Advances in Anterolateral Approaches to the Lumbar Spine

A Focus on Technological Developments

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KEYWORDS

• Spinal surgery • Anterolateral approaches • Intraoperative image guidance • Robotics • Augmented reality • Machine learning

KEY POINTS

- Anterolateral approaches to the spine have undergone significant advances in the past few decades.
- Advances in intraoperative imaging, such as three-dimensional (3D) imaging and computer-assisted navigation, have demonstrated advantages for patients and surgeons.
- Technologies such as robotics, augmented reality, and machine learning show great potential but require careful evaluation.

HISTORICAL PERSPECTIVES

The history of spine surgery has been a continual journey of innovation and adaptation, driven by the relentless pursuit to better the human condition. Early documented treatments for spine pathology date back to the sixteenth century BC with accounts of the cervical spine and associated cord injury management by Egyptian priests, the physicians of that era. Simply put, the prescription was rest, bandages, and dressings.[1] It was only two millennia later that the first surgical intervention of the spine was reported.[2] This article discusses the technological advances since then, particularly related to anterolateral approaches to spine surgery. The term anterolateral encompasses anterior, lateral, and oblique approaches.

Anterior Approach

In 1906, Müller documented one of the earliest anterior approaches to the lumbar spine. Müller attempted to use a transperitoneal approach to excise a tuberculosis abscess of the spine (ie, Pott's disease). Unfortunately, the procedure did not have favorable outcomes overall and was abandoned.[3] Nonetheless, Norman Capener built on this approach in 1932 and described the anterior lumbar interbody fusion (ALIF). In 1960, Paul Harmon revised Capener's ALIF procedure to use an extraperitoneal approach instead of a transperitoneal approach. In particular, this procedure was employed for those patients who had already failed two or more posterior surgeries.[4] Harmon demonstrated satisfactory outcomes, even at a 12-year

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follow-up.[4] Despite Harmon's efforts early on, the ALIF remained controversial.[3]

However, in 1997, the ALIF was reinvigorated by Michael Mayer with the introduction of his mini-open approach. The new approach reduced operative time and resulted in less trauma to the patient.[5] The mini-open ALIF also became the seed for the lateral and oblique approaches that followed in the decades after.[3]

The anterior approach to the spine is achieved by making an incision in the lower abdomen, moving aside the abdominal viscera, and carefully retracting the abdominal vasculature in front of the spine. This creates a corridor that allows direct access to the disc space and avoids direct manipulation of the spinal nerves, reducing the risk of nerve injury.[6] In its current form, the ALIF allows surgeons to achieve maximal disc space visualization and consequentially maximize the implant footprint. To this end, endplate subsidence can be minimized.[7] For degenerative disc disease, the stand-alone ALIF has been shown to have better clinical and radiographic outcomes, reduced operative time, and blood loss compared to conventional posterior approaches.[8] In addition, the ALIF demonstrates adequate clinical and radiographic outcomes for spinal deformity. However, there remains a 13% overall complication rate.[7,9,10] Complications include vascular injury, abdominal organ injury, and retrograde ejaculation.[11]

Lateral Approach

Despite the advances of the ALIF, there was still a need for less traumatic approaches to the spine. This need was met by Luiz Pimenta in 2006 with his pioneering of the lateral lumbar interbody fusion (LLIF). The patient is placed in the lateral decubitus position. The surgeon makes an incision in the side of the patient's torso before traversing through the psoas muscle to the intervertebral disc. This retroperitoneal, transpsoas approach avoids the great vessels, thecal sac, and spinal nerve roots.[12] Furthermore, the LLIF does not require a general or vascular surgeon for access as the norm for spine surgeons employing the ALIF approach. Moreover, the incision is smaller, and there is earlier postoperative patient mobilization.[11] In addition, the LLIF with posterior spinal fusion (PSF) is superior to conventional PSF techniques (ie, TLIF and PLIF) in clinical and radiographic improvements without differences in complication rates.[13,14]

However, the LLIF has its limitations. These limitations include difficulty accessing the L5-S1 disc space, increased lumbar plexus injury risk, psoas muscle trauma, and reliance on neuromonitoring.[11,15] Furthermore, using the procedure in isolation may not be ideal in cases with severe central canal stenosis, bony lateral recess stenosis, and high-grade spondylolisthesis.[11]

Oblique Approach

The anterior-to-psoas technique (ATP), also known as the oblique lateral interbody fusion (OLIF), was introduced to address the limitations of the LLIF.[3] The ATP is a retroperitoneal, antepsoas method to access the lumbar spine. In this approach, the patient is situated in the lateral decubitus position, and a slightly ventral incision is created to grant entry into the retroperitoneal space. The psoas muscle is gently retracted aside and safeguarded instead of being penetrated. The disc space can then be visualized.[16,17] The benefits of this approach included shorter operative times and reduced risk of injuring the psoas muscle and nearby nerves, with some reports citing a lower incidence of transient and permanent weakness (1% vs 3%) compared to the LLIF.[18]

Additionally, the ATP can be performed at the L5-S1 disc level, which, in essence, is an ALIF performed in the lateral position. This approach allows access to the traditional ALIF corridor but with the benefits of a lateral/anterolateral approach. Evidence in the current literature shows that stand-alone ATP is safe and effective for mild to moderate adult spinal deformity.[19] Additionally, it may allow greater sagittal deformity correction without needing a posterior subtraction osteotomy, although further studies are needed to confirm this.[15,20,21]

Nevertheless, the ATP has several associated risks, such as a higher rate of vascular complications than the LLIF (2% vs <0.5%). Other risks include abdominal ileus from manipulation of the retroperitoneal space and numbness or weakness in the psoas or quadriceps muscles from excessive muscle retraction.[16] Overall, there is still a high incidence of intraoperative (4.9%) and postoperative (29.6%) complications.[19]

TECHNOLOGICAL INNOVATIONS

Interbody Cages

There have been significant developments in cage technology that have translated to improved postoperative outcomes. One example is the introduction of the polyetheretherketone (PEEK) cage in the 1990s, which allowed surgeons to address the issue of cage subsidence. Subsidence refers to the phenomenon whereby the operated disc space decreases postoperatively.[22] This occurs when the cage sinks into the vertebral body leading to several clinical implications such as loss of spinal alignment, persistent or recurrent symptoms of pain, instability, and in severe cases, neurologic symptoms due to compression.[23] PEEK cages have been reported to have similar fusion rates as solid titanium cages but with decreased subsidence rates.[23]

On the contrary, studies have also indicated that titanium cages have superior fusion and subsidence rates.[24,25] In particular, three-dimensional (3D) printed porous titanium (pTi) cages were approved in 2017 and have been shown to yield lower subsidence rates than PEEK.[26] This is partly due to the low modulus of elasticity of pTi, which is closer to the modulus of elasticity of native bone than solid titanium.[27]

Apart from making pTi viable, 3D printing has revolutionized interbody graft technology by making patient-specific cages a reality. Spine surgeons can order cages that are customized specifically for the anatomy of each patient and that can distribute the load more evenly due to increased contact area.[28] There is weak evidence that this translates to potentially superior subsidence and pseudarthrosis rates. However, patient-specific cages are estimated to cost two to five times more than off-the-shelf cages. Additionally, it may take up to two to four weeks for the production of a patient-specific cage.[29]

Another significant advancement in interbody cage technology has been the hyperlordotic cage for complex spinal deformity surgery. Correction of severe spinal deformities has traditionally been from the posterior approach using the posterior subtraction osteotomy (PSO).[30] However, the PSO is a particularly morbid procedure with a complication rate of up to 58% (11% of which is neurologic), mean estimated blood loss of 1.1 L, and high rates of pseudarthrosis. Hyperlordotic cages allow similar lordosis correction but with drastically reduced complication rates (21% overall and 4.1% neurologic) and blood loss (240 mL) in combination with the ALIF.[30] Moreover, hyperlordotic cages can overpower prior posterior spinal instrumentation to restore lumbar lordosis in patients with pseudarthrosis.[31]

Intraoperative Image Guidance

Intraoperative image guidance has significantly improved the accuracy of surgical procedures such as pedicle screw fixation. Posterior fixation is often used with LLIF and ATP procedures, especially in cases demonstrating abnormal preoperative dynamic motion.[32] Some suggest that intraoperative image guidance for screw placement yields fewer complications and improved clinical measures.[33] One advancement in the intraoperative imaging realm was the introduction of 3D fluoroscopic imaging which showed significantly higher screw placement accuracy (95.5%) than conventional fluoroscopy (68.1%) or two-dimensional (2D) fluoroscopy (84.3%).[34] An additional downside of conventional fluoroscopy is the continuous radiation exposure to the patient and surgical staff. This has been effectively addressed with computer-assisted navigation in which an apparatus utilizes stereotactic cameras to track instruments in 3D space. This is then overlayed with a computed tomography (CT) or MRI image to generate a map that can guide instrumentation.[33] In a single-center study comparing navigation with conventional fluoroscopy for the ATP, there was no difference in operative time, estimated blood loss, length of hospitalization, or perioperative complications. However, there was significantly less radiation in the navigation group (which a single CT image) than in the fluoroscopy group (which used - several X-rays). However, the authors noted that the opposite may be true at centers where fewer fluoroscopy images are captured.[35]

Robotics

The accuracy of surgical procedures can be further enhanced using robotic assistance. Robotic assistance has been shown to place pedicle screws with improved accuracy and yield decreased average length of stay for patients.[36] Regarding anterolateral approaches, studies have investigated the utility of robots for percutaneous PSF in the lateral position while performing single-position LLIF and ATP. Single-position LLIF and ATP eliminate the need for patient repositioning, reducing the risk of injury and operative time.[37,38] However, percutaneous PSF is difficult in the lateral position. Some initial studies showed that robotic assistance increased the safety and accuracy of percutaneous PSF in this position.[39,40] However, a systematic review by Patel and colleagues found no significant difference in pedicle screw placement accuracy with robotic assistance compared to conventional techniques.[39] Aside from pedicle screw fixation, there is limited literature on using robots for anterior, lateral, and oblique approaches to the spine. Case series have been published reporting fusion rates, complication rates, and clinical and radiographical outcomes for robot-assisted ALIFs that are comparable to the mini-open ALIF.[41,42] Despite the feasibility and safety of robot-assisted ALIF, large-scale studies need to be conducted before widespread adoption. Furthermore, small-scale studies need to be undertaken to evaluate robot-assisted approaches to the LLIF and ATP.

Spatial Computing

Despite the promise of robotics for surgery, there exist multiple limitations, including a lack of tactile feedback, misplacement of pedicle screws due to skiving, and the exorbitant cost of purchasing a robot (often over $1,000,000).[43] In addition, other advancements, such as computer-assisted navigation, also pose challenges, including interruption of the surgeon's workflow due to line of sight disturbances and attention displacement.[44]

Spatial computing (SC) devices seek to bypass the challenges of robotics and computer-assisted navigation. One subtype of SC is augmented reality (AR) which, in the spine, generally works by overlaying 3D reconstructions of the spine on the surgeon's view, generating a "see-through effect."[45] Although there is limited literature on the effectiveness of AR devices for spine surgery, a recent dual-center prospective study examined the use of AR devices for pedicle screw placement supplementing ALIFs and LLIFs. The study found that the accuracy of screw placement with AR was comparable to screw placement with a robot. Additionally, the intraoperative screw revision rate was 0.49%, and no instrumentation was revised postoperatively.[46]

Virtual reality (VR) is another subtype of SC. In VR, the surgeon's entire environment is computer-generated.[45] VR allows the surgeon to assess musculature, ligaments, abdominal viscera, and neurovasculature preoperatively and plan the trajectory appropriately. Postoperatively, VR allows surgeons to assess the placement of instrumentation and changes in radiographic parameters.[47] However, a drawback of VR is that it cannot be used intraoperatively.[47] Additionally, an obstacle common to AR and VR use is the physical discomfort (eg, vertigo and headaches) associated with head-mounted devices.[45] Moreover, as with AR, there is limited literature on the effectiveness of VR.

Machine Learning

Machine learning is increasingly being used to optimize outcomes, particularly in the field of surgery. Prior to surgical procedures, machine learning can assist in conducting a comprehensive risk-benefit analysis. By analyzing large volumes of data from similar previous cases, these algorithms can provide accurate predictions regarding patient-specific outcomes, such as the potential complications and expected improvement in quality of life measures. Such data-driven insights can significantly enhance point-of-care decision-making and facilitate tailored surgical planning.[48] For instance, Agarwal and colleagues used machine learning to predict surgical outcomes based on body mass index for patients with preoperative obesity and lumbar spondylolisthesis.[49] Additionally, Shahrestani and colleagues utilized machine learning to predict the postoperative length of stay in patients who underwent decompression for spondylolisthesis based on comorbidities, intraoperative factors, and socioeconomic attributes.[50] Moreover, machine learning has begun to find its place in surgical navigation systems through the integration of AR by generating patient-specific 3D reconstructions of the spine based on CT or MRI scans.[51] Overall, the incorporation of machine learning into surgical practice holds great promise for improving patient outcomes and the overall efficiency of health care delivery.

LIMITATIONS

The technologies such as robotics, extended reality, and machine learning covered in this article are still in the early stages of clinical use. The current body of literature on these technologies is relatively limited; as such, additional robust, large-scale studies on these topics are required. Therefore, it is difficult to draw definitive conclusions about their effectiveness and utility based solely on the available literature. Even more so, given the rapid pace of advancements in spinal surgery, the information contained in this article may soon become outdated.

SUMMARY

The field of spine surgery has seen remarkable progress over the centuries, with unprecedented advancements in the last few decades. The evolution of anterolateral approaches to the spine has greatly expanded the surgical armamentarium available for treating spinal pathologies. Modern technological innovations, such as interbody cages, intraoperative image guidance, robotics, augmented reality, and machine learning, have significantly improved surgical outcomes and patient safety. Despite these achievements, challenges and limitations persist, presenting opportunities for further research and development. The future of spine surgery lies in harnessing the full potential of these advancements, addressing the existing limitations, and continuing the trend of patient-centered, outcome-focused innovation. As the understanding of the spine and its pathologies grows and technology advances, the emergence of even more effective and minimally invasive techniques is anticipated.

CLINICS CARE POINTS

- Hyperlordotic cages coupled with the anterior or lateral approaches can yield comparable results to posterior subtraction osteotomy for spinal deformity without the associated morbidity.
- When feasible, computer-assisted navigation should be considered for pedicle screw placement to improve accuracy.
- Robotics, augmented reality, and machine learning for spine surgery are nascent technologies that still require large-scale studies before broader adoption.

STATEMENTS AND DECLARATIONS

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REFERENCES

1. Knoeller SM, Seifried C. Historical Perspective: History of Spinal Surgery. Spine 2000;25(21):2838.
2. Smith AG. ARTICLE IX.–Account of a Case in which Portions of Three Dorsal Vertebrae were removed for the relief of Paralysis from Fracture, with partial success. The North American Medical and Surgical Journal (1826-1831) 1829;8(15):94.
3. Matur AV, Mejia-Munne JC, Plummer ZJ, et al. The History of Anterior and Lateral Approaches to the Lumbar Spine. World Neurosurgery 2020;144:213–21.
4. Harmon Paul H. Anterior extraperitoneal lumbar disk excision and vertebral body fusion. Clin Orthop Relat Res 1960;(18):169–98.
5. Mayer MH. A New Microsurgical Technique for Minimally Invasive Anterior Lumbar Interbody Fusion1996 Scientific Program Committee. Spine 1997;22(6):691.
6. Brau SA. Mini-open approach to the spine for anterior lumbar interbody fusion: description of the procedure, results and complications. Spine J 2002;2(3):216–23.
7. Rao PJ, Phan K, Giang G, et al. Subsidence following anterior lumbar interbody fusion (ALIF): a prospective study. Journal of Spine Surgery 2017;3(2):168–75.
8. Udby PM, Bech-Azeddine R. Clinical outcome of stand-alone ALIF compared to posterior instrumentation for degenerative disc disease: A pilot study and a literature review. Clin Neurol Neurosurg 2015;133:64–9.
9. Agarwal N, White MD, Zhang X, et al. Impact of endplate-implant area mismatch on rates and grades of subsidence following stand-alone lateral lumbar interbody fusion: an analysis of 623 levels. J Neurosurg Spine 2020;33(1):12–6.
10. Marchi L, Abdala N, Oliveira L, et al. Radiographic and clinical evaluation of cage subsidence after stand-alone lateral interbody fusion: Clinical article. J Neurosurg Spine 2013;19(1):110–8.
11. Mobbs RJ, Phan K, Malham G, et al. Lumbar interbody fusion: techniques, indications and comparison of interbody fusion options including PLIF, TLIF, MI-TLIF, OLIF/ATP, LLIF and ALIF. J Spine Surg 2015;1(1):2–18.
12. Pawar A, Hughes A, Girardi F, et al. Lateral Lumbar Interbody Fusion. Asian Spine J 2015;9(6):978–83.
13. Yang H, Liu J, Hai Y, et al. What Are the Benefits of Lateral Lumbar Interbody Fusion on the Treatment of Adult Spinal Deformity: A Systematic Review and Meta-Analysis Deformity. Global Spine J 2023;13(1):172–87.
14. Nayar G, Roy S, Lutfi W, et al. Incidence of adjacent-segment surgery following stand-alone lateral lumbar interbody fusion. J Neurosurg Spine 2021;35(3):270–4.
15. Woods KRM, Billys JB, Hynes RA. Technical description of oblique lateral interbody fusion at L1–L5 (OLIF25) and at L5–S1 (OLIF51) and evaluation of complication and fusion rates. Spine J 2017;17(4):545–53.
16. Phan K, Maharaj M, Assem Y, et al. Review of early clinical results and complications associated with oblique lumbar interbody fusion (OLIF). J Clin Neurosci 2016;31:23–9.
17. Silvestre C, Mac-Thiong JM, Hilmi R, et al. Complications and Morbidities of Mini-open Anterior Retroperitoneal Lumbar Interbody Fusion: Oblique Lumbar Interbody Fusion in 179 Patients. Asian Spine J 2012;6(2):89–97.
18. Walker CT, Farber SH, Cole TS, et al. Complications for minimally invasive lateral interbody arthrodesis: a systematic review and meta-analysis comparing prepsoas and transpsoas approaches. J Neurosurg Spine 2019;30(4):446–60.
19. Zhu L, Wang JW, Zhang L, et al. Outcomes of Oblique Lateral Interbody Fusion for Adult Spinal Deformity: A Systematic Review and Meta-Analysis. Global Spine J 2022;12(1):142–54.
20. Molloy S, Butler JS, Benton A, et al. A new extensile anterolateral retroperitoneal approach for lumbar interbody fusion from L1 to S1: a prospective series with clinical outcomes. Spine J 2016;16(6):786–91.
21. Zairi F, Sunna TP, Westwick HJ, et al. Mini-open oblique lumbar interbody fusion (OLIF) approach for multi-level discectomy and fusion involving L5–S1:

Preliminary experience. J Orthop Traumatol: Surgery & Research 2017;103(2):295–9.
22. Godolias P, Tataryn ZL, Plümer J, et al. Cage subsidence—A multifactorial matter. Orthopädie 2023. https://doi.org/10.1007/s00132-023-04363-9.
23. Seaman S, Kerezoudis P, Bydon M, et al. Titanium vs. polyetheretherketone (PEEK) interbody fusion: Meta-analysis and review of the literature. J Clin Neurosci 2017;44:23–9.
24. Tan JH, Cheong CK, Hey HWD. Titanium (Ti) cages may be superior to polyetheretherketone (PEEK) cages in lumbar interbody fusion: a systematic review and meta-analysis of clinical and radiological outcomes of spinal interbody fusions using Ti versus PEEK cages. Eur Spine J 2021;30(5):1285–95.
25. Alan N, Deng H, Muthiah N, et al. Graft subsidence and reoperation after lateral lumbar interbody fusion: a propensity score-matched and cost analysis of polyetheretherketone versus 3D-printed porous titanium interbodies. J Neurosurg Spine 2023;1–9.
26. Alan N, Vodovotz L, Muthiah N, et al. Subsidence after lateral lumbar interbody fusion using a 3D-printed porous titanium interbody cage: single-institution case series. J Neurosurg Spine 2022; 37(5):663–9.
27. El-Hajje A, Kolos EC, Wang JK, et al. Physical and mechanical characterisation of 3D-printed porous titanium for biomedical applications. J Mater Sci Mater Med 2014;25(11):2471–80.
28. Fernandes RJR, Gee A, Kanawati AJ, et al. Biomechanical Comparison of Subsidence Between Patient-Specific and Non-Patient-Specific Lumbar Interbody Fusion Cages. Global Spine Journal 2022. https://doi.org/10.1177/21925682221134913. 21925682221134910.
29. Wallace N, Schaffer NE, Aleem IS, et al. 3D-printed Patient-specific Spine Implants: A Systematic Review. Clinical Spine Surgery: A Spine Publication. 2020;33(10):400–7.
30. Saville PA, Kadam AB, Smith HE, et al. Anterior hyperlordotic cages: early experience and radiographic results. J Neurosurg Spine 2016;25(6): 713–9.
31. Kadam A, Wigner N, Saville P, et al. Overpowering posterior lumbar instrumentation and fusion with hyperlordotic anterior lumbar interbody cages followed by posterior revision: a preliminary feasibility study. J Neurosurg Spine 2017;27(6):650–60.
32. Blizzard DJ, Thomas JA. MIS Single-position Lateral and Oblique Lateral Lumbar Interbody Fusion and Bilateral Pedicle Screw Fixation. Spine 2018;43(6): 440–6.
33. Rawicki N, Dowdell JE, Sandhu HS. Current state of navigation in spine surgery. Ann Transl Med 2021; 9(1):85.
34. Mason A, Paulsen R, Babuska JM, et al. The accuracy of pedicle screw placement using intraoperative image guidance systems: A systematic review. J Neurosurg Spine 2014;20(2):196–203.
35. Zhang YH, White I, Potts E, et al. Comparison Perioperative Factors During Minimally Invasive Pre-Psoas Lateral Interbody Fusion of the Lumbar Spine Using Either Navigation or Conventional Fluoroscopy. Global Spine J 2017;7(7):657–63.
36. Momin AA, Steinmetz MP. Evolution of Minimally Invasive Lumbar Spine Surgery. World Neurosurgery 2020;140:622–6.
37. Blizzard DJ, Thomas JA. MIS Single-position Lateral and Oblique Lateral Lumbar Interbody Fusion and Bilateral Pedicle Screw Fixation: Feasibility and Perioperative Results. Spine 2018;43(6):440.
38. Ziino C, Konopka JA, Ajiboye RM, et al. Single position versus lateral-then-prone positioning for lateral interbody fusion and pedicle screw fixation. J Spine Surg 2018;4(4):717–24.
39. Patel NA, Kuo CC, Pennington Z, et al. Robot-assisted percutaneous pedicle screw placement accuracy compared with alternative guidance in lateral single-position surgery: a systematic review and meta-analysis. J Neurosurg Spine 2023;1(aop):1–9.
40. Diaz-Aguilar LD, Shah V, Himstead A, et al. Simultaneous Robotic Single-Position Surgery (SR-SPS) with Oblique Lumbar Interbody Fusion: A Case Series. World Neurosurgery 2021;151:e1036–43.
41. Lee Z, Lee JYK, Welch WC, et al. Technique and surgical outcomes of robot-assisted anterior lumbar interbody fusion. J Robotic Surg 2013;7(2):177–85.
42. Beutler WJ, Peppelman WCJ, DiMarco LA. The da Vinci Robotic Surgical Assisted Anterior Lumbar Interbody Fusion: Technical Development and Case Report. Spine 2013;38(4):356.
43. D'Souza M, Gendreau J, Feng A, et al. Robotic-Assisted Spine Surgery: History, Efficacy, Cost, And Future Trends. RSRR 2019;6:9–23.
44. Nottmeier EW. A review of image-guided spinal surgery. J Neurosurg Sci 2012;56(1):35–47.
45. Yoo JS, Patel DS, Hrynewycz NM, et al. The utility of virtual reality and augmented reality in spine surgery. Ann Transl Med 2019;7(Suppl 5):S171.
46. Butler AJ, Colman MW, Lynch J, et al. Augmented reality in minimally invasive spine surgery: early efficiency and complications of percutaneous pedicle screw instrumentation. Spine J 2023;23(1):27–33.
47. Elsayed GA, Lavadi RS, Pugazenthi S, et al. Spatial Computing for preoperative planning and postoperative evaluation of single-position lateral approaches in spinal revision surgery. J Craniovertebral Junction Spine 2023;14(2):208–11.
48. Scheer JK, Smith JS, Schwab F, et al. Development of a preoperative predictive model for major complications following adult spinal deformity surgery. J Neurosurg Spine 2017;26(6):736–43.
49. Agarwal N, Aabedi AA, Chan AK, et al. Leveraging machine learning to ascertain the implications of

preoperative body mass index on surgical outcomes for 282 patients with preoperative obesity and lumbar spondylolisthesis in the Quality Outcomes Database. J Neurosurg Spine 2022;38(2):182–91.
50. Shahrestani S, Chan AK, Bisson EF, et al. Developing nonlinear k-nearest neighbors classification algorithms to identify patients at high risk of increased length of hospital stay following spine surgery. Neurosurg Focus 2023;54(6):E7.
51. Overley SC, Cho SK, Mehta AI, et al. Navigation and Robotics in Spinal Surgery: Where Are We Now? Neurosurgery 2017;80(3S):S86.