longevity of short construct fusions[3-5]. This review will discuss the importance of sagittal plane alignment in the setting of degenerative lumbar disease based on recent literature, with the aim of assisting surgeons in improving outcomes following surgical management of degenerative spinal pathology.

Sagittal Alignment and Degenerative Lumbar Pathologies

The implications of abnormal spinopelvic alignment in degenerative lumbar pathologies have been recently investigated[6-10]. Patients with higher pelvic incidence (PI) are more prone to

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJS/H867).

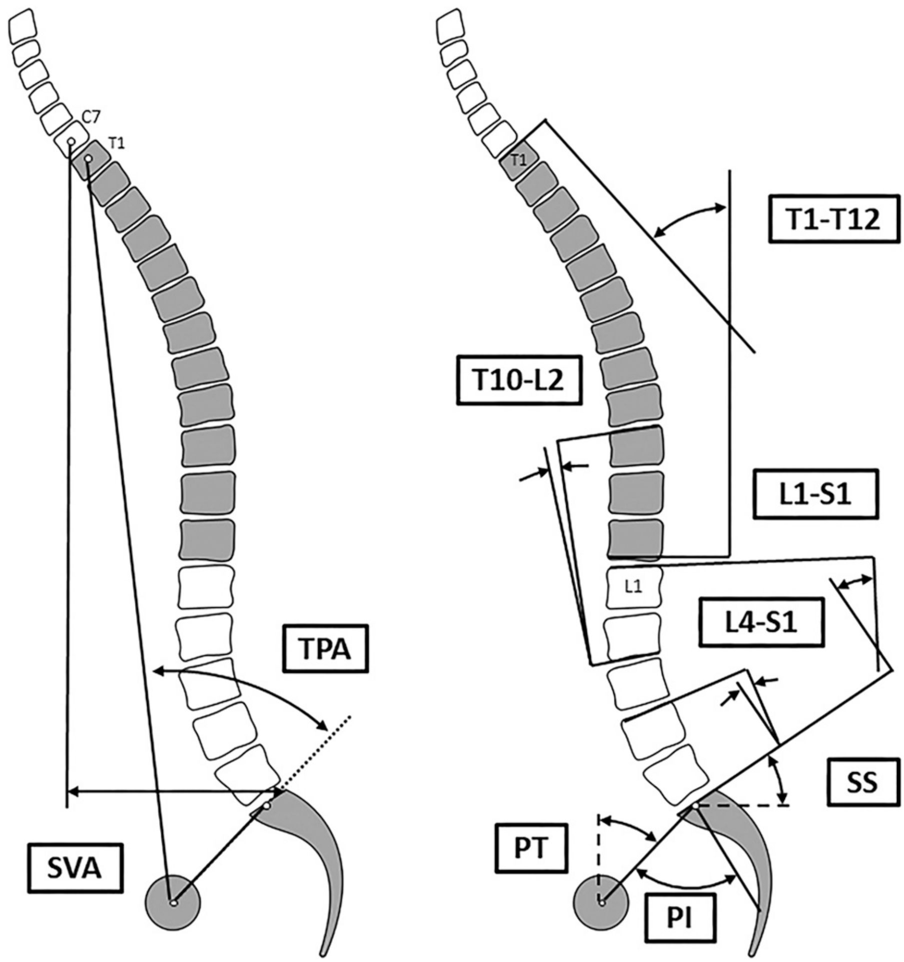


Fig. 1
Schematic representation of radiographic parameters used for sagittal alignment assessment. TPA = T1-pelvic angle, SVA = sagittal vertical axis, T1-T12 = thoracic kyphosis, T10-L2 = thoracolumbar junction, L1-S1 = LL, and L4-S1 = distal LL or lower LL.

experiencing lumbar spondylolisthesis, and those with extremely high PI values have a greater likelihood of developing 2-level disease[10-20]. Although the literature has been conflicting with regard to the impact of degenerative spondylolisthesis on global lumbar lordosis (LL), a nuanced evaluation found that patients with degenerative spondylolisthesis have decreased LL in the caudal L4-S1 levels and increased LL in the cranial L1-L3 levels[11,13,16,18].

Sagittal alignment is also a factor in the clinical presentation of patients with spinal stenosis. However, in comparison with degenerative spondylolisthesis, where the anatomy exacerbates the clinical symptoms, the opposite appears to be the case in spinal stenosis. The loss of LL and increased sagittal vertical axis in patients with spinal stenosis are, in some cases, a compensatory mechanism in the flexible spine in order to open the neural foramen, although it should be noted that spinal stenosis occurs at different rates in patients depending on spinopelvic morphology[8,21]. As malalignment progresses in spinal stenosis, these patients maintain their pelvic tilt (PT) and compensate by shifting the pelvis posteriorly, with pelvic retroversion considered a late finding in this cohort of patients[22]. This differs from patients with primary adult spinal deformity, who use pelvic retroversion as an earlier means of compensation[22]. For patients with lumbar spinal stenosis, simple lumbar decompression can potentially improve spinopelvic alignment, with Ham et al. demonstrating improvement in relative spinopelvic measures in patients with preoperative pain within 10 minutes of standing[23]. The application of sagittal alignment principles to lumbar degenerative disease may help to improve outcomes because one of the main issues facing degenerative spine surgery is the increased prevalence of overcorrected and undercorrected lordosis in patients with short-segment fusions[24]. This is partly due to the ambiguity in defining lordosis targets for any given lumbar disc-vertebral segment. Evaluating the contribution to lordosis from each segment is important, as it varies from one subject to another, even in the non-pathologic spine. The following sections will delve deeper into the normal lordosis and shape of the lumbar spine and the impact of age and degeneration on both.

LL, the Body, and the Disc

LL, a critical component of the sagittal plane for maintaining an upright posture, is primarily formed by a combination of wedging of the lumbar vertebral bodies and intervertebral discs[25-28]. Vaz et al. demonstrated that more lordosis is achieved by intervertebral disc wedging than by vertebral body wedging[27]. Been et al. confirmed these results and noted a progression from increased dorsal (lordotic) wedging of the vertebral bodies in the lower lumbar spine to slight ventral (kyphotic) wedging of the upper lumbar spine as LL transitions to thoracic kyphosis[28]. This transition usually occurs at the L2 vertebra, although this is influenced by normal variations in sagittal alignment among humans. Additionally, variations in sagittal alignment also influence the relative proportions of lordosis generated from the body and the disc.

Roussouly et al. was the first to describe different lumbar spinal shapes based on normal variations in sacral slope (SS)[25]. In this work, Roussouly et al.[25] redemonstrated an earlier finding from Legaye et al.[29], showing global LL to significantly correlate with SS and PI, although a weaker correlation was demonstrated with PI. PI describes the orientation of the sacrum within the ilium. PI increases throughout skeletal maturation, with anterior-posterior growth of the pelvis, before becoming fixed in adulthood, with a range from 20° to >80° in normative data[30]. PI is thought to remain unchanged in adulthood, even with degeneration[31-33]. However, recent data revealed that PI actually may change over time via increased stress over the sacroiliac joints and subsequent remodeling of these joints and the sacral end plate, a process evident in patients with long fusions involving S1 as the lower instrumented vertebra[34,35]. Nevertheless, given the relative stability of PI compared with SS, LL is often evaluated relative to PI[25]. In asymptomatic subjects, PI affects the magnitude and distribution of LL; subjects with a larger PI have a more horizontal sacrum, a higher SS, and a larger LL with a more proximal apex compared with those with a low PI[34,36,37]. LL is also correlated with thoracic kyphosis; in particular, the upper arch of the lordosis is often equal to the lower arch of the thoracic kyphosis[38,39]. Therefore, it is favorable to evaluate LL based on its relationship with PI and thoracic kyphosis.

Defining Normal Global, Regional, and Segmental LL

Defining surgical targets for LL has evolved over the years. The historical target was "as much lordosis as possible." This continued until several authors, including Schwab et al. and Lafage et al., proposed matching PI to LL within 10°, which has been shown to improve outcomes even in surgical procedures for degenerative pathology[35,40-51]. It has been suggested to correct LL to PI + 10° if the PI is low and to PI − 10° if the PI is high[52]. Since then, this simple concept of PI–LL has progressed into targeting the ideal lumbar apex and distribution of lordosis between the cephalad and caudal segments[36,53]. Those measurements are of particular importance in the degenerative lumbar spine because patients may have a poor distribution of LL even though global lordosis may appear normal. In one formative study, Pesenti et al. helped to define the regional distribution of lordosis in normal subjects[34]. The distribution of caudal lordosis (L4-S1) and cephalad lordosis (L1-L4) as a percentage of global lordosis varies by PI, with cephalad lordosis increasing its contribution to total lordosis as PI increases[34]. Their study also built on the work by Roussouly et al.[25] and redemonstrated that, as PI increases, the apex of lordosis migrates to a more cephalad location, with a concomitant increase in the magnitude of proximal lordosis. Therefore, lordosis of the lumbar segments above and below the apex became better appreciated. It is important to note that authors have differed in their definitions of caudal and cephalad lordosis. Roussouly et al. defined cephalad lordosis as the lordosis proximal to the apex, which varies by PI[25]. However, to simplify the concept, Pesenti et al. analyzed lordosis within fixed boundaries of L1-L4 and L4-S1 (Fig. 2)[34]. The application of these measurements in degenerative spine diseases has been shown to reduce the risk of postoperative malalignment, adjacent segment disease, and revision surgery[24,54-56]. Recent studies have furthered the understanding of a harmonious sagittal plane, reporting the mean segmental lordosis values based on PI[34,35]. Table I includes the mean segmental lordosis per PI category; these values were extrapolated from recent normative segmental lordosis publications[34,35]. The table provides a general reference for surgical planning; however, surgical planning should be personalized for each patient's spinopelvic anatomy. For example, in cases of low PI, it can be normal for the proximal lumbar vertebrae to be kyphotic, and aiming for a neutral T10-L2 alignment would be appropriate for most patients.

Impact of Age and Degeneration on LL

Prost et al. examined the correlation between age and sagittal alignment of the spine in asymptomatic volunteers[57]. They found that, in individuals with low PI, there was a global decrease in LL in both cephalad and caudal segments; in contrast, in individuals with high PI, more prominent loss of caudal lordosis was associated with increased PT and more prominent loss of cephalad lordosis was associated with increasing kyphosis and positive sagittal malalignment[57]. These findings have important implications and call for thorough assessment of PI and caudal and cephalad lordosis, with a surgical plan that aims to restore appropriate segmental lordosis based on spinopelvic anatomy[58].

In the degenerative setting, decreased global LL (or flattening of the lumbar spine) can occur by squaring of the intervertebral discs from their previous dorsal wedging and degeneration of the intervertebral discs to a more kyphotic alignment, leading to alteration of segmental lordosis[59-62]. Thus, measurement of vertebral body wedging and intervertebral disc lordosis of the segment of interest will inform decisions with regard to the type of interbody device required in terms of magnitude of lordosis, height, location of the end-plate contact, and need for posterior compression of that segment[25]. For example, in isthmic spondylolisthesis, as the L5 vertebra translates anteriorly, the vertebral body has been shown to become more trapezoidal, the sacral dome becomes more dysplastic, and relative kyphosis develops at the intervertebral disc and lower lumbar segments[59]. Therefore, careful assessment of the L5 body and L5-S1 segmental alignment is important in surgical decision-making and choices of implants and techniques (Fig. 3). Overall, when performing a short-segment lumbar fusion, one should always be aware of the magnitude of lordosis in the level of interest, as well as in adjacent segments.

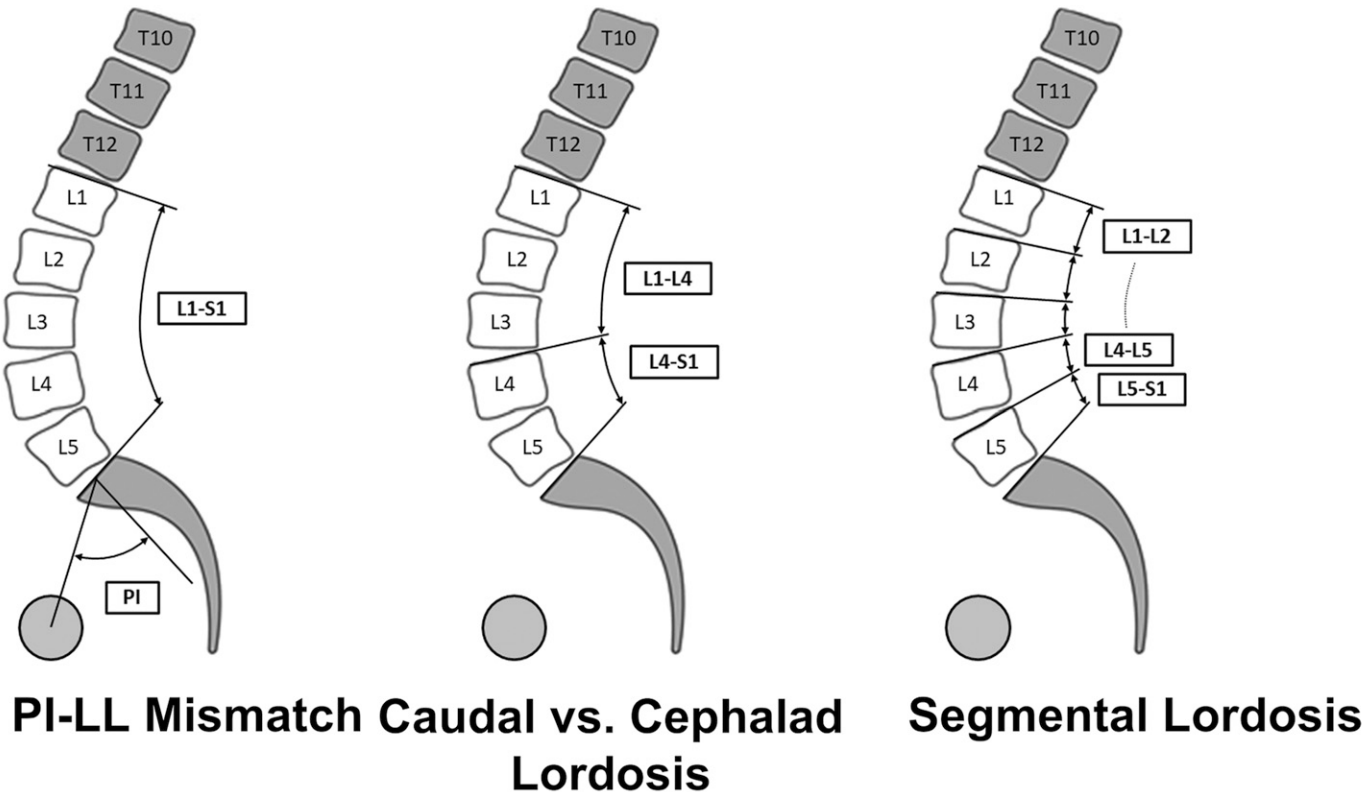


Fig. 2
Evaluating global LL (left), regional LL (middle), and segmental LL (right).

Degenerative changes altering the magnitude of lordosis in 1 segment induce compensatory changes in other segments to maintain sagittal alignment. Thus, global lordosis may appear normal, but focused analysis will reveal the suboptimal lumbar distribution between cephalad and caudal segments[63,64]. The implications of this concept may explain some biomechanical failures in short lumbar fusions that include both pathologic segments and those in compensated positions; however, there have been no data yet to support this hypothesis. Similarly, fusion might be indicated for a hyperlordotic-compensated segment with resultant stenosis; recognizing this phenomenon enables surgeons to fuse in a proper segmental lordosis. In this scenario, the alignment goal might be to reduce (rather than increase) lordosis in that segment.

TABLE I Mean Segmental Sagittal Alignment Values for the Lumbar and Thoracolumbar Spinal Regions*

PI Category	T10-L2	L1-L2	L2-L3	L3-L4	L4-L5	L5-S1
40°	−6.9°	1.7°	4.4°	9.5°	15°	17.5°
50°	−4.3°	1.7°	6.2°	10.1°	15°	20°
60°	−4.3°	3.1°	7.9°	11.2°	15°	20°
70°	2.1°	4.9°	9.2°	15.4°	15°	20°
80°	2.1°	5.5°	11.9°	17°	19°	20°
90°	2.1°	7.3°	14.6°	12.9°	22°	20°

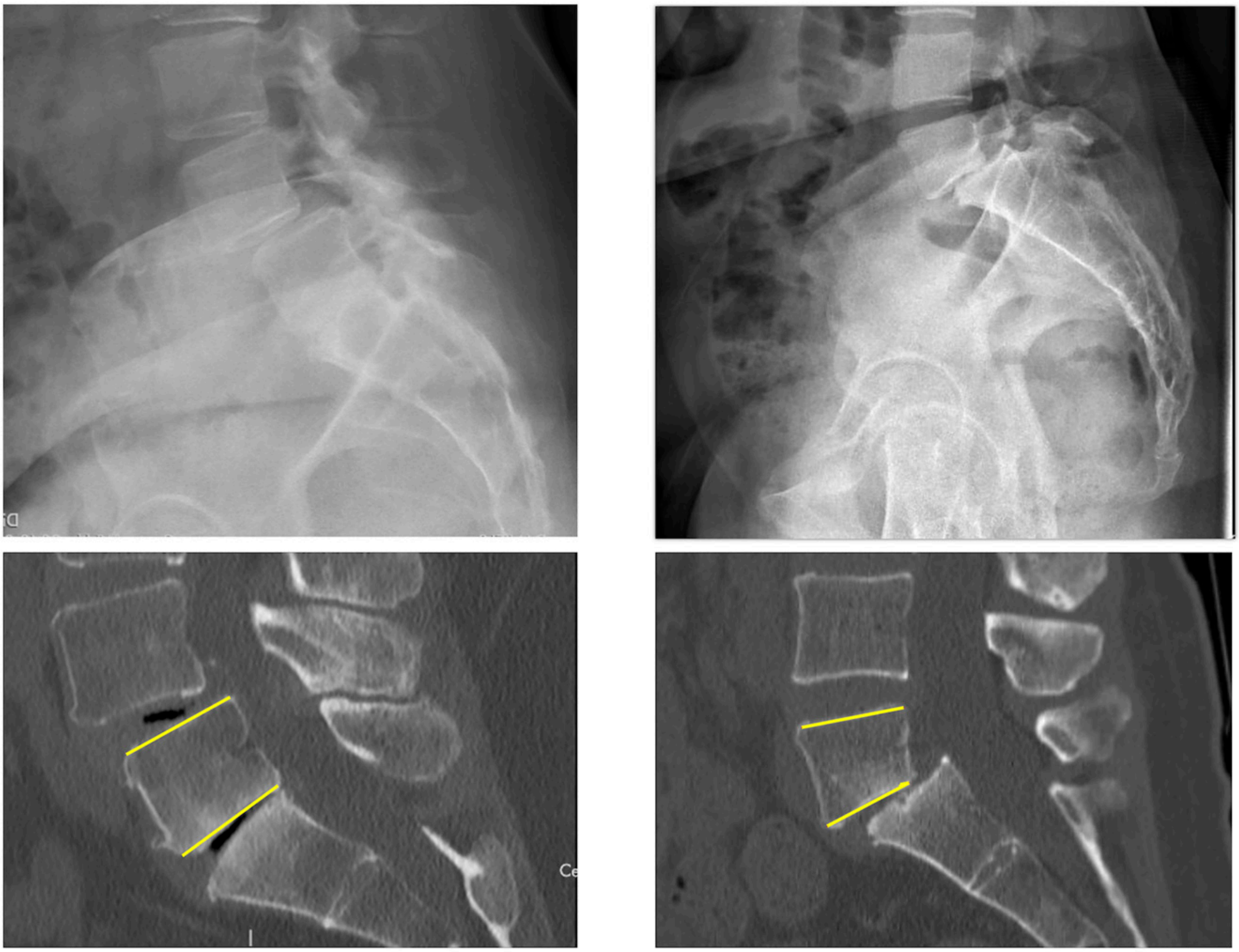
*These data should be interpreted with caution, as the values are means and thus may not be prescriptive for every patient.

Although the prior argument emphasizes the importance of sagittal alignment in the degenerative spine, alignment itself is not an indication for surgical intervention. Patients' physical examination, symptomology, and clinical correlation of radiographic findings to patient-reported outcome measures remain the first line to indicate patients for a surgical procedure. Therefore, it is imperative to note that we do not encourage fusing additional segments to optimize the sagittal plane, but rather encourage a critical analysis of segmental lordosis throughout the lumbar spine and an aim of restoring the surgically indicated levels to the normative targets. Figure 4 illustrates 3 types of degenerative spine conditions; note the associated loss of segmental lordosis, cephalad or caudal, and hyperlordotic compensation in adjacent segments[65-67].

Why Should Surgeons Preserve or Restore the Sagittal Plane in Degenerative Lumbar Surgery?

The decision to fuse the lumbar spine for degenerative pathology can be challenging. We believe that there are 3 important concepts to which to adhere (Table II).

The first concept is to not create malalignment. The spinal surgery community remains poor at restoring alignment, with 1 study showing that 28% of patients remained malaligned following short-segment fusion for degenerative lumbar pathologies[68]. Despite advances in segmental fixation and the power of newer interbody devices, there remains a



A. Square L5 vertebral body, 6° of lordosis B. Trapezoidal L5 vertebral body, 17° of lordosis

Fig. 3

Two examples of L5 vertebral body shapes that could factor into restoring segmental lordosis. The yellow lines indicate L5 vertebral end plates.

high prevalence of iatrogenic sagittal plane deformity following short-segment fusions[69-72]. Subsequent management of these patients can include the need for invasive procedures such as pedicle subtraction osteotomies, with complication rates as high as 60%. This indicates the importance of careful preoperative planning at the index surgical procedure[68].

Specific approaches to the spine and the use of selected interbody devices can profoundly impact spinopelvic parameters and regional alignment. Anterior lumbar interbody fusion (ALIF) is a reliable procedure that can provide powerful correction exceeding 30° of segmental lordosis; this may be vital at the L5-S1 segment. However, moving cranially in the spine can make the approach for ALIF cage placement challenging. Lateral approach techniques such as lateral lumbar interbody fusion (LLIF) and oblique lumbar interbody fusion (OLIF) can provide access to upper lumbar disc spaces and provide a substantial increase in segmental lordosis when combined with an anterior column realignment approach, compared with posterior-based approaches[73-77]. LLIF and OLIF can be combined with a posterior approach for posterior-column osteotomies to further improve segmental and global alignment[78,79]. Posterior-based approaches include transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF). Multiple studies have shown that surgeons and implants vary in their ability to achieve lordosis at an individual segmental level utilizing TLIF[44,80,81]. Successful restoration (or retention) of segmental lordosis can be challenging via TLIF, but may be achieved with the aid of dedicated spinal tables, anteriorly placed TLIF cages, posterior column osteotomies, and compression posteriorly before the final tightening of the set screws[82,83]. Therefore, after the ideal segmental lordosis and the overall lumbar shape and apex have been chosen, choosing the proper surgical technique and implant may optimize achievement of alignment goals for the individual lumbar segments[84].

In vertebral levels that already have substantial disc height and segmental lordosis, it can be challenging to further increase lordosis, and interbody device placement may induce kyphosis without appropriate attention to technical detail[85]. Bilateral

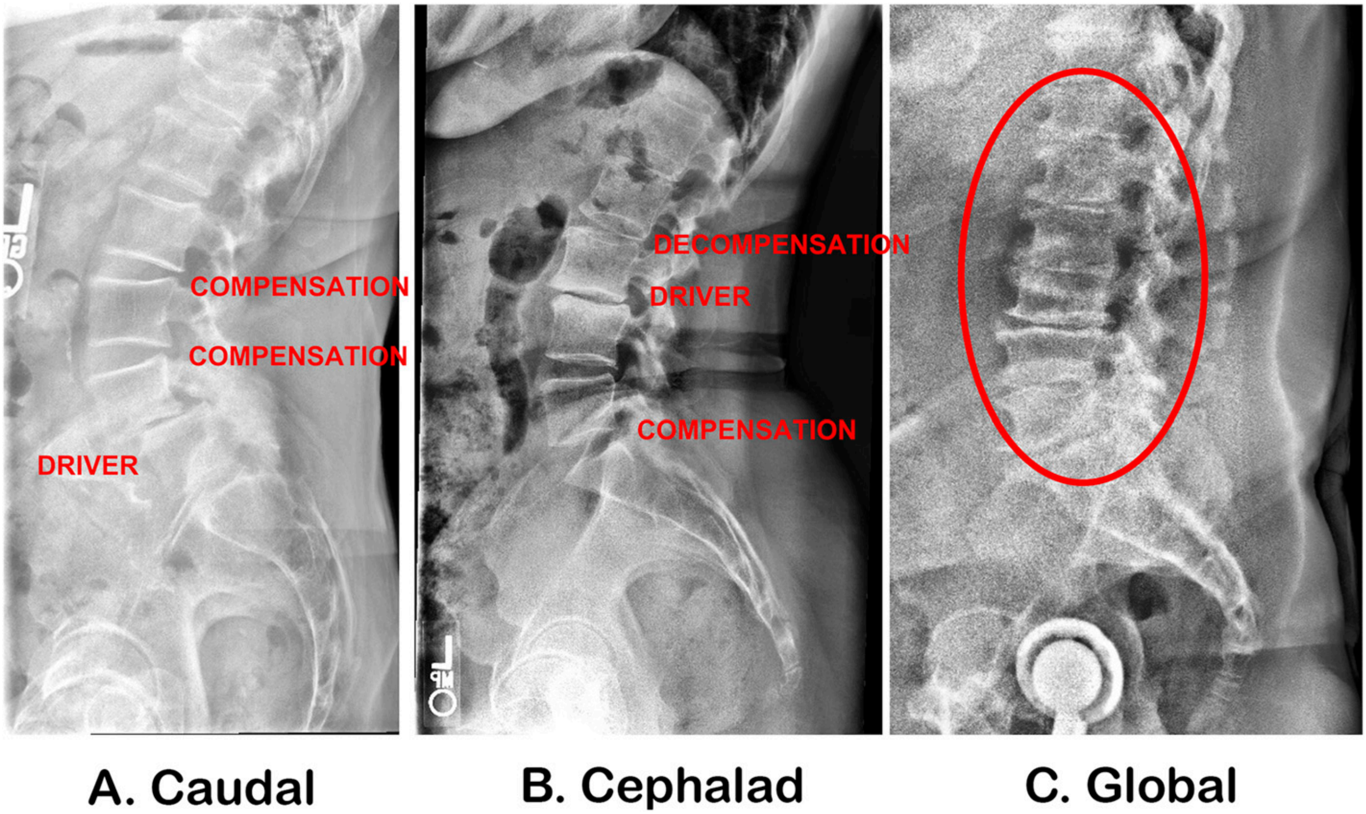


Fig. 4
Three types of degenerative lumbar disease from a sagittal alignment standpoint: loss of lordosis in caudal segments (**Fig. 4-A**), cephalad segments (**Fig. 4-B**), and globally throughout the lumbar spine (**Fig. 4-C**). L2-L3 and L3-L4 compensatory hyperlordosis is noted in **Figure 4-A**, L2-L3 decompensation (rotational failure) and L5-S1 compensatory hyperlordosis are noted in **Figure 4-B**, and no compensation due to regional degeneration (red oval) is noted in **Figure 4-C**.

facetectomy, anterior cage placement with compression across the posterior pedicle screws, and the use of expandable cages have been shown to mitigate these risks, although surgeons should be aware of the increased risk of subsidence with expandable cage placement[86,87]. Furthermore, iatrogenic foraminal stenosis and inadequate restoration of foraminal height are potential issues with lordosis restoration that need to be carefully considered. In general, and regardless of the approach and type of interbody device utilized, targeting segmental lordosis ideals should be the goal from an alignment perspective. It is important to note that restoring the segmental lordosis or achieving ideal alignment does not mean fusing an additional level, but rather ensuring that the indicated segment has adequate lordosis by increasing it, maintaining it, or sometimes decreasing it (Table I).

The second concept is to aim to prevent the development of adjacent segment disease. Sagittal malalignment may be a risk factor for developing adjacent segment disease, even following short-segment lumbar fusion for degenerative pathology. This is likely due to altered spinal biomechanics and stress concentration at the adjacent disc segments. This point was exemplified by Herrington et al., who showed that surgically reducing lordosis at L4-L5 led to increased focal lordosis at L3-L4 and a higher reoperation rate for adjacent segment disease at that location[55]. Similarly, Bari et al.[24] and Zheng et al.[56] demonstrated that, postoperatively, patients in whom <50% of the total lordosis was generated at L4-S1 experienced higher revision rates compared with patients with an adequate distribution of lordosis. Other studies have corroborated these findings, demonstrating

TABLE II Recommendations for Restoring the Sagittal Plane in Degenerative Lumbar Surgery

Benefits of Ideal Segmental Lordosis	Grade of Recommendation*
No creation of lumbar segmental malalignment during spinal fusion surgery	B
Prevention of adjacent segment disease	B
Reduction of the incidence of low back pain	B

*According to Wright[112], grade A indicates good evidence (Level-I studies with consistent findings) for or against recommending intervention; grade B, fair evidence (Level-II or III studies with consistent findings) for or against recommending intervention; grade C, poor-quality evidence (Level-IV or V studies with consistent findings) for or against recommending intervention; and grade I, insufficient or conflicting evidence not allowing a recommendation for or against intervention.

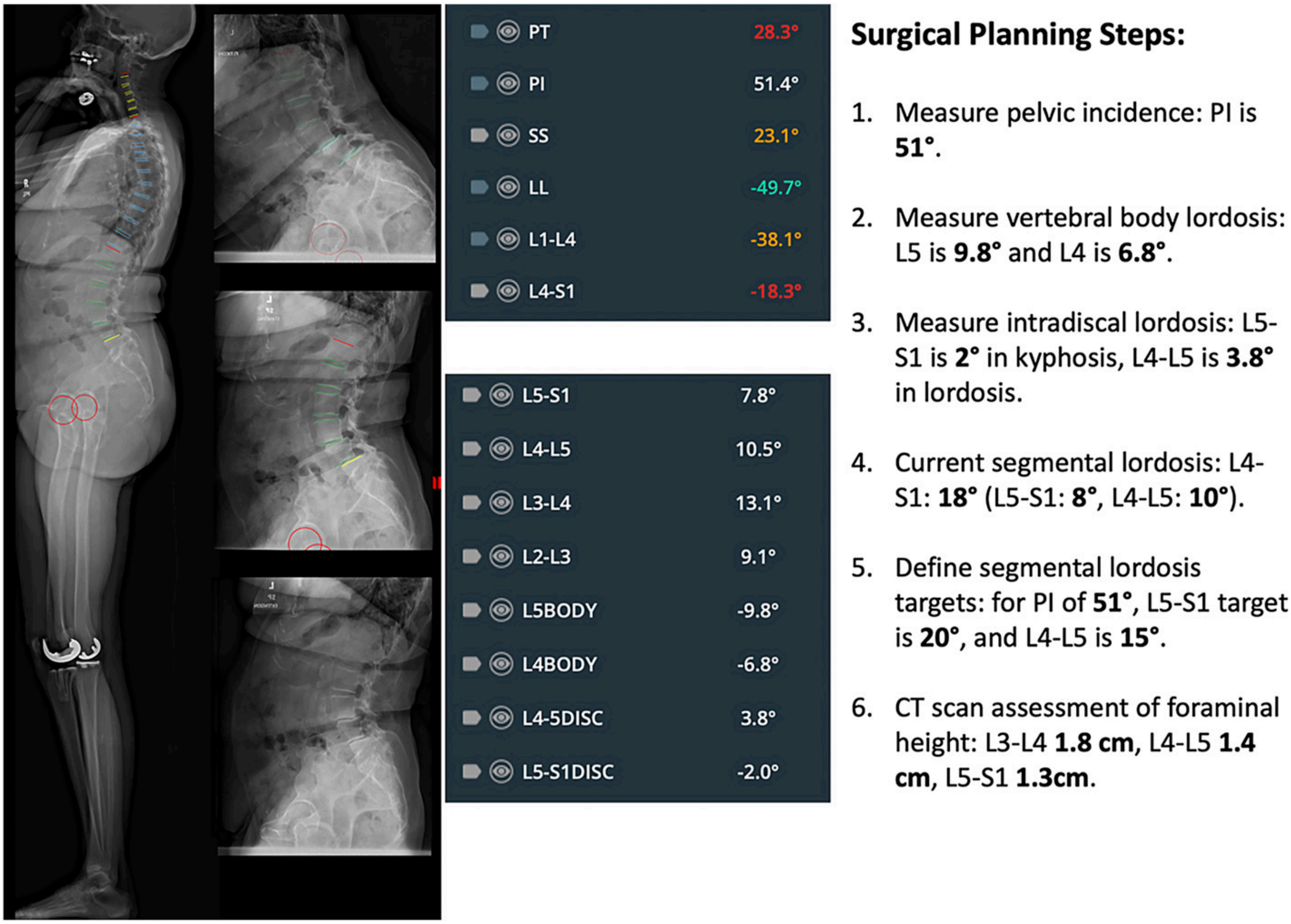


Fig. 5

Preoperative sagittal alignment, with spinopelvic parameters. CT = computed tomography.

the importance of sagittal alignment in lowering the risk of adjacent segment disease after lumbar fusion for degenerative pathology[88-93]. Although multiple studies have found an association between adjacent segment disease and sagittal alignment, Toivonen et al. found no association in their study with 10-year clinical outcome follow-up but only 3-month postoperative radiographic follow-up[94]. Hsieh et al. reported similar findings in a smaller study sample without a control group[95]. Furthermore, Hsieh et al. focused on global LL using PI–LL, instead of assessing segmental lordosis, which may have misclassified patients with compensatory changes adjacent to the indicated levels[95].

The goal should not simply be to obtain as much disc height or segmental lordosis as possible, but to follow segmental lordosis targets[96]. Thus, harmonious restoration of level-specific sagittal parameters may help to reduce the risk of adjacent segment disease after lumbar fusion. Other factors that may contribute to the development of adjacent segment disease include preexisting facet degeneration cranial to the fusion, increased preoperative PT that does not correct after fusion, inadequate restoration of lordosis, advanced age, osteoporosis, higher body mass index, and longer fusion length[97-102].

The third concept is to decrease the incidence of low back pain and spine-related disability by improving spinopelvic alignment parameters. In cases where spinopelvic alignment improves after isolated decompression, the associated back pain experienced by patients also improves[103]. This finding has carried over into cases of fusion, where restoration of both segmental lordosis and PT has resulted in decreased low back pain[104]. More globally, the correction of PI–LL as well as a positive sagittal vertical axis have also been shown to aid in the reduction of back pain for degenerative pathologies[105]. Back pain and fatigue in patients with spinopelvic malalignment may be driven by compensatory changes that occur outside of the fusion construct due to flattening of the thoracic kyphosis, elevated PT and posterior shift, knee flexion, cervical alignment compensation, and muscle fatigue due to increased energy expenditure[106-108].

Case Example

Brief History

A 73-year-old patient presented with progressive low back pain, unresponsive to conservative measures, and bilateral lower-extremity radiculopathy. Magnetic resonance imaging (MRI) scans revealed moderate central and neuroforaminal stenosis bilaterally at the L4-L5 and L5-S1 levels. The preoperative patient-reported outcome measures were an Oswestry Disability Index (ODI) of 40, EuroQol Index Score (estimated health utility) of 0.60, Patient-Reported Outcomes Measurement Information System (PROMIS) Global Mental Health (GMH) of 50.80 and Global Physical Health (GPH) of 37.40, and Moderate to Vigorous Physical Activity (MVPA), determined from the Exercise Vital Sign (EVS), of 90.00.

Preoperative Radiographic Alignment

Obtaining imaging that captures the entire spine and the lower extremities is preferred to assess any compensatory changes that have occurred. Lumbar and full-body lateral free-standing radiographs revealed L4-L5 and L5-S1 grade-2 spondylolisthesis, dynamic in nature when compared between flexion and extension radiographs. In addition, compensatory L3-L4 lordosis and L2-L3 hyperlordosis were noted. The patient had an L1-L4 lordosis of 38.1° and an L4-S1 lordosis of 18.3°, indicating a maldistribution of lordosis (Fig. 5). The PT was 28°, indicating compensatory pelvic retroversion.

Surgical Planning

Preoperatively

To obtain 20° of lordosis at L5-S1, an ALIF device with 18° of lordosis was provisionally planned, pending confirmation of a preserved shape rather than plastic deformation of the L5 body intraoperatively (the preoperative L5 body lordosis was approximately 10°, but it was mostly driven by the concavity of the inferior end plate). A 12° ALIF device was planned at L4-L5 to obtain the segmental goal of 15°, pending intraoperative assessment of end-plate contact, as L4 vertebral body lordosis was only 7°. Finally, the baseline height difference between the L4-L5 and L5-S1 foramina was expected to factor into the heights of the cages (a 14-mm cage at L5-S1 compared with a 12-mm cage at

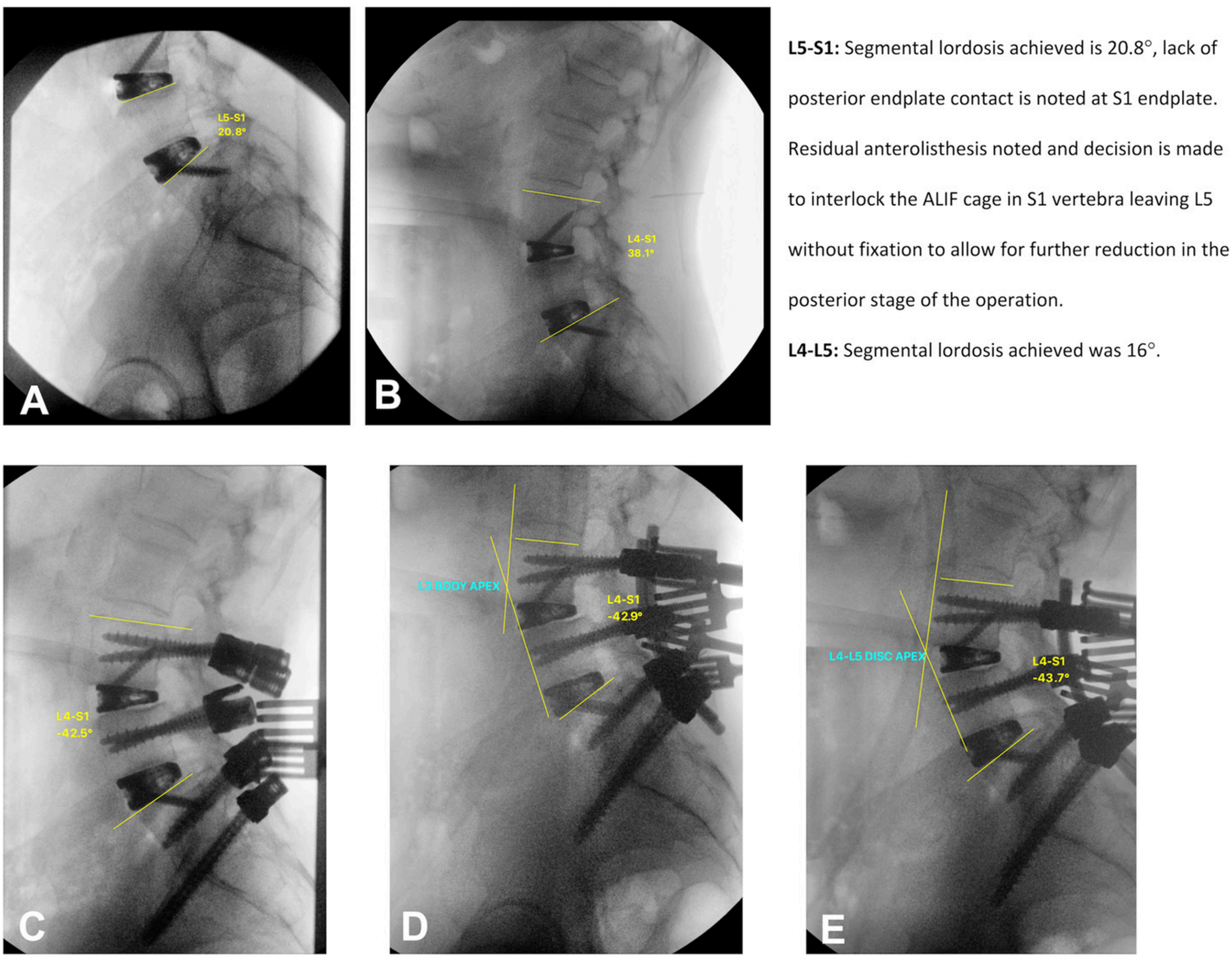


Fig. 6

Intraoperative fluoroscopy during the anterior stage (**Figs. 6-A and 6-B**) and the posterior stage (**Figs. 6-C, 6-D, and 6-E**) of the surgical procedure.

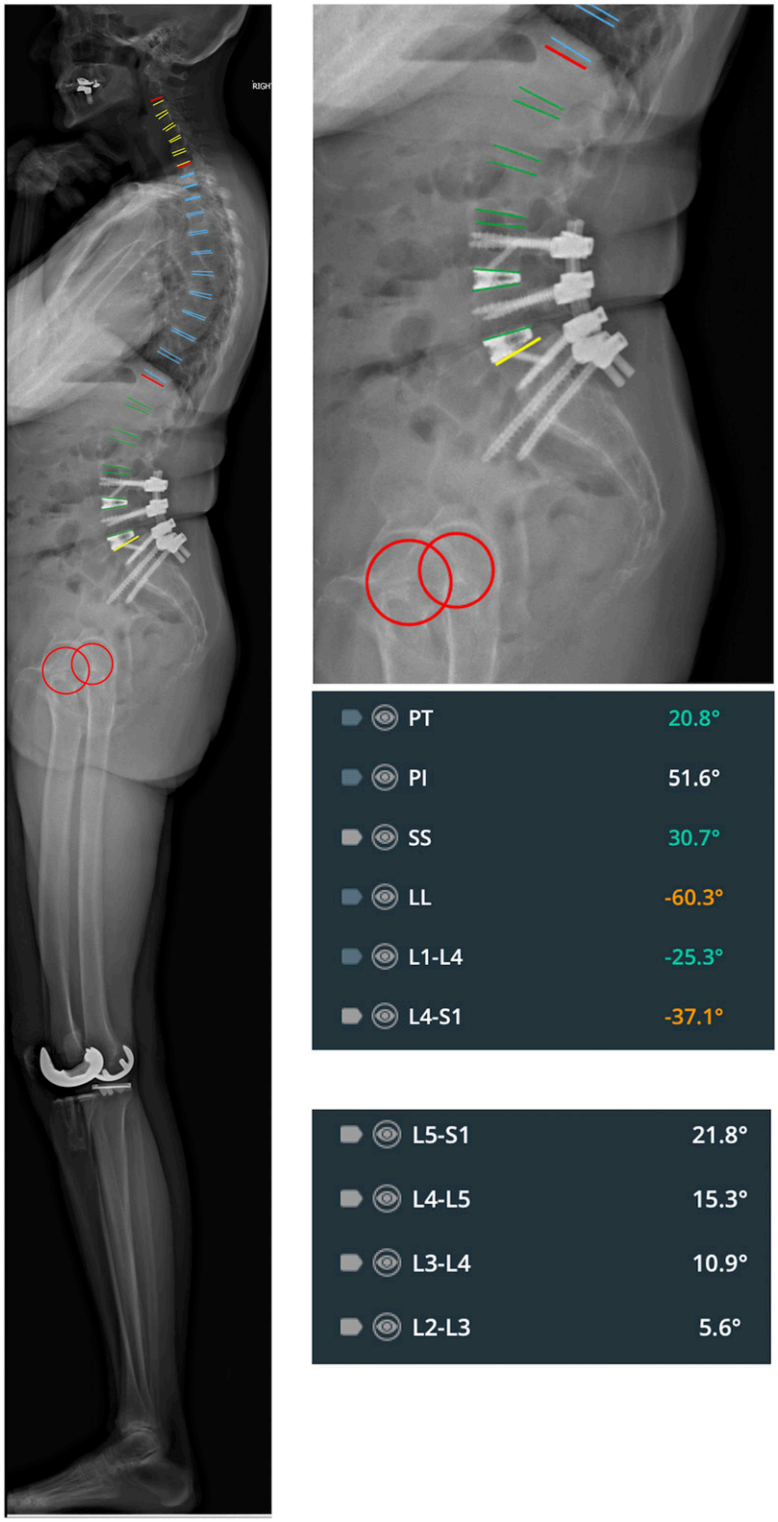


Fig. 7

Postoperative sagittal alignment, with spinopelvic parameters.

L4-L5). We perform intraoperative measurements to ensure the achievement of segmental lordosis targets. Interbody device plans can be modified according to end-plate contact, reduction of spondylolisthesis, the impact on segmental lordosis, and lordosis gained from the cage. The decision was made to perform posterior instrumentation and fusion from L4 to the pelvis, and the plan was simulated via dedicated software; 5.5-mm titanium rods that could be prebent were requested.

Intraoperatively

During the anterior stage of the operation, the anterior edge of the inferior end plate of the L5 body had plastically deformed, necessitating an 18° L5-S1 ALIF cage, whereas the L4-L5 plan remained a 12° cage. During the second stage, and in a prone position, intraoperative fluoroscopy revealed that 39° of L4-S1 lordosis was achieved, which was the ideal target based on the PI that the patient had. Following instrumentation, L4-S1 increased to 42°, which remained within an acceptable range of the target. To achieve better end-plate contact of the ALIF cages, the decision was made to compress the screws posteriorly by the final tightening of the L4 pedicle screws and the compression of the L5 and S1 screws (our preferred method of compression), which migrated the apex from the L4 body to the L4-L5 disc. Subsequently, S2-alar-iliac fixation was performed because of the magnitude of spondylolisthesis and lordosis correction (Fig. 6).

Postoperatively

Full-body standing EOS radiographs (EOS Imaging) revealed restoration of caudal and cephalad lordosis and relaxation of adjacent segment compensation at L2-L3 and L3-L4. Imaging also revealed relaxation of the PT. At the 1-year follow-up (Fig. 7), the patient was satisfied with the surgical procedure, and the postoperative patient-reported outcome measures were an ODI of 3, a EuroQol Index Score of 0.81, a GMH of 62.50, a GPH of 50.80, and an MVPA of 210.00.

Future Directions

Sagittal alignment in degenerative spine disease will probably be the focus of numerous future studies. Future research could explore the impact of PI-adjusted relative spinopelvic measurements on outcomes following short-segment lumbar fusion, given their demonstrated benefits in adult spinal deformity correction[109-111]. Specifically, and more tailored to patients with spinal degeneration, there remains the need to investigate the impact of segmental lordosis surgical targets on patient-reported outcomes and rates of long-term complications and revision surgery. Restoring the shape of the lumbar spine requires carefully planning each lumbar fusion operation and tailoring interbody selection, rod contouring, and segmental correction to the patient's need, primarily driven by the morphology of the pelvis.

Summary

Sagittal alignment of the degenerative lumbar spine is important for spinal surgeons to measure and assess prior to the surgical procedure. A detailed examination of segmental (level-specific) lordosis is likely more important in degenerative conditions than in spinal deformity, due to the performance of short fusions for degenerative conditions rather than long-segment deformity fusion crossing the spinal junctions. Importantly, sagittal realignment, in itself, is not an indication for longer fusions. Our preferred approach is foundational and focuses on proper LL distribution in the indicated levels, which may include maintenance, restoration, or even reduction of lordosis. The subtle deterioration of the sagittal profile in revision surgery is often overlooked. Chasing adjacent segment failure without analyzing the sagittal plane can lead to avoidable revisions. Thus, optimizing caudal lordosis, avoiding fusing cephalad segments with too much lordosis, and ensuring a proper thoracolumbar inflection point are integral concepts in realignment of the degenerative lumbar spine. ■

Bassel G. Diebo, MD[1]
Mariah Balmaceno-Criss, BS[1]
Renaud Lafage, MS[2]
Christopher L. McDonald, MD[1]
Daniel Alsoof, MBBS[1]
Sereen Halayqeh, MD[1]
Kevin J. DiSilvestro, MD[1]
Eren O. Kuris, MD[1]
Virginie Lafage, PhD[2]
Alan H. Daniels, MD[1]

[1]Department of Orthopaedic Surgery, Warren Alpert Medical School, Brown University, Providence, Rhode Island

[2]Department of Orthopaedic Surgery, Lenox Hill Hospital, Northwell Health, New York, NY

Email for corresponding author: Alan_daniels@brown.edu

References

1. Hasegawa K, Dubousset JF. Cone of economy with the chain of balance-historical perspective and proof of concept. Spine Surg Relat Res. 2022 Apr 20; 6(4):337-49.

2. Iyer S, Sheha E, Fu MC, Varghese J, Cunningham ME, Albert TJ, Schwab FJ, Lafage VC, Kim HJ. Sagittal spinal alignment in adult spinal deformity: an overview of current concepts and a critical analysis review. JBJS Rev. 2018 May;6(5):e2.

3. Cowan JA Jr, Dimick JB, Wainess R, Upchurch GR Jr, Chandler WF, La Marca F. Changes in the utilization of spinal fusion in the United States. Neurosurgery. 2006 Jul;59(1):15-20, discussion: 15-20.

4. Deyo RA, Mirza SK. Trends and variations in the use of spine surgery. Clin Orthop Relat Res. 2006 Feb;443(443):139-46.

5. O'Lynnger TM, Zuckerman SL, Morone PJ, Dewan MC, Vasquez-Castellanos RA, Cheng JS. Trends for spine surgery for the elderly: implications for access to healthcare in North America. Neurosurgery. 2015 Oct;77(Suppl 4):S136-41.

6. Mehta VA, Amin A, Omeis I, Gokaslan ZL, Gottfried ON. Implications of spinopelvic alignment for the spine surgeon. Neurosurgery. 2015 Mar;76(Suppl 1): S42-56, discussion S56.

7. Pratali RR, Battisti R, Oliveira CEAS, Maranho DAC, Herrero CFPS. Correlation between the severity of the lumbar degenerative disease and sagittal spinopelvic alignment. Rev Bras Ortop (Sao Paulo). 2022 Feb 18;57(1):41-6.

8. Zárate-Kalfópulos B, Reyes-Tarrago F, Navarro-Aceves LA, García-Ramos CL, Reyes-Sánchez AA, Alpízar-Aguirre A, Rosales-Olivarez LM. Characteristics of spinopelvic sagittal alignment in lumbar degenerative disease. World Neurosurg. 2019 Jun; 126:e417-21.

9. Lv X, Liu Y, Zhou S, Wang Q, Gu H, Fu X, Ding Y, Zhang B, Dai M. Correlations between the feature of sagittal spinopelvic alignment and facet joint degeneration: a retrospective study. BMC Musculoskelet Disord. 2016 Aug 15;17(1): 341.

10. Barrey C, Jund J, Noseda O, Roussouly P. Sagittal balance of the pelvis-spine complex and lumbar degenerative diseases. A comparative study about 85 cases. Eur Spine J. 2007 Sep;16(9):1459-67.

11. Lai Q, Gao T, Lv X, Liu X, Wan Z, Dai M, Zhang B, Nie T. Correlation between the sagittal spinopelvic alignment and degenerative lumbar spondylolisthesis: a retrospective study. BMC Musculoskelet Disord. 2018 May 16;19(1):151.

12. Lim JK, Kim SM. Comparison of sagittal spinopelvic alignment between lumbar degenerative spondylolisthesis and degenerative spinal stenosis. J Korean Neurosurg Soc. 2014 Jun;55(6):331-6.

13. Funao H, Tsuji T, Hosogane N, Watanabe K, Ishii K, Nakamura M, Chiba K, Toyama Y, Matsumoto M. Comparative study of spinopelvic sagittal alignment between patients with and without degenerative spondylolisthesis. Eur Spine J. 2012 Nov;21(11):2181-7.

14. Ferrero E, Ould-Slimane M, Gille O, Guigui P; French Spine Society (SFCR). Sagittal spinopelvic alignment in 654 degenerative spondylolisthesis. Eur Spine J. 2015 Jun;24(6):1219-27.

15. Lim JK, Kim SM. Difference of sagittal spinopelvic alignments between degenerative spondylolisthesis and isthmic spondylolisthesis. J Korean Neurosurg Soc. 2013 Feb;53(2):96-101.

16. Schuller S, Charles YP, Steib JP. Sagittal spinopelvic alignment and body mass index in patients with degenerative spondylolisthesis. Eur Spine J. 2011 May;20(5):713-9.

17. Barrey C, Jund J, Perrin G, Roussouly P. Spinopelvic alignment of patients with degenerative spondylolisthesis. Neurosurgery. 2007 Nov;61(5):981-6.

18. Aono K, Kobayashi T, Jimbo S, Atsuta Y, Matsuno T. Radiographic analysis of newly developed degenerative spondylolisthesis in a mean twelve-year prospective study. Spine (Phila Pa 1976). 2010 Apr 15;35(8):887-91.

19. Kobayashi H, Endo K, Sawaji Y, Matsuoka Y, Nishimura H, Murata K, Takamatsu T, Suzuki H, Aihara T, Yamamoto K. Global sagittal spinal alignment in patients with degenerative low-grade lumbar spondylolisthesis. J Orthop Surg (Hong Kong). 2019 Sep-Dec;27(3):2309499019885190.

20. Ferrero E, Simon AL, Magrino B, Ould-Slimane M, Guigui P. Double-level degenerative spondylolisthesis: what is different in the sagittal plane? Eur Spine J. 2016 Aug;25(8):2546-52.

21. Buckland AJ, Ramchandran S, Day L, Bess S, Protopsaltis T, Passias PG, Diebo BG, Lafage R, Lafage V, Sure A, Errico TJ. Radiological lumbar stenosis severity predicts worsening sagittal malalignment on full-body standing stereoradiographs. Spine J. 2017 Nov;17(11):1601-10.

22. Buckland AJ, Vira S, Oren JH, Lafage R, Harris BY, Spiegel MA, Diebo BG, Liabaud B, Protopsaltis TS, Schwab FJ, Lafage V, Errico TJ, Bendo JA. When is compensation for lumbar spinal stenosis a clinical sagittal plane deformity? Spine J. 2016 Aug;16(8):971-81.

23. Ham CH, Park YK, Kim JH, Kwon WK, Kim DW, Moon HJ. Characteristics of sagittal spinopelvic alignment changes after symptom relief after simple lumbar decompression. Neurosurgery. 2022 Aug 1;91(2):331-8.

24. Bari TJ, Heegaard M, Bech-Azeddine R, Dahl B, Gehrchen M. Lordosis Distribution Index in short-segment lumbar spine fusion - can ideal lordosis reduce revision surgery and iatrogenic deformity? Neurospine. 2021 Sep;18(3):543-53.

25. Roussouly P, Gollogly S, Berthonnaud E, Dimnet J. Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. Spine (Phila Pa 1976). 2005 Feb 1;30(3):346-53.

26. Gracovetsky SA, Iacono S. Energy transfers in the spinal engine. J Biomed Eng. 1987 Apr;9(2):99-114.

27. Vaz G, Roussouly P, Berthonnaud E, Dimnet J. Sagittal morphology and equilibrium of pelvis and spine. Eur Spine J. 2002 Feb;11(1):80-7.

28. Been E, Barash A, Marom A, Kramer PA. Vertebral bodies or discs: which contributes more to human-like lumbar lordosis? Clin Orthop Relat Res. 2010 Jul;468(7):1822-9.

29. Legaye J, Duval-Beaupère G, Hecquet J, Marty C. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. Eur Spine J. 1998;7(2):99-103.

30. Odland K, Yson S, Polly DW Jr. Wide anatomical variability of PI normative values within an asymptomatic population: a systematic review. Spine Deform. 2023 May;11(3):559-66.

31. Mac-Thiong JM, Berthonnaud E, Dimar JR 2nd, Betz RR, Labelle H. Sagittal alignment of the spine and pelvis during growth. Spine (Phila Pa 1976). 2004 Aug 1;29(15):1642-7.

32. Abelin-Genevois K, Idjerouidene A, Roussouly P, Vital JM, Garin C. Cervical spine alignment in the pediatric population: a radiographic normative study of 150 asymptomatic patients. Eur Spine J. 2014 Jul;23(7):1442-8.

33. Hou C, Chen K, Chen Y, Zhou T, Yang M, Li M. Assessment of sagittal spinopelvic alignment in asymptomatic Chinese juveniles and adolescents: a large cohort study and comparative meta-analysis. J Orthop Surg Res. 2021 Nov 2;16(1):656.

34. Pesenti S, Lafage R, Stein D, Elysee JC, Lenke LG, Schwab FJ, Kim HJ, Lafage V. The amount of proximal lumbar lordosis is related to pelvic incidence. Clin Orthop Relat Res. 2018 Aug;476(8):1603-11.

35. Charles YP, Bauduin E, Pesenti S, Ilharreborde B, Prost S, Laouissat F, Riouallon G, Wolff S, Challier V, Obeid I, Boissière L, Ferrero E, Solla F, Le Huec JC, Bourret S, Faddoul J, Abi Lahoud GN, Fière V, Vande Kerckhove M, Campana M, Lebhar J, Giorgi H, Faure A, Sauleau EA, Blondel B; French Spine Surgery Society (SFCR). Variation of global sagittal alignment parameters according to gender, pelvic incidence, and age. Clin Spine Surg. 2022 Aug 1;35(7):E610-20.

36. Anwar HA, Butler JS, Yarashi T, Rajakulendran K, Molloy S. Segmental pelvic correlation (SPeC): a novel approach to understanding sagittal plane spinal alignment. Spine J. 2015 Dec 1;15(12):2518-23.

37. Mendoza-Lattes S, Ries Z, Gao Y, Weinstein SL. Natural history of spinopelvic alignment differs from symptomatic deformity of the spine. Spine (Phila Pa 1976). 2010 Jul 15;35(16):E792-8.

38. Berthonnaud E, Labelle H, Roussouly P, Grimard G, Vaz G, Dimnet J. A variability study of computerized sagittal spinopelvic radiologic measurements of trunk balance. J Spinal Disord Tech. 2005 Feb;18(1):66-71.

39. Sebaaly A, Silvestre C, Rizkallah M, Grobost P, Chevillotte T, Kharrat K, Roussouly P. Revisiting thoracic kyphosis: a normative description of the thoracic sagittal curve in an asymptomatic population. Eur Spine J. 2021 May;30(5):1184-9.

40. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V. Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine (Phila Pa 1976). 2010 Dec 1;35(25):2224-31.

41. Schwab F, Lafage V, Patel A, Farcy JP. Sagittal plane considerations and the pelvis in the adult patient. Spine (Phila Pa 1976). 2009 Aug 1;34(17):1828-33.

42. Lafage V, Schwab F, Patel A, Hawkinson N, Farcy JP. Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine (Phila Pa 1976). 2009 Aug 1;34(17):E599-606.

43. Ames CP, Smith JS, Scheer JK, Bess S, Bederman SS, Deviren V, Lafage V, Schwab F, Shaffrey CI. Impact of spinopelvic alignment on decision making in deformity surgery in adults: a review. J Neurosurg Spine. 2012 Jun;16(6):547-64.

44. Youn YH, Cho KJ, Na Y, Kim JS. Global sagittal alignment and clinical outcomes after 1-3 short-segment lumbar fusion in degenerative spinal diseases. Asian Spine J. 2022 Aug;16(4):551-9.

45. Eun IS, Son SM, Goh TS, Lee JS. Sagittal spinopelvic alignment after spinal fusion in degenerative lumbar scoliosis: a meta-analysis. Br J Neurosurg. 2020 Apr;34(2):176-80.

46. Kakadiya DG, Gohil DK, Soni DY, Shakya DA. Clinical, radiological and functional results of transforaminal lumbar interbody fusion in degenerative spondylolisthesis. N Am Spine Soc J. 2020 Jun 13;2:100011.

47. Vazifehdan F, Karantzoulis VG, Igoumenou VG. Sagittal alignment assessment after short-segment lumbar fusion for degenerative disc disease. Int Orthop. 2019 Apr;43(4):891-8.

48. Oikonomidis S, Meyer C, Scheyerer MJ, Grevenstein D, Eysel P, Bredow J. Lumbar spinal fusion of low-grade degenerative spondylolisthesis (Meyerding grade I and II): Do reduction and correction of the radiological sagittal parameters correlate with better clinical outcome? Arch Orthop Trauma Surg. 2020 Sep;140(9):1155-62.

49. Bai H, Li Y, Liu C, Zhao Y, Zhao X, Lei W, Feng Y, Wu Z. Surgical management of degenerative lumbar scoliosis associated with spinal stenosis: does the PI-LL matter? Spine (Phila Pa 1976). 2020 Aug 1;45(15):1047-54.

50. Kong LD, Zhang YZ, Wang F, Kong FL, Ding WY, Shen Y. Radiographic restoration of sagittal spinopelvic alignment after posterior lumbar interbody fusion in degenerative spondylolisthesis. Clin Spine Surg. 2016 Mar;29(2):E87-92.

51. Phan K, Nazareth A, Hussain AK, Dmytriw AA, Nambiar M, Nguyen D, Kerferd J, Phan S, Sutterlin C 3rd, Cho SK, Mobbs RJ. Relationship between sagittal balance and adjacent segment disease in surgical treatment of degenerative lumbar spine disease: meta-analysis and implications for choice of fusion technique. Eur Spine J. 2018 Aug;27(8):1981-91.

52. Berjano P, Langella F, Ismael MF, Damilano M, Scopetta S, Lamartina C. Successful correction of sagittal imbalance can be calculated on the basis of pelvic incidence and age. Eur Spine J. 2014 Oct;23(Suppl 6):587-96.

53. Kalidindi KKV, Sangondimath G, Bansal K, Vishwakarma G, Chhabra HS. Introduction of a novel "segmentation line" to analyze the variations in segmental lordosis, location of the lumbar apex, and their correlation with spinopelvic parameters in asymptomatic adults. Asian Spine J. 2022 Aug;16(4):502-9.

54. Wang M, Xu L, Chen X, Zhou Q, Du C, Yang B, Zhu Z, Wang B, Qiu Y, Sun X. Optimal reconstruction of sagittal alignment according to global alignment and proportion score can reduce adjacent segment degeneration after lumbar fusion. Spine (Phila Pa 1976). 2021 Feb 15;46(4):E257-66.

55. Herrington BJ, Fernandes RR, Urquhart JC, Rasoulinejad P, Siddiqi F, Bailey CS. L3-L4 hyperlordosis and decreased lower lumbar lordosis following short-segment L4-L5 lumbar fusion surgery is associated with L3-L4 revision surgery for adjacent segment stenosis. Global Spine J. 2023 Jul 24:21925682231191414.

56. Zheng G, Wang C, Wang T, Hu W, Ji Q, Hu F, Li J, Chaudhary SK, Song K, Song D, Zhang Z, Hao Y, Wang Y, Li J, Zheng Q, Zhang X, Wang Y. Relationship between postoperative lordosis distribution index and adjacent segment disease following L4-S1 posterior lumbar interbody fusion. J Orthop Surg Res. 2020 Apr 3;15(1):129.

57. Prost S, Blondel B, Bauduin E, Pesenti S, Ilharreborde B, Laouissat F, Riouallon G, Wolff S, Challier V, Obeid I, Boissière L, Ferrero E, Solla F, Le Huec JC, Bourret S, Faddoul J, Abi Lahoud GN, Fière V, Vande Kerckhove M, Campana M, Lebhar J, Giorgi H, Faure A, Sauleau EA, Charles YP; French Spine Surgery Society (SFCR). Do age-related variations of sagittal alignment rely on spinopelvic organization? An observational study of 1540 subjects. Global Spine J. 2023 Oct;13(8):2144-54.

58. Lafage R, Obeid I, Liabaud B, Bess S, Burton D, Smith JS, Jalai C, Hostin R, Shaffrey CI, Ames C, Kim HJ, Klineberg E, Schwab F, Lafage V; International Spine Study Group. Location of correction within the lumbar spine impacts acute adjacent-segment kyphosis. J Neurosurg Spine. 2018 Oct 26;30(1):69-77.

59. Hanson DS, Bridwell KH, Rhee JM, Lenke LG. Correlation of pelvic incidence with low- and high-grade isthmic spondylolisthesis. Spine (Phila Pa 1976). 2002 Sep 15;27(18):2026-9.

60. Protopsaltis TS, Soroceanu A, Tishelman JC, Buckland AJ, Mundis GM Jr, Smith JS, Daniels A, Lenke LG, Kim HJ, Klineberg EO, Ames CP, Hart RA, Bess S, Shaffrey CI, Schwab FJ, Lafage V; International Spine Study Group (ISSG). Should sagittal spinal alignment targets for adult spinal deformity correction depend on pelvic incidence and age? Spine (Phila Pa 1976). 2020 Feb 15;45(4):250-7.

61. Aoki Y, Kubota G, Inoue M, Takahashi H, Watanabe A, Nakajima T, Sato Y, Nakajima A, Saito J, Eguchi Y, Orita S, Fukuchi H, Sakai T, Ochi S, Yanagawa N, Nakagawa K, Ohtori S. Age-specific characteristics of lumbopelvic alignment in patients with spondylolysis: how bilateral L5 spondylolysis influences lumbopelvic alignment during the aging process. World Neurosurg. 2021 Mar;147:e524-32.

62. Asai Y, Tsutsui S, Oka H, Yoshimura N, Hashizume H, Yamada H, Akune T, Muraki S, Matsudaira K, Kawaguchi H, Nakamura K, Tanaka S, Yoshida M. Sagittal spino-pelvic alignment in adults: the Wakayama Spine Study. PLoS One. 2017 Jun 6; 12(6):e0178697.

63. Zhou Z, Hou C, Li D, Si J. The pelvic radius technique in the assessment of spinopelvic sagittal alignment of degenerative spondylolisthesis and lumbar spinal stenosis. J Orthop Sci. 2018 Nov;23(6):902-7.

64. Chuang CY, Liaw MY, Wang LY, Huang YC, Pong YP, Chen CW, Wu RW, Lau YC. Spino-pelvic alignment, balance, and functional disability in patients with low-grade degenerative lumbar spondylolisthesis. J Rehabil Med. 2018 Nov 7;50(10):898-907.

65. Wang Q, Sun CT. Characteristics and correlation analysis of spino-pelvic sagittal parameters in elderly patients with lumbar degenerative disease. J Orthop Surg Res. 2019 May 9;14(1):127.

66. Yang X, Kong Q, Song Y, Liu L, Zeng J, Xing R. The characteristics of spinopelvic sagittal alignment in patients with lumbar disc degenerative diseases. Eur Spine J. 2014 Mar;23(3):569-75.

67. Ogon I, Takashima H, Morita T, Oshigiri T, Terashima Y, Yoshimoto M, Takebayashi T, Yamashita T. Association between spinopelvic alignment and lumbar intervertebral disc degeneration quantified with magnetic resonance imaging T2 mapping in patients with chronic low back pain. Spine Surg Relat Res. 2019 Nov 1; 4(2):135-41.

68. Leveque JA, Segebarth B, Schroerlucke SR, Khanna N, Pollina J Jr, Youssef JA, Tohmeh AG, Uribe JS. A multicenter radiographic evaluation of the rates of preoperative and postoperative malalignment in degenerative spinal fusions. Spine (Phila Pa 1976). 2018 Jul 1;43(13):E782-9.

69. Wiggins GC, Ondra SL, Shaffrey CI. Management of iatrogenic flat-back syndrome. Neurosurg Focus. 2003 Sep 15;15(3):E8.

70. Boody BS, Rosenthal BD, Jenkins TJ, Patel AA, Savage JW, Hsu WK. Iatrogenic flatback and flatback syndrome: evaluation, management, and prevention. Clin Spine Surg. 2017 May;30(4):142-9.

71. Potter BK, Lenke LG, Kuklo TR. Prevention and management of iatrogenic flatback deformity. J Bone Joint Surg Am. 2004 Aug;86(8):1793-808.

72. Gottfried ON, Daubs MD, Patel AA, Dailey AT, Brodke DS. Spinopelvic parameters in postfusion flatback deformity patients. Spine J. 2009 Aug;9(8):639-47.

73. Nakashima H, Kanemura T, Satake K, Ishikawa Y, Ouchida J, Segi N, Yamaguchi H, Imagama S. Changes in sagittal alignment following short-level lumbar interbody fusion: comparison between posterior and lateral lumbar interbody fusions. Asian Spine J. 2019 Dec 31;13(6):904-12.

74. Nakashima H, Kanemura T, Satake K, Ishikawa Y, Ouchida J, Segi N, Yamaguchi H, Imagama S. Comparative radiographic outcomes of lateral and posterior lumbar interbody fusion in the treatment of degenerative lumbar kyphosis. Asian Spine J. 2019 Jun;13(3):395-402.

75. Baghdadi YMK, Larson AN, Dekutoski MB, Cui Q, Sebastian AS, Armitage BM, Nassr A. Sagittal balance and spinopelvic parameters after lateral lumbar interbody fusion for degenerative scoliosis: a case-control study. Spine (Phila Pa 1976). 2014 Feb 1;39(3):E166-73.

76. Leveque JA, Drolet CE, Nemani V, Krause KL, Shen J, Rathore A, Baig Y, Louie PK. The impact of surgical approach on sagittal plane alignment in patients undergoing one- or two- level fusions for degenerative pathology: a multicenter radiographic evaluation 6 months following surgery. World Neurosurg. 2022 Aug;164:e311-7.

77. Saadeh YS, Joseph JR Jr, Smith BW, Kirsch MJ, Sabbagh AM, Park P. Comparison of segmental lordosis and global spinopelvic alignment after single-level lateral lumbar interbody fusion or transforaminal lumbar interbody fusion. World Neurosurg. 2019 Jun;126:e1374-8.

78. Wu J, Ge T, Zhang N, Li J, Tian W, Sun Y. Posterior fixation can further improve the segmental alignment of lumbar degenerative spondylolisthesis with oblique lumbar interbody fusion. BMC Musculoskelet Disord. 2021 Feb 23;22(1):218.

79. Ahlquist S, Thommen R, Park HY, Sheppard W, James K, Lord E, Shamie AN, Park DY. Implications of sagittal alignment and complication profile with stand-alone anterior lumbar interbody fusion versus anterior posterior lumbar fusion. J Spine Surg. 2020 Dec;6(4):659-69.

80. Pan W, Zhao JL, Xu J, Zhang M, Fang T, Yan J, Wang XH, Zhou Q. Lumbar alignment and patient-reported outcomes after single-level transforaminal lumbar interbody fusion for degenerative lumbar spondylolisthesis with and without local coronal imbalance. J Neurosurg Spine. 2020 Dec 4;34(3):464-70.

81. Zhu C, Qiu X, Zhuang M, Cheng D, Liu Z. Surgical outcomes of single-level transforaminal lumbar interbody fusion for degenerative spondylolisthesis with and without kyphotic alignment. World Neurosurg. 2018 Sep;117:e396-402.

82. Toop N, Viljoen S, Baum J, Hatef J, Maggio D, Oosten J, Deistler K, Gilkey T, Close L, Farhadi HF, Grossbach AJ. Radiographic and clinical outcomes in one- and two-level transforaminal lumbar interbody fusions: a comparison of bullet versus banana cages. J Neurosurg Spine. 2021 Dec 17;36(6):918-27.

83. Miyazaki M, Ishihara T, Abe T, Kanezaki S, Notani N, Kataoka M, Tsumura H. Effect of intraoperative position in single-level transforaminal lumbar interbody fusion at the L4/5 level on segmental and overall lumbar lordosis in patients with lumbar degenerative disease. Medicine (Baltimore). 2019 Sep;98(39):e17316.

84. Sabou S, Tseng THJ, Stephenson J, Siddique I, Verma R, Mohammad S. Correction of sagittal plane deformity and predictive factors for a favourable radiological outcome following multilevel posterior lumbar interbody fusion for mild degenerative scoliosis. Eur Spine J. 2016 Aug;25(8):2520-6.

85. Alahmari A, Thornley P, Glennie A, Urquhart JC, Al-Jahdali F, Rampersaud R, Fisher C, Siddiqi F, Rasoulinejad P, Bailey CS. Preoperative disc angle is an important predictor of segmental lordosis after degenerative spondylolisthesis fusion. Global Spine J. 2022 Aug 10:21925682221118845.

86. Chang CC, Chou D, Pennicooke B, Rivera J, Tan LA, Berven S, Mummaneni PV. Long-term radiographic outcomes of expandable versus static cages in transforaminal lumbar interbody fusion. J Neurosurg Spine. 2020 Nov 13;34(3):471-80.

87. Shiga Y, Orita S, Inage K, Sato J, Fujimoto K, Kanamoto H, Abe K, Kubota G, Yamauchi K, Eguchi Y, Inoue M, Kinoshita H, Aoki Y, Nakamura J, Matsuura Y, Hynes R, Furuya T, Koda M, Takahashi K, Ohtori S. Evaluation of the location of intervertebral cages during oblique lateral interbody fusion surgery to achieve sagittal correction. Spine Surg Relat Res. 2017 Nov 27;1(4):197-202.

88. Kumar MN, Baklanov A, Chopin D. Correlation between sagittal plane changes and adjacent segment degeneration following lumbar spine fusion. Eur Spine J. 2001 Aug;10(4):314-9.

89. Kiss L, Szoverfi Z, Bereczki F, Eltes PE, Szollosi B, Szita J, Hoffer Z, Lazary A. Impact of patient-specific factors and spinopelvic alignment on the development of adjacent segment degeneration after short-segment lumbar fusion. Clin Spine Surg. 2023 Aug 1;36(7):E306-10.

90. Kim KH, Lee SH, Shim CS, Lee DY, Park HS, Pan WJ, Lee HY. Adjacent segment disease after interbody fusion and pedicle screw fixations for isolated L4-L5 spondylolisthesis: a minimum five-year follow-up. Spine (Phila Pa 1976). 2010 Mar 15; 35(6):625-34.

91. Rothenfluh DA, Mueller DA, Rothenfluh E, Min K. Pelvic incidence-lumbar lordosis mismatch predisposes to adjacent segment disease after lumbar spinal fusion. Eur Spine J. 2015 Jun;24(6):1251-8.

92. Tempel ZJ, Gandhoke GS, Bolinger BD, Khattar NK, Parry PV, Chang YF, Okonkwo DO, Kanter AS. The influence of pelvic incidence and lumbar lordosis mismatch on development of symptomatic adjacent level disease following single-level transforaminal lumbar interbody fusion. Neurosurgery. 2017 Jun 1;80(6): 880-6.

93. Matsumoto T, Okuda S, Maeno T, Yamashita T, Yamasaki R, Sugiura T, Iwasaki M. Spinopelvic sagittal imbalance as a risk factor for adjacent-segment disease after single-segment posterior lumbar interbody fusion. J Neurosurg Spine. 2017 Apr; 26(4):435-40.

94. Toivonen LA, Mäntymäki H, Häkkinen A, Kautiainen H, Neva MH. Postoperative sagittal balance has only a limited role in the development of adjacent segment disease after lumbar spine fusion for degenerative lumbar spine disorders: a subanalysis of the 10-year follow-up study. Spine (Phila Pa 1976). 2022 Oct 1;47(19): 1357-61.

95. Hsieh MK, Kao FC, Chen WJ, Chen IJ, Wang SF. The influence of spinopelvic parameters on adjacent-segment degeneration after short spinal fusion for degenerative spondylolisthesis. J Neurosurg Spine. 2018 Oct;29(4):407-13.

96. Kaito T, Hosono N, Mukai Y, Makino T, Fuji T, Yonenobu K. Induction of early degeneration of the adjacent segment after posterior lumbar interbody fusion by excessive distraction of lumbar disc space. J Neurosurg Spine. 2010 Jun;12(6):671-9.

97. Lee CS, Hwang CJ, Lee SW, Ahn YJ, Kim YT, Lee DH, Lee MY. Risk factors for adjacent segment disease after lumbar fusion. Eur Spine J. 2009 Nov;18(11): 1637-43.

98. Yamasaki K, Hoshino M, Omori K, Igarashi H, Nemoto Y, Tsuruta T, Matsumoto K, Iriuchishima T, Ajiro Y, Matsuzaki H. Risk factors of adjacent segment disease

after transforaminal inter-body fusion for degenerative lumbar disease. Spine (Phila Pa 1976). 2017 Jan 15;42(2):E86-92.
99. Ahn DK, Park HS, Choi DJ, Kim KS, Yang SJ. Survival and prognostic analysis of adjacent segments after spinal fusion. Clin Orthop Surg. 2010 Sep;2(3): 140-7.
100. Min JH, Jang JS, Jung BJ, Lee HY, Choi WC, Shim CS, Choi G, Lee SH. The clinical characteristics and risk factors for the adjacent segment degeneration in instrumented lumbar fusion. J Spinal Disord Tech. 2008 Jul;21(5):305-9.
101. Ankrah NK, Eli IM, Magge SN, Whitmore RG, Yew AY. Age, body mass index, and osteoporosis are more predictive than imaging for adjacent-segment reoperation after lumbar fusion. Surg Neurol Int. 2021 Sep 6;12:453.
102. Sears WR, Sergides IG, Kazemi N, Smith M, White GJ, Osburg B. Incidence and prevalence of surgery at segments adjacent to a previous posterior lumbar arthrodesis. Spine J. 2011 Jan;11(1):11-20.
103. Ikuta K, Masuda K, Tominaga F, Sakuragi T, Kai K, Kitamura T, Senba H, Shidahara S. Clinical and radiological study focused on relief of low back pain after decompression surgery in selected patients with lumbar spinal stenosis associated with grade I degenerative spondylolisthesis. Spine (Phila Pa 1976). 2016 Dec 15; 41(24):E1434-43.
104. He S, Zhang Y, Ji W, Liu H, He F, Chen A, Yang H, Pi B. Analysis of spinopelvic sagittal balance and persistent low back pain (PLBP) for degenerative spondylolisthesis (DS) following posterior lumbar interbody fusion (PLIF). Pain Res Manag. 2020 Jan 11;2020:5971937.
105. Li J, Zhang D, Shen Y, Qi X. Lumbar degenerative disease after oblique lateral interbody fusion: sagittal spinopelvic alignment and its impact on low back pain. J Orthop Surg Res. 2020 Aug 14;15(1):326.
106. Barrey C, Roussouly P, Le Huec JC, D'Acunzi G, Perrin G. Compensatory mechanisms contributing to keep the sagittal balance of the spine. Eur Spine J. 2013 Nov;22(Suppl 6)(Suppl 6):S834-41.
107. Pourtaheri S, Sharma A, Savage J, Kalfas I, Mroz TE, Benzel E, Steinmetz MP. Pelvic retroversion: a compensatory mechanism for lumbar stenosis. J Neurosurg Spine. 2017 Aug;27(2):137-44.
108. Takahashi S, Hoshino M, Ohyama S, Hori Y, Yabu A, Kobayashi A, Tsujio T, Kotake S, Nakamura H. Relationship of back muscle and knee extensors with the compensatory mechanism of sagittal alignment in a community-dwelling elderly population. Sci Rep. 2021 Jan 26;11(1):2179.
109. Yucekul A, Ozpinar A, Kilickan FDB, Dalla M, Muthiah N, Zulemyan T, Yavuz Y, Pizones J, Obeid I, Kleinstück F, Pérez-Grueso FJS, Pellisé F, Yilgor C, Alanay A; European Spine Study Group (ESSG). Relationship between pelvic incidence-adjusted relative spinopelvic parameters, global sagittal alignment and lower extremity compensations. Eur Spine J. 2023 Oct;32(10):3599-607.
110. Yilgor C, Yavuz Y, Sogunmez N, Haddad S, Mannion AF, Abul K, Boissiere L, Obeid I, Kleinstück F, Pérez-Grueso FJS, Acaroglu E, Pellise F, Alanay A; European Spine Study Group (ESSG). Relative pelvic version: an individualized pelvic incidence-based proportional parameter that quantifies pelvic version more precisely than pelvic tilt. Spine J. 2018 Oct;18(10):1787-97.
111. Cawley DT, Boissiere L, Yilgor C, Larrieu D, Fujishiro T, Kieser D, Alanay A, Kleinstück F, Pérez-Grueso FS, Pellisé F, Obeid I; European Spine Study Group (ESSG). Relative pelvic version displays persistent compensatory measures with normalised sagittal vertical axis after deformity correction. Spine Deform. 2021 Sep;9(5):1449-56.
112. Wright JG. Revised grades of recommendation for summaries or reviews of orthopaedic surgical studies. J Bone Joint Surg Am. 2006 May;88(5):1161-2.