State of the union: a review of lumbar fusion indications and techniques for degenerative spine disease

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Lumbar fusion is an accepted and effective technique for the treatment of lumbar degenerative disease. The practice has evolved continually since Albee and Hibbs independently reported the first cases in 1913, and advancements in both technique and patient selection continue through the present day. Clinical and radiological indications for surgery have been tested in trials, and other diagnostic modalities have developed and been studied. Fusion practices have also advanced; instrumentation, surgical approaches, biologics, and more recently, operative planning, have undergone stark changes at a seemingly increasing pace over the last decade. As the general population ages, treatment of degenerative lumbar disease will become a more prevalent—and costlier—issue for surgeons as well as the healthcare system overall. This review will cover the evolution of indications and techniques for fusion in degenerative lumbar disease, with emphasis on the evidence for current practices.

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LUMBAR degenerative disease is a common and debilitating ailment, causing pain and disability in patients and burdening our healthcare system and economy with high and ever-increasing costs. The prevalence of low-back pain due to lumbar spondylosis is estimated at 3.6% worldwide, and 4.5% in North America.¹¹⁹ Eighty-three million quality-adjusted life years were lost to disability from low-back pain in 2010.⁵⁸ As the population ages, rates of diagnosis and treatment of lumbar degenerative disease have been increasing, and the burden of lumbar spondylosis—both disability and cost—will rise with it.

Lumbar surgery rates have increased steadily over time.⁹⁰ A clear benefit of lumbar fusion surgery has been demonstrated in many patients as evidenced by lowered pain and disability scores and the ability to return to work. However, fusion procedures have not been effective for all patients, and as rates of both disease and treatments have risen, the number of patients undergoing unsuccessful fusion operations has increased as well.^{55,162}

Indications for lumbar fusion continue to evolve, in part due to new techniques, technologies, and recent findings in

outcomes research. Justification for spinal stabilization has changed as our understanding of lumbar instability and spinal alignment has grown, and outcomes research has more precisely defined those patients who do well with, or without, fusion procedures. Less invasive techniques for fusion procedures have also lowered the threshold for fusion operations in less healthy patients, providing more options for patients who otherwise would be considered too frail for surgery.

New techniques have also developed rapidly, incorporating not only advances in technology but also outcomes research, further refining what we know about the practice of lumbar stabilization. Advances in fixation techniques, approach, biologics, and operative planning have been steady, and will continue to affect the way we treat our patients.

This paper will review and update modern indications and techniques in lumbar fusion for degenerative disease, including the best evidence to support current practices. It will include clinical and radiological indications for fusion, as well as diagnostic modalities for delineating instability and patients with the highest likelihood for signifi-

ABBREVIATIONS ALIF = anterior lumbar interbody fusion; ALL = anterior longitudinal ligament; CFRP = carbon fiber reinforced PEEK; cPS = cortical pedicle screw; LLIF = lateral lumbar interbody fusion; ODI = Oswestry Disability Index; PEEK = polyetheretherketone; PLIF = posterior lumbar interbody fusion; PS = pedicle screw; SPORT = Spine Patient Outcomes Research Trial; TFS = transfacet screw; TL = translaminar; TLIF = transforaminal lumbar interbody fusion.

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cant improvement following surgery. We will also review modern fixation, including interbody implants, and recent advances in operative planning and navigation.

Indications for Fusion

Clinical

The hallmark symptom of lumbar degenerative disease is low-back pain. Back pain is extremely common, and unfortunately, it is a nonspecific complaint when trying to determine which patients will benefit most from surgery. Historically, moderate back pain has an annual incidence rate of approximately 15%, with 20% of those patients reporting that the pain is severe enough to prevent them from working.⁹ A careful patient history and physical examination, while rarely definitive, are nonetheless key in determining which patients are most likely to improve with fusion.

Aside from offering guidance in diagnosing degenerative disease—importantly, ruling out more malignant conditions such as infection or neoplasm—a careful history and physical examination will often offer clues as to which patients with spondylosis may benefit from stabilization. The hallmark of mechanical back pain, due to degeneration of the lumbar disc–joint complex, has classically been deep, agonizing pain, exacerbated by loading and relieved by unloading, but other elements of the history and physical are pertinent and have demonstrated some predictive validity for successful operative selection.

There are few randomized trials examining lumbar fusion for degenerative disease. Two studies have shown improvement in chronic back pain (Table 1). Fritzell et al. in 2001 randomized 294 adults with chronic low-back pain for at least 2 years, radiographic evidence of lumbar degeneration between L4 and S1, who had been on “sick leave” from work for at least 1 year, had back pain greater than leg pain, and had high scores on validated, functional disability questionnaires.⁴³ The authors excluded patients with radiographic nerve root compression, a history of spine surgery (except discectomy more than 2 years in the past), and “obvious ongoing psychiatric illness.” All patients had failed a trial of conservative management. The mean preoperative Oswestry Disability Index (ODI) score of patients randomized to the surgical arm was 47.3, which improved to 35.7 at the 2-year follow-up. This represented a statistically significant improvement over patients randomized to the nonsurgical group (mean ODI score of 48.4 to 45.6).

In 2003 Brox et al. conducted a smaller randomized trial, enrolling 64 patients with lumbar spondylosis.¹⁹ Patients in this trial showed significant postoperative improvement at 1-year follow-up, improving from an ODI of 42.0 to 26.4. To be enrolled, patients needed an ODI score greater than 30, pain present for more than 1 year, and radiographic evidence of spondylosis. Radiculopathy and psychiatric disease were again among the exclusion criteria.

Both studies showed good results from lumbar fusion. They enrolled only patients with high levels of disability who had already failed conservative management. The average postoperative ODI score remained high in both studies, however, and in the larger study, surgical results

TABLE 1. Studies of fusion for low-back pain

Authors & Year	Evidence Class*	Description
Fritzell et al., 2001	II	294 patients w/ lumbar spondylosis randomized to fusion vs conservative care; surgery significantly better in back pain, ODI, and return to work
Brox et al., 2003	II	64 patients w/ lumbar spondylosis, randomized to surgery vs physical and cognitive therapy; both groups improved, ODI reduced significantly, with no significant difference for surgery or conservative care

* Levels of evidence assigned based on criteria from Kaiser et al: Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 1: Introduction and methodology. *J Neurosurg Spine* 21:2–6, 2014.

were statistically superior to conservative management. Ultimately, patients with severe disability from back pain can improve with surgery, but the clinical examination is an imprecise tool for selecting these patients.

An aspect of patient history that has consistently predicted patient outcomes is the presence of psychiatric disease, most commonly anxiety or depression. It should be noted that both the Brox and Fritzell studies excluded patients with significant psychiatric comorbidity. Multiple studies have demonstrated that this aspect of the patient history is an independent predictor of outcomes following lumbar fusion surgery.^{5,96,143}

The clinical examination is useful in excluding masqueraders of spinal pathology. Low-back pain may be referred from sources other than the lumbar vertebrae, such as the hip or the sacroiliac joint. Twenty to 25% of patients with low-back pain have some positive findings on provocative testing of the hip joint.¹¹⁵ Hip osteoarthritis can be tested with flexion, abduction, and rotation, such as the Faber test. Trochanteric bursitis is another common extra-spinal source of back pain: a 20% rate of greater trochanteric pain syndrome has been reported in patients referred for low-back pain.¹⁴²

Radiological

The diagnosis of spondylosis is confirmed with imaging. Like clinical back pain, lumbar spondylosis is very common, and not in and of itself a favorable indicator for improvement following fusion procedures. Fritzell and Brox in their prospective studies specifically selected patients with evidence of spondylosis, without nerve compression, and showed good results in an otherwise rigorously selected cohort of patients.^{19,43} Other imaging findings may be more useful in selecting candidates for lumbar fusion.

Radiculopathy and/or back pain resulting from a herniated disc is common. Evidence for fusion in the context of back pain and disc herniation is sparse (Table 2). Takeshima et al. examined 95 patients with disc herniations, 51 of whom had fusion surgery, and 44 with decom-

TABLE 2. Studies of fusion for a herniated lumbar disc

Authors & Year	Evidence Class*	Description
Takeshima et al., 2000	III	95 patients w/ lumbar disc herniation undergoing decompression (n = 44) or decompression and fusion (n = 51); retrospective analysis showed no significant benefit for fusion
Fu et al., 2005	III	41 patients w/ recurrent disc herniation underwent discectomy and fusion vs discectomy alone; no differences in postop back pain scores at 88 mos follow-up

* Levels of evidence assigned based on criteria from Kaiser et al: Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 1: Introduction and methodology. *J Neurosurg Spine* 21:2–6, 2014.

pression alone. Patients undergoing fusion had better results for low-back pain and recurrence, but overall clinical outcome scores were not significantly different.¹⁴⁰ Satoh et al. performed a retrospective analysis of patients with disc herniations who underwent either discectomy alone (n = 147) or discectomy and fusion (n = 78).¹³⁰ Patients undergoing fusion surgery had lower rates of revision and lower low-back pain scores than those undergoing only decompression. Recurrent disc herniations following initial discectomy are more widely considered an indication for fusion, but again, supporting evidence is sparse. Fu et al. followed 41 patients with symptomatic recurrent disc herniations who underwent discectomy alone (n = 21) or discectomy and fusion (n = 18), who showed no significant difference in outcomes.⁴⁴ El Shazly et al. published a prospective study in which patients with recurrent herniation were randomized to discectomy or fusion, with superior pain outcomes noted in the fusion group, but no significant difference in overall outcomes and high satisfaction rates in both groups.³⁵ Zhou et al. published several studies comparing endoscopic discectomy and fusion for recurrent herniations, none of which showed a statistically significant difference in long-term patient outcomes.^{85,160,161} Due to the increased costs, greater risks, and the lack of compelling evidence of superior outcomes, it is difficult to recommend a lumbar fusion for patients presenting with an uncomplicated lumbar herniated disc.¹²²

Spinal stenosis resulting in compression of the lumbar nerves, either in the canal or the neural foramen, is a common indication for surgery. While these patients regularly do well with decompression procedures, in part due to the greater specificity in identifying the location of symptom generation, lumbar fusion for spinal stenosis remains controversial. Chou et al. published a systematic review of 24 studies examining lumbar fusion surgery for spinal stenosis, finding no benefit for fusion surgery over decompression alone.²⁷ Uncomplicated stenosis is not considered an indication for lumbar fusion.¹²³ The etiology of the stenosis, however, may play a role in the suitability of the patient for a fusion procedure.

TABLE 3. Studies of fusion for stenosis with spondylolisthesis

Authors & Year	Evidence Class*	Description
SPORT 2007, ¹⁵⁴ 2009, ¹⁵⁵ & 2018 ³	II	Randomized (n = 304) and observational (n = 303) patients w/ lumbar spondylolisthesis, surgery vs conservative care; surgery better in each outcome measure at 2-, 4-, and 8-year follow-up
Ghogawala et al., 2016	I	66 patients w/ grade I spondylolisthesis randomized to decompression vs decompression and fusion; decompression and fusion significantly improved quality of life at 4-year follow-up
Försth et al., 2016	II	247 patients w/ lumbar stenosis (135 w/ spondylolisthesis) randomized to decompression w/ fusion vs decompression alone; no difference in ODI or 6-minute walk test at 2- and 5-year follow-up
Chou et al., 2009	II	Systematic review of 24 full-text articles on surgery vs conservative management for low-back pain and lumbar spondylolisthesis; found surgery equivalent to intense rehabilitation program

* Levels of evidence assigned based on criteria from Kaiser et al: Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 1: Introduction and methodology. *J Neurosurg Spine* 21:2–6, 2014.

The argument for fusion is stronger in patients with lumbar spondylosis/stenosis with evidence of instability (Table 3). Instability from degenerative disease is rarely acute; it is typically glacial, or partial. Radiological signs of instability can be inconsistent, and interpretations vary. A commonly used radiological proxy for instability is spondylolisthesis. Both prospective and retrospective trials have indicated that patients with stenosis due to spondylolisthesis have better outcomes with fusion than with decompression alone. The spondylolisthesis arm of the SPORT (Spine Patient Outcomes Research Trial) represented a large cohort of patients undergoing surgical and conservative treatment, with enrollment of more than 600 patients.¹⁵⁴ That trial found a benefit for surgery in patients with stenosis and spondylolisthesis. Ninety-five percent of patients in SPORT underwent fusion procedures, 75% of which were instrumented. Improved outcomes were maintained through 4- and 8-year follow-up.^{3,155} This trial, although large, was complicated by heterogeneity in both patient characteristics and surgical technique. Multiple smaller trials have also demonstrated benefit for fusion surgery in patients with spondylolisthesis. More recently, Ghogawala et al. published a prospective randomized trial comparing patients treated with decompression alone (n = 35) to decompression and fusion (n = 31), demonstrating a benefit in those patients undergoing fusion surgery.⁴⁸ Försth et al. published a similarly designed trial demonstrating no benefit for fusion over decompression.⁴¹ The topic remains controversial.

Fusion for degenerative deformity is less studied than that for spondylolisthesis, and deformity surgery specifically will be covered by other reviews in this series. Patients with moderate symptoms and significant or progressive sagittal or coronal deformities are generally considered appropriate candidates for lumbar fusion.²⁴ Sophisticated parameters have been developed that account for a more global evaluation of spinal mechanics and positioning, including sacropelvic and femoral head position in relation to the upper cervical spine, and even the skull.^{49,73,74,91} Given the mounting evidence linking sagittal balance to outcomes and progression of spinal disease, including adjacent-segment disease, even the degenerative spine surgeon performing a single-level fusion should consider and account for lumbopelvic and global sagittal parameters.⁹⁵

Diagnostic Tests for Evaluation of Back Pain

Evidence of disc degeneration on MRI can be useful in ruling out disc degeneration as the etiology of low-back pain, but can be nonspecific, especially when determining which patients will benefit from lumbar fusion. Modic endplate changes—demonstrating increased signal in the vertebral body endplate—often correlate with overall degenerative progression in the spine. Although previously reported as a factor in the surgical decision-making process, it is of limited utility when used in isolation.^{14,94} Diagnostic procedures, used in conjunction with MRI findings, can be useful in guiding management.

Epidural steroid injections are commonly used in the management of radiculopathy but have little evidence to support their use in the management of back pain.¹⁵² Trigger point injections likewise may have efficacy in treatment of pain from the lumbar musculature, but less in the treatment of spinal degenerative disease. The facet joint is considered to be a pain generator in 15%–45% of patients with low-back pain.¹³³ This joint presents an attractive target for focal treatments that can be both therapeutic and diagnostic. Injections of steroids and local anesthetics have resulted in temporary pain relief for properly selected patients. Their use in predicting which patients will benefit from lumbar fusion, however, is less consistent.

Injections into the joint itself have been controversial. Medial nerve blocks, addressing the innervation of the joint, have been more consistent in controlled trials:⁹³ multiple randomized controlled trials have shown improvement of ODI and visual analog scale scores. While it is reasonable that these patients would have similar relief following arthrodesis across these presumably symptomatic joints, no studies have yet shown a correlation between relief from a focal facet block and improvement following lumbar fusion.

Discography has been used as a diagnostic test to evaluate potentially pathologic intervertebral discs as pain generators. While some trials have shown an association between concordant pain on discography and improvement following lumbar fusion, several have shown no association, and there is no high-quality evidence in favor of discography as a predictive tool for patient selection. Discoblock, a related procedure in which an anesthetic

TABLE 4. Studies of discoblock as diagnostic tool

Authors & Year	Evidence Class*	Description
Ohtori et al., 2009	II	42 patients undergoing ALIF underwent preop discoblock vs discography; those w/ positive discoblock had significantly improved pain and disability scores

* Levels of evidence assigned based on criteria from Kaiser et al: Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 1: Introduction and methodology. *J Neurosurg Spine* 21:2–6, 2014.

agent is injected into the disc, has shown an association with improvement following lumbar fusion.¹⁰⁶ However, this was only in 1 study, with a small sample size (n = 42), and further investigation is needed (Table 4).

Predictive Analytics

The challenges of executing a randomized controlled study for lumbar surgery are many. Trials are lengthy and expensive, and patient enrollment is difficult. With the widespread use of electronic record keeping, the volume of data available for clinical research has rapidly increased. The use of analytics to identify trends and possible predictive tools for determining patients who will have good (or bad) outcomes from surgery has become more common and will be more widely studied as technologies and techniques for collating, organizing, and interpreting the volume of data are refined.

Significant strides have already been made toward qualifying patients, surgeries, and outcomes in a meaningful way. Frailty indices have been used to quantify the preoperative physiological reserve in patients and predict the likelihood of favorable or unfavorable outcomes in patients undergoing lumbar fusion. The modified frailty index has been applied to patients undergoing lumbar fusion to predict complications, length of stay, readmission, reoperation, and other adverse events.^{82,108,153} Disease-specific predictive tools have been developed to assess patients and inform decision-making, including spine surgery.^{99,120} As more data become available, these predictive tools will become more precise, informative, and useful.

Quantifying the invasiveness of a given surgical procedure is also a useful tool in more uniformly defining that surgery's risks, costs, and benefits. Mirza et al. developed a score to define the invasiveness of a spinal procedure, correlated with blood loss and operative time (Table 5).¹⁰⁰ More specialized scores have been subsequently developed, and when used in concert with patient frailty, will be a valuable tool in surgical decision-making. These predictive tools are dependent on the quality of data available to them. Databases such as the National Surgical Quality Improvement Program, International Spine Study Group, and National Inpatient Sample provide varying sizes and granularity. As more data become available, more uniform, and more organized, predictive analytics will provide a valuable tool for fields as heterogeneous and complicated as lumbar fusion surgery.

TABLE 5. Examples of surgical invasiveness scoring

Procedure	Anterior (Score)			Posterior (Score)			Invasiveness Index Value
	Decompression	Fusion	Instrumentation	Decompression	Fusion	Instrumentation	
L4–5 microdiscectomy	0	0	0	1	0	0	1
L3–4, 4–5 TLIF, L4–5 laminectomy	0	3	3	2	3	3	14
T10–pelvis posterior fusion, L2–4 laminectomy, L4–5 and L5–S1 TLIF	0	3	3	3	10	10	29
Wound debridement	0	0	0	0	0	0	0

From Mirza et al., 2008.¹⁰⁰

Lumbar Instrumentation Technologies in Degenerative Disease

Thoracolumbar instrumentation emerged initially for treatment of idiopathic and neuromuscular deformity. The Harrington rod provided correction in the coronal plane but its inadequacies included sagittal imbalance, flatback syndrome, and persistent vertebral rotational deformity.¹ The Cotrel-Dubousset system used a bilateral rod construct fixed to segmentally placed laminar hooks, which introduced the attempt at 3D spinal correction.^{30,31,98} A multicenter case series using the Cotrel-Dubousset system in degenerative cases with fewer than 5 fused levels revealed improved fusion, pain, and complication outcomes without an increase in neurological dysfunction when compared to historical controls. Soon thereafter, a multicenter trial confirmed statistically significantly improved fusion rates.⁹⁸ Pedicle screw (PS) fixation subsequently replaced the hook system, demonstrating excellent fusion rates compared to previous historical rates in degenerative cases.¹⁵⁸ PSs are also more robust in 3D manipulation of the vertebral body.^{47,76,84} Current posterolateral fusion techniques include several options.

Hooks

PSs have largely replaced hook constructs as the pri-

mary fixation device for fusion in the spine.^{16,147} Use of hooks at the proximal-end vertebra of long-deformity PS constructs to diminish rates of proximal junctional kyphosis has demonstrated some benefits in several reports and no difference in another series.^{56,109} Use of a mixed laminar hook–PS construct also is preferred in cases of spondylolysis without significant spondylolisthesis where the repair is attempting to fuse across the pars defect and not across vertebral segments.^{25,66}

Classic Cancellous Trajectory PSs

Currently, PSs (Figs. 1 and 2) are the most commonly used form of lumbar spinal fixation, with biomechanical stressors being distributed across all three vertebral body columns.^{16,147} Superior fusion rates and outcomes have been consistently, but not universally, demonstrated over noninstrumented fusion.^{8,40,42,61,79,87,163} Current data would suggest PS-related complications are low, reported in less than 3% of cases.⁸⁶ Although associated with an increased risk of complications, the widespread use of PSs has been justified due to the observed increase in fusion rate and poor outcomes associated with a pseudarthrosis, although definitive evidence of improved outcomes is lacking.^{51,145} Reported starting trajectories vary for open PS fixation, but are universally lateral to or at the lateral border of the pars interarticularis as it meets the superior articulating process

FIG. 1. Axial (A), posterior (B), and lateral (C) schematics demonstrating the trajectories of PSs (gray) and cPSs (green) in a single pedicle. From Mullin JP, Perlmutter B, Schmidt E, Benzel E, Steinmetz MP: Radiographic feasibility study of cortical bone trajectory and traditional pedicle screw dual trajectories. *J Neurosurg Spine* 25(6):727–732, 2016. Reprinted with permission, Cleveland Clinic Center for Medical Art & Photography © 2015–2109. All Rights Reserved. Figure is available in color online only.

FIG. 2. Demonstrated are TL (A), TFS (B), and PS (C) trajectories. Images obtained with permission from Ferrara LA, Secor JL, Jin BH, Wakefield A, Inceoglu S, Benzel EC: A biomechanical comparison of facet screw fixation and pedicle screw fixation: Effects of short-term and long-term repetitive cycling. *Spine (Phila Pa 1976)* 28(12):1226–1234, 2003 (<https://journals.lww.com/spinejournal/pages/default.aspx>).

and the transverse process. A wide dissection is therefore required, with a medialized trajectory toward the prevertebral vascular structures and central neural elements.^{15,37,105} Alternative fixation techniques that require less dissection have therefore been sought with some success.¹⁴⁸

Percutaneous options for PS placement are numerous and are used for trauma, tumors, deformity, and degenerative processes. Appropriate patient selection is mandatory when utilizing percutaneous PSs for degenerative processes and usually requires inclusion of an interbody grafting, given the limited posterolateral fusion options with percutaneous PS fixation.¹⁰² Classic techniques include C-arm-guided screw placement, which increases the risk of extensive radiation exposure. New navigation, robotic, and computer-assisted techniques are an option for reduced radiation exposure for minimally invasive fusion options.¹⁴¹

Cortical Pedicle Screws

Cortical pedicle screws (cPSs; Fig. 1), first reported in 2009, start at the inferomedial aspect of the pedicle and

are directed inferior-to-superior and medial-to-lateral. They tend to be shorter and of a smaller diameter than traditional PSs.¹²⁹ Cadaveric biomechanical studies reveal marginally higher stiffness in flexion-extension but slightly lower stiffness with lateral bending and axial rotation compared to PSs in conjunction with an interbody graft at one level.¹¹⁰ Cortical pedicle screws were noted to be associated with shorter surgical time and decreased blood loss compared with either open or percutaneous PSs, without differences in fusion rates or lordotic correction. Advantages in health-related quality of life measures were also noted in cPSs compared to PSs. Definitive conclusions regarding superiority cannot be made given variable and limited follow-up of less than a year.⁶⁷ Small cohort sizes with 10 or fewer patients in each arm also limit generalizability of the clinical reports.^{67,101} Although CT was performed on each patient, fusion was assessed based on plain radiography, limiting sensitivity for pseudarthrosis.⁶⁷ While some suggestion for improved pullout strength has been reported, most studies have used cPSs in conjunction with an interbody graft. Freehand trajectories have not been adequately characterized and there may be some increased risk of medial breach into the central canal at the proximal insertion site of the screw in examination of cadaveric models.^{129,148}

Transfacet Screw Fixation

Transfacet screw (TFS; Fig. 2) fixation is a relatively shorter lag screw that traverses the facet joint of the levels being fused. It was described in the middle of the last century and has been more recently studied in conjunction with anteriorly or laterally placed interbody devices.^{17,77} Cadaveric biomechanical studies have demonstrated improved rigidity with adjunct facet screw fixation, which may be equivalent to PS adjunct fixation.^{39,57,89,103,150,164} When posterior fixation was placed as a standalone construct without anterior column fixation, PSs were noted to be superior to TFSs in axial rotation and lateral bending, but no difference was noted in flexion and extension.⁴ Unfortunately, the TFS may be limited based on orientation of the facet and an overly vertical facet orientation, which is more common in higher lumbar levels such as L1 and L2, and may make this technique difficult.¹³⁶ Bilateral TFS clinical use has not been reported to date. The use of TFSs contralateral to PSs as an adjunct to an interbody fusion has been reported in small clinical cohort trials with comparable results. Although there may be a trend toward a slightly increased risk of pseudarthrosis with the combined PS and TFS technique, the studies were not powered to establish this conclusion.^{22,59,134}

Contralateral Translaminar Fixation

The translaminar (TL; Fig. 2) screw is intended to start on the inferior spinous process contralaterally and pass through the ipsilateral lamina and through the facet joint. Like the TFS, TL screws lack fixation that spans the middle or anterior column and are therefore usually studied in conjunction with an interbody technique.¹⁴⁸ Biomechanical reports have been conflicting as TL fixation is either equivalent or slightly less rigid compared to PS fixation when used concomitantly with interbody fixation.^{36,50,53,113}

FIG. 3. Demonstrated are the iliac wing (superior, black line), S1-alar iliac (middle, blue line), and S2-alar iliac (inferior, red line) screw trajectories. Images obtained with permission from DePasse JM, Valdes M, Palumbo MA, Daniels AH, Eberson CP: S-1 alar/iliac screw technique for spinopelvic fixation. *J Neurosurg Spine* 28(5):543–547, 2018. Image adapted from Gray H: *Anatomy of the Human Body*. Philadelphia: Lea & Febiger, 1918 (public domain). Figure is available in color online only.

Use in clinical patients has yielded acceptable outcomes, although there are limited studies investigating the efficacy of this technique in lumbar degenerative disease.⁹²

Adjunctive Pelvic and Sacropelvic Fixation

Adjunctive pelvic fixation (Fig. 3) is now considered a favorable technique in lumbosacral fusions where the mechanical stress on the sacral fixation points would increase the risk of failure and development of pseudarthrosis. Mechanical studies have confirmed the excessive strain placed at the base of long constructs and most agree that any lumbosacral fusion starting above L3 should incorporate pelvic fixation.^{32,111,126} The threshold for use of pelvic fixation should be even lower in the presence of anterior column malalignment or manipulation—whether pathologic, as in cases of substantial spondylolisthesis,^{97,114} or iatrogenic, such as in cases of low lumbar 3-column osteotomies.^{18,75,137,138} Historical fixation techniques of the pelvis include Galveston rods, Kostuik intrasacral fixation, and Jackson transiliac fixation. Most modern reports of degenerative, idiopathic, and neuromuscular deformity cases use pelvic screw fixation, which is placed through the iliac wing and directed at the acetabular cortical bone.⁶² Fixation that goes through the sacroiliac joint, such as the S2-alar iliac screw, has been described as an option with excellent success, and possibly lower rates of screw fracture and reoperation when compared with iliac wing screw fixation in the adult degenerative population.^{60,62} Advantages of the S2-alar iliac technique include less dissection of the iliac wing and in-line screw head position with the rest of the lumbosacral PS construct. An S1-alar iliac screw trajectory has also been described but has not been adequately studied, requiring even less dissection of the

FIG. 4. Demonstrated are the various surgical approaches to the intervertebral disc space. Orthogonal maneuvers of antepsoas lumbar interbody fusion (APsLIF) toward the LLIF (a) and ALIF (b) positions are also described. Image obtained with permission from Larson SJ, Holst RA, Hemmy DC, Sances A Jr: Lateral extracavitary approach to traumatic lesions of the thoracic and lumbar spine. *J Neurosurg* 45(6):628–637, 1976. Arrows and annotation are added by the current authors. Figure is available in color online only.

sacrum while maintaining in-line alignment.^{34,151} Extensive clinical series are lacking for this technique.

Interbody Technologies in the Degenerative Lumbar Spine

Interbody fusion with adjunctive posterior fixation in the degenerative lumbar spine has a lower pseudarthrosis and reoperation rate when compared to posterolateral fusion alone. Despite a tendency toward improved functional outcomes as well, this has not been shown to be statistically significant.²⁸ Improved sagittal correction has also been reported with interbody grafting compared to standalone posterior techniques,⁷² although this finding could not be reproduced by another group, and may thus be technique-dependent.¹⁴⁹ Treatment of single-level degenerative spondylolisthesis was reviewed in a meta-analysis of previous retrospective studies, which revealed no statistically significant difference between posterolateral fusion alone and interbody fusion with posterolateral fixation.²⁰ Several options for interbody fusion have been described and no definitive superior technique has been demonstrated (Fig. 4). Anterior interbody fusion may provide earlier mobilization and improved function, but the difference does not persist when 2-year outcomes are analyzed. Additionally, anterior fixation with fusion combined with posterior fusion is likely equivalent in outcomes compared to cases that also had a posterolateral fusion performed, with the latter having increased blood loss and operative time.^{2,104,131} The posterior lumbar interbody fusion (PLIF) with bilateral cage placement was shown to be equivalent in fusion rate to the transforaminal lumbar interbody fusion (TLIF) with a unilateral interbody device. A routine bilateral approach is therefore not recommended, as exposing the patient to

greater risk for iatrogenic dural or nerve root injury cannot be justified based on outcomes.¹⁵⁹

Structural and Engineering Developments in Devices for Anterior Interbody Insertion

The anterior interbody device was first described in horses.^{11,33} The evolution of implants has included autografts, allografts, threaded-type cages (usually placed in pairs), and standalone cages with anterior fixation. A variety of anterior fixation options are also available, including an interbody device with a separate unattached plate that spans across the disc space and is fixed by screws into the respective vertebral bodies. The threaded cages were useful in achieving fusion but were superseded by the tapered, wider construction cages that allowed for more robust angular correction.¹¹² Several options are available for fixation in the standalone tapered devices. Most commonly, screws or blades are placed into the endplate through an opening in the interbody device. Devices that allow a combination of screw and blade options are also on the market. A new option in wedge-shaped anterior lateral interbody fusion (ALIF) cages includes the possibility to insert a relatively flat implant with the ability to increase the angulation in situ with a “ratcheting” function. These designs have demonstrated more robust angular correction in cadavers.¹⁵⁶ Well-designed clinical trials and comparisons of the rapidly developing new designs have not yet been performed.¹¹²

Structural and Engineering Developments in Devices for Posterior Interbody Insertion

Biomechanical studies reveal that all interbody spacer geometrical alignments have similar rigidity in cadaver models when used concomitantly with posterior pedicle fixation. When studied alone, the asymmetrical, obliquely placed, unilateral TLIF implant was noted to be inferior in lateral bending stiffness when compared to bilateral cages or articulating anteriorly placed cages.^{26,38,144} Retrospective clinical studies revealed that old age and central placement of the implant were the biggest predictors of subsidence.⁴⁶ The recommendation is that cages be placed ventrally along the cortical rim. Despite the intended design for “kidney”- or “banana”-type cages to be placed anteriorly, most were indeed inadequately placed in the ventral component and tended to be placed in the central portion of the endplate.⁴⁶ Predictably, laterally expanding TLIF cages were noted to be stiffer than other cages and may even provide as much or greater lateral stiffness as ALIF cages. Multiple models have been described. Most are either delivered in a collapsed state and subsequently expanded and filled with bone graft in situ, or delivered in a straightforward fashion and via use of articulations expanded into a broader footprint in situ.²¹ Posteriorly placed implants provide significantly inferior lordosis correction overall compared to anteriorly placed implants.¹² Lordosis creation in prone PLIF cases is directly correlated with extent of anterior placement of the implant.⁸⁰ Craniostrally expanding TLIF cages, which are inserted at a smaller height and are then expanded, have been proposed to achieve further lordosis. Unfortunately, long-term clinical follow-up does not reveal advantages in Cobb angle and, although statisti-

cally significant, likely produce clinically inconsequential benefits in disc height.^{6,70} Nevertheless, several experienced centers have reported improved clinical outcomes with minimal subsidence if the endplates are prepared appropriately.^{54,127} These clinical studies have small sample sizes and do not report extensively on the learning curve required to avoid overexpansion and sufficiently careful endplate preparation without endplate violation. In most cases of posterior interbody implants, bilateral PS fixation is recommended due to its significantly superior rigidity when compared to unilateral PS fixation.⁷

Developments in Lateral Lumbar Interbody Fusion

Laterally placed interbody devices have been used safely in the degenerative spine, with most complications being transient and approach-related, including muscular hip-flexion weakness, lumbosacral plexopathy and neurological injury, and vascular injury.¹³⁵ Reported fusion rates range from 85% to 93%.¹³ Standalone laterally placed cages have been noted to be less rigid than either augmentation with unilateral or bilateral PSs in biomechanical models. Although a lateral plate provided some increased rigidity, this was noted to be inferior to PS fixation. Bilateral PSs, although more rigid in the axial plane than unilateral PS augmentation of lateral lumbar interbody fusion (LLIF), provide similar reductions in range of motion. Some models have demonstrated lateral plating concomitant with interspinous devices to be equivalent to use of bilateral PS fixation.^{121,128} On average, insertion of a cage through a lateral approach provides between 2.8° and 5° of lordosis per level, which is markedly less than anterior techniques that require resection of the anterior longitudinal ligament (ALL) for graft placement, such as the ALIF.^{88,135} Biomechanical studies indicate robust improvement in lordosis correction with concomitant ALL release at the price of introducing substantial instability into the construct. With ALL release, robust concomitant posterior pedicle fixation is recommended. Anterior plating has not proven to restore sufficient stability to the construct. Hyperlordotic cages in the setting of ALL release have been proposed as a substitute to 3-column posterior osteotomies.^{69,146}

Conceptualization of the “Oblique” Antepsoas Approach

A new option that allows for lateral or anterior access to the interbody space is the antepsoas approach. Theoretical advantages of this approach include lower rates of retrograde ejaculation compared to ALIF, and lower rates of traction nerve injury compared to the transpsoas LLIF approach.^{65,83} With the patient positioned in the lateral position similar to LLIF, dissection is carried anterior to the psoas and lateral to the great vessels. Above L4, where a lateral interbody approach is the preferred method, one performs an “orthogonal maneuver” to position the implants in the same direction as LLIF. At L5–S1 where the vasculature is positioned laterally, the final direction of placement of the implants can mimic that of the ALIF. Both options are possible at L4–5 and the decision is made based on the particular placement of arterial and venous vasculature.^{29,64} Clinical outcomes have been comparable to the ALIF and LLIF approaches.^{64,83}

Interbody Device Materials

Interbody device materials vary. Metals include titanium, stainless steel, and cobalt chromium. Plastics include polyetheretherketone (PEEK) and carbon fiber, and carbon fiber–reinforced PEEK (CFRP). All solid metal implants have an elastic modulus that is more than 13 times as strong as cancellous bone. PEEK is closest to cancellous bone, and CFRP is closest to cortical bone.¹⁰²

Microscopic titanium surface roughness increases osteogenic cell differentiation factors in ex vivo experiments. Nanometric roughening of the titanium surface also encourages bone ingrowth and adhesion. Together, these characteristics may improve the osteointegration of titanium-coated implants. Multiple technologies have been attempted, including heat, alkali, and electron beam melting, with success in bone interaction. Electron beam coating of titanium onto PEEK surfaces is also available, with some benefit compared to PEEK alone.¹¹⁸ Ex vivo studies show titanium creates an environment supportive of osteoblastic activity in comparison to PEEK, which promotes an inflammatory proapoptotic cellular response.¹⁰⁷ Porous titanium has been used to promote bone integration in the spine as well as for other bony surfaces, such as the acetabulum during arthroplasty. An advantage of this porosity is the decreased modulus, which approached that of PEEK and thus cancellous bone and is therefore suggested to be safer than solid titanium for use in osteoporotic or weakened bone.¹¹⁸ Although there are preliminary reports that this would cause a lower chance of subsidence, the sample size is small.⁴⁵ While PEEK does have the advantage of radiolucency, lack of artifact on CT and MRI, and likely lower rates of subsidence, the theoretical bone growth and fusion advantages of titanium have yet to be definitively confirmed.^{63,132} Clinical outcomes comparisons have been inconclusive.⁶³

Silicon nitride is a ceramic material that is utilized for implants in spinal and other orthopedic products. It is purported to have excellent biointegration and antimicrobial properties, and early reports on its clinical use in cases of infection are now available.¹¹⁷ Whereas its use in the anterior cervical fusion cases has been favorably reported in a trial comparison with PEEK,¹⁰ the results from a trial regarding a TLIF ceramic implant in degenerative cases has yet to be reported.⁶⁸

Robotics, Intraoperative Navigation, and Stereotaxy

Stereotaxy has a long tradition in cranial procedures and surgery, even predating computerized technology. Two primary forms of stereotaxy are currently in use for placement of PSs: intraoperative image-guided infrared navigation with real-time image representation on a computer screen, and robotic trajectory guidance based on a preoperatively selected trajectory on CT.⁷⁸ Randomized controlled trials have reported improved accuracy of PS placement with intraoperative navigation compared to freehand placement.^{81,116} Trials comparing robotic placement to freehand placement have had conflicting results, with one study demonstrating equivalent accuracy to conventional fluoroscopy, with possibly less violation of the facet joint in robotic placement of the screws.⁷¹ Another study demonstrated inferior screw accuracy and higher

rates of screw revision in the robotic arm.¹²⁴ A prospective study comparing robotic placement with navigated screw placement was underpowered to allow definitive comparison.¹²⁵ The variable results in cases of robotic screw placement may be due to its more recent introduction into the clinical setting and may reflect differing positions on the learning curve.¹³⁹ Further reports, including studies characterizing the surgeon learning curve, are required as robotic technology becomes more available and familiar.

Evaluation of Fusion

Surgical exploration is the gold standard for evaluation of fusion, although errors may be observed even when fusion is surgically explored.⁵² CT is proposed as the best noninvasive imaging modality for evaluation of fusion.^{52,157} Visualization of bony trabeculation across the interspace without any area of bone lucency is consistent with a successful fusion. Conversely, implant subsidence, “haloing” or loosening surrounding screw instrumentation, lucency in areas of bridging bone, and cystic endplate changes are all consistent with a failure of fusion.²³ Other proposed modalities include MRI, ultrasonography, bone scans, and dynamic plain radiographs. Fusion and pseudarthrosis are clinical conclusions and should be addressed in light of patient symptomatology.⁵²

Conclusions

Lumbar fusion surgery for degenerative conditions has been extensively studied. Although our understanding of indications and outcomes is steadily increasing, rigorous evaluation of indications and characterization of risks and outcomes is still required. Technologies and techniques have proliferated to the great benefit of patients and surgeons. Extensive large and well-designed clinical testing remains to be reported for many new techniques.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: all authors. Acquisition of data: Reid, Morr. Analysis and interpretation of data: Reid, Morr. Drafting the article: Reid, Morr. Critically revising the article: Kaiser, Reid. Reviewed submitted version of manuscript: Reid, Morr. Approved the final version of the manuscript on behalf of all authors: Kaiser.

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