

Using Novel Segmentation Technology to Define Safe Corridors for Minimally Invasive Posterior Lumbar Interbody Fusion

Troy Q. Tabarestani, BA ¹, David S. Salven, BS, MS ¹, David A. W. Sykes, AB ¹, Anas M. Bardeesi, MBBS², Alyssa M. Bartlett, BS, MPH ³, Timothy Y. Wang, MD⁴, Mounica R. Paturu, MD ⁵, Christopher F. Dibble, MD, PhD⁶, Christopher I. Shaffrey, MD ⁷, Wilson Z. Ray, MD⁸, John H. Chi, MD, MPH⁹, Walter F. Wiggins, MD, PhD ¹⁰, Muhammad M. Abd-El-Barr, MD, PhD ¹¹

¹Department of Neurosurgery, Duke University School of Medicine, Durham, North Carolina, USA; ²Department of Neurosurgery, Duke University Hospital, Durham, North Carolina, USA; ³Department of Neurosurgery, Washington University, St. Louis, Missouri, USA; ⁴Department of Neurosurgery, Brigham and Women's Hospital, Boston, Massachusetts, USA; ⁵Department of Radiology, Duke University Hospital, Durham, North Carolina, USA

CNS 2023 Annual Meeting (Washington, DC, USA)—Poster Presentation on September 12, 2023 titled “Novel Segmentation Technology to Define a Safe Corridor for Transfacet Percutaneous Lumbar Interbody Fusion.”

Correspondence: Troy Q. Tabarestani, BA, Department of Neurosurgery, Duke University School of Medicine, DUMC 2927, 40 Duke Medicine Circle, Durham, NC 27710, USA. Email: tqt5@duke.edu

Twitter: @QTabarestani; Muhammad M. Abd-El-Barr, MD, PhD, Department of Neurosurgery, Duke University Hospital, 40 Duke Medicine Cir, Durham, NC 27710, USA. Email: muhammad.abd.el.barr@duke.edu Twitter: @abdelbarrspine

Received, October 12, 2023; **Accepted,** November 15, 2023; **Published Online,** December 27, 2023.

© Congress of Neurological Surgeons 2023. All rights reserved.

BACKGROUND AND OBJECTIVES: There has been a rise in minimally invasive methods to access the intervertebral disk space posteriorly given their decreased tissue destruction, lower blood loss, and earlier return to work. Two such options include the percutaneous lumbar interbody fusion through the Kambin triangle and the endoscopic transfacet approach. However, without accurate preoperative visualization, these approaches carry risks of damaging surrounding structures, especially the nerve roots. Using novel segmentation technology, our goal was to analyze the anatomic borders and relative sizes of the safe triangle, trans-Kambin, and the transfacet corridors to assist surgeons in planning a safe approach and determining cannula diameters.

METHODS: The areas of the safe triangle, Kambin, and transfacet corridors were measured using commercially available software (BrainLab, Munich, Germany). For each approach, the exiting nerve root, traversing nerve roots, theca, disk, and vertebrae were manually segmented on 3-dimensional T2-SPACE magnetic resonance imaging using a region-growing algorithm. The triangles' borders were delineated ensuring no overlap between the area and the nerves.

RESULTS: A total of 11 patients (65.4 ± 12.5 years, 33.3% female) were retrospectively reviewed. The Kambin, safe, and transfacet corridors were measured bilaterally at the operative level. The mean area ($124.1 \pm 19.7 \text{ mm}^2$ vs $83.0 \pm 11.7 \text{ mm}^2$ vs $49.5 \pm 11.4 \text{ mm}^2$) and maximum permissible cannula diameter ($9.9 \pm 0.7 \text{ mm}$ vs $6.8 \pm 0.5 \text{ mm}$ vs $6.05 \pm 0.7 \text{ mm}$) for the transfacet triangles were significantly larger than Kambin and the traditional safe triangles, respectively ($P < .001$).

CONCLUSION: We identified, in 3-dimensional, the borders for the transfacet corridor: the traversing nerve root extending inferiorly until the caudal pedicle, the theca medially, and the exiting nerve root superiorly. These results illustrate the utility of preoperatively segmenting anatomic landmarks, specifically the nerve roots, to help guide decision-making when selecting the optimal operative approach.

KEY WORDS: Image fusion, Kambin triangle, Lumbar fusion, Safe triangle, Segmentation, Transfacet

Operative Neurosurgery 00:1–9, 2023

<https://doi.org/10.1227/ons.0000000000001046>

Over the past decade, the utility of anatomic segmentation, whether automatic, manual, or machine learning based, has demonstrated unparalleled potential for application in

the field of neurosurgery ranging from its diagnostic to its intraoperative usage. Widely applicable, segmentation research has been used to characterize trigeminal nerves, odontogenic cysts,

ABBREVIATIONS: ENR, exiting nerve root; IAP, inferior articulating process; SAP, superior articulating process; TLIF, transforaminal lumbar interbody fusion; TNR, traversing nerve root.

thalamic nuclei, brain tumors, and cerebral arteries.¹⁻⁷ Most notably, there has been a surge of research interest surrounding deep segmentation for brain tumors that has driven significant technological advancement and incorporation of segmentation within the tumor and vascular fields. For example, preoperative planning in conjunction with 3-dimensional (3D) segmentation has allowed surgeons to better visualize the topographical relation of tumors to important vessels and improve the delineation between normal and abnormal tissues.^{8,9} The overarching goal of this research is to augment certain elements of surgical planning and decision-making with the hope of benefiting both the surgeon and patients alike.¹⁰

When examining the landscape of segmentation within spine surgery, there is a clear delineation in the volume of segmentation research and the scope of its usage intraoperatively. Most focus has been placed on vertebral body segmentation and pedicle screw placement, with studies showing that deep learning can assist both the preoperative planning and intraoperative autonomous placement of pedicle screws with high levels of accuracy.¹¹ This technology has been already used to help place pedicle screws with the correct length, diameter, and angulation for correction surgery, all calculated automatically from patient data.^{12,13} For preoperative planning, there have been recent advancements in generating 3D-printed models for interbody cages based on segmented images of a patient's vertebral body endplates to reduce cage fitting time and improve radiographic correction parameters.^{14,15} As spine surgery has advanced in conjunction with imaging modalities, minimally invasive procedures have also grown in popularity for their improved outcomes, smaller incisions, and decreased surgical footprint. Namely, more minimally invasive methods of lumbar interbody fusion continue to expand as surgeons are being trained in the various approaches.¹⁶⁻¹⁹

One of the most common techniques for interbody fusion is the transforaminal lumbar interbody fusion (TLIF). There are many nuances around this technique including the increased use of tubular retractors or endoscopic ports to decrease tissue, nerve, and muscle retraction. In essence, there are 3 main pathways to access the intervertebral disk during a TLIF (Figure 1).

1. Hemilaminectomy, medial facetectomy, or the traditional pathway: This requires retraction on the exiting nerve root (ENR) and diskectomy through the safe triangle.^{20,21}
2. Transfacet: This uses the natural pathway between the superior articulating process (SAP) and the inferior articulating process (IAP) to enter the disk.^{22,23}
3. Trans-Kambin: This uses the previously described boundaries of the Kambin triangle to enter the disk.²⁴ This corridor has been defined by the ENR, SAP, and the superior endplate of the caudal vertebral body.

To date, the choice of which pathway to use has been mostly due to surgeon preference and comfort. In addition, each method introduces a risk for postoperative ENR injury depending on the distance between the nerve and the facet joint, with rates having been reported of up to 45% in the literature.²⁵ Studies have also speculated

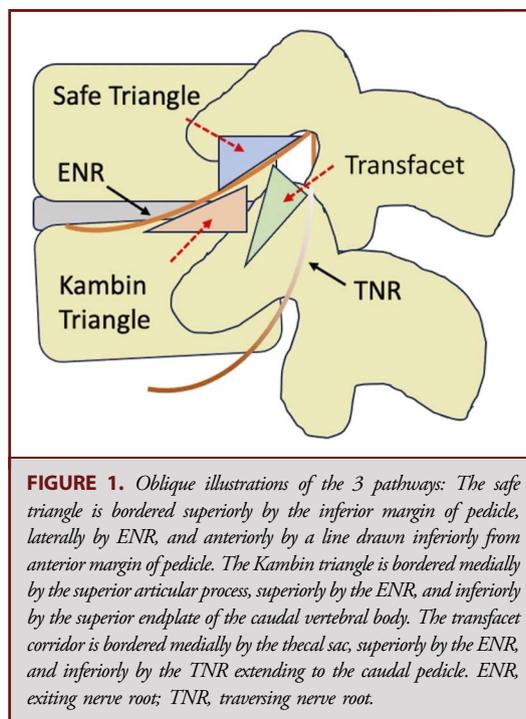


FIGURE 1. Oblique illustrations of the 3 pathways: The safe triangle is bordered superiorly by the inferior margin of pedicle, laterally by ENR, and anteriorly by a line drawn inferiorly from anterior margin of pedicle. The Kambin triangle is bordered medially by the superior articular process, superiorly by the ENR, and inferiorly by the superior endplate of the caudal vertebral body. The transfacet corridor is bordered medially by the thecal sac, superiorly by the ENR, and inferiorly by the TNR extending to the caudal pedicle. ENR, exiting nerve root; TNR, traversing nerve root.

the safety of these minimally invasive procedures given the lack of intraoperative visualization and apparent higher rates of ENR injuries when compared with their open counterparts.²⁶ With the advent of new segmentation software, it is now possible to know the exact dimensions of these working corridors and hence preoperatively make an assessment of the safety of each depending on the desired interbody dimensions, cannula sizes, and proximity to key structures.^{27,28} Our study's goals were to (1) illustrate the ability of using segmentation technology to define these 3 key anatomic corridors in 3D, (2) clearly define the borders of the transfacet approach, and (3) compare the surgically relevant dimensions of the safe triangle, Kambin triangle, and the transfacet corridor.

METHODS

Study Design

The authors performed a single-center retrospective review of patients being evaluated for low back pain at a major academic research institution from August 2021 to August 2023. Informed consent was obtained before each procedure. Patient permission to publish deidentified data was not necessary because this study fell under the university's Institutional Review Board's guidelines for "exempt" patient research. Data were collected by electronic health record review.

Kambin Triangle With ENR Segmentation

3D isotropic T2-weighted magnetic resonance imaging (MRI) sequences acquired at 1-mm slice thickness were used during the preoperative planning

phase. First, the individual ENRs were identified in the axial and sagittal planes with the *Smartbrush* feature in BrainLab (BrainLab) completing segmentation based on a region-growing algorithm. Each ENR was “drawn out” bilaterally starting from where they became individually visible in the thecal sac to as far lateral as seen clearly on the image (Figure 2). In addition, the caudal/rostral vertebrae, TNR, thecal sac, and disk were all segmented to obtain a clear 3D view of the operative level. To maximize the cross-sectional area of the triangle, the *Align* tool was used to manipulate the images in each plane (Figure 2). BrainLab then created a 3D model of the segmented objects to help visualize their spatial proximity to each other (Figure 3). A board-certified neuroradiologist and neurosurgeon confirmed each segmentation. We used an approximation of the largest triangle that contained every part of the outlined space and calculated the area using the formula: $0.5 \times \text{base} \times \text{height}$.²⁷ For cannula diameter, we drew the largest circle that can be confined to the Kambin triangle and measured its diameter. During surgery, MRI scans were fused with an intraoperative computed tomography (CT) scan to help plan the trajectory into the disk space as described in our previous work^{28,29} (Figure 4).

Transfacet Corridor Segmentation

Key anatomy was segmented in the same way as described above. The *Align* feature was used to orient the images based on a trajectory through the facet joint between the SAP and IAP into the disk space (Figure 5). By segmenting the ENR and TNR, it helped ensure that we were not overlapping the outlined corridor with any parts of the neural anatomy (Figure 6). To measure area and cannula diameters, the same methodology as stated above was used.

Traditional Safe Triangle Segmentation

Key anatomy was segmented in the same way as described above. The *Align* feature was again used to orient the image based on a trajectory lateral to the facet joint to give a clear path toward the neural foramina. Based on previous literature, the roof of the safe triangle was the inferior margin of pedicle, the hypotenuse was the ENR, and anterior border was created by a line drawn inferiorly from anterior boundary of pedicle.³⁰ Because the ENR

had already been segmented, it helped ensure that we were not overlapping the outlined corridor (Figure 3). To measure mean area and maximum cannula diameters, the same methodology as stated above was used.

Statistics

When comparing the 3 different approaches, the 1-way analysis of variance test was used to assess for any significant differences in mean area of cannula diameter size. A Tukey Honestly Significant Difference test was then used to further assess differences between each group. Values are reported as mean \pm standard deviations unless otherwise specified. Significance was determined if $P < .05$ with a confidence interval of 95%.

RESULTS

A total of 11 patients (65.4 ± 12.5 years, 33.3% female, body mass index 27.3 ± 4.3 kg/m²) were included. Each of them underwent a percTLIF through the Kambin triangle with the assistance of pre-operative nerve segmentation and intraoperative MRI/CT fusion. At the 11 operative levels, the Kambin triangle, safe triangle, and the transfacet corridor were outlined in 3D bilaterally, resulting in a total of 22 areas measured for each approach. The most commonly operated level was L4-L5 (8/11), followed by L5-S1 (2/11) and L3-L4 (1/11). The borders for the Kambin and safe triangle approaches are what has been predefined in the literature.³⁰ Of note, no facetectomies were done, thus the medial border for the Kambin triangle was the SAP instead of the thecal sac. To define the transfacet approach, neurosurgeons worked in tandem with our neuroradiologists to identify the ENR above, the TNR inferomedial, the thecal sac medially, and the caudal pedicle laterally. Based on these borders, the areas and cannula diameters for each approach were recorded bilaterally at the operative level for the 11 patients.

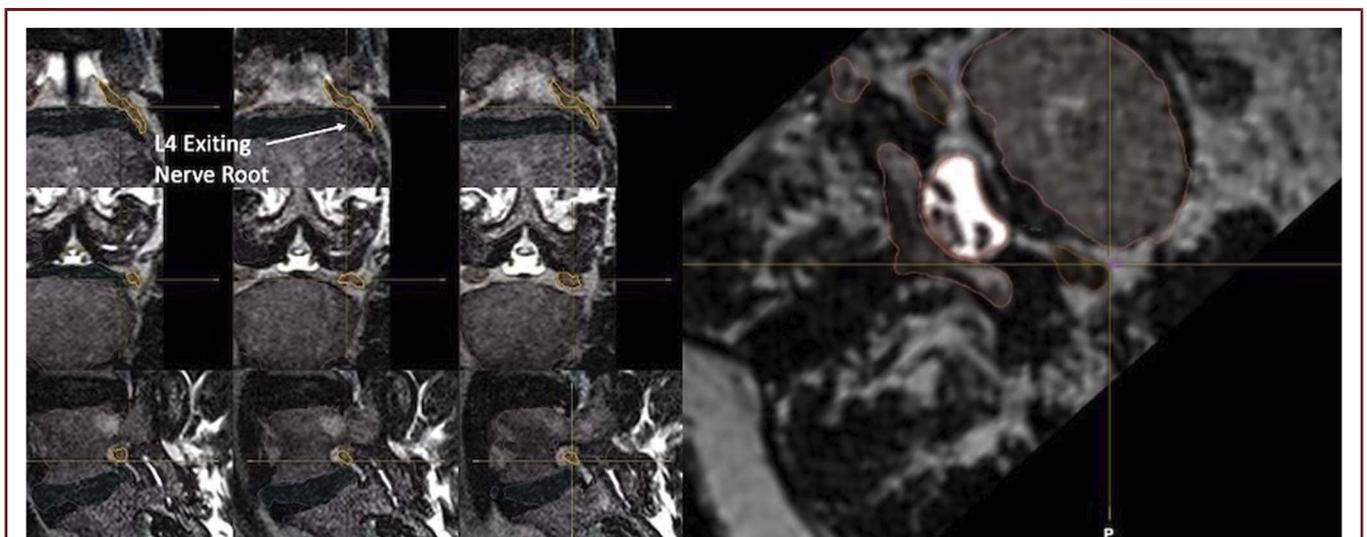
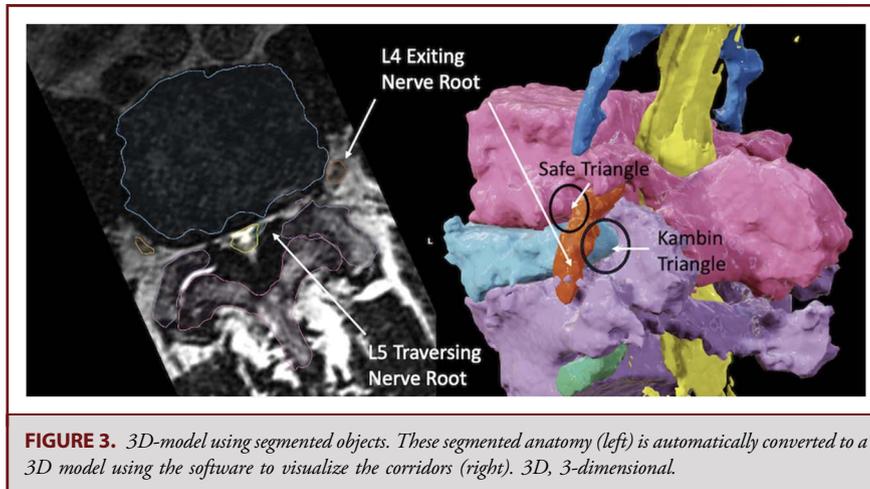
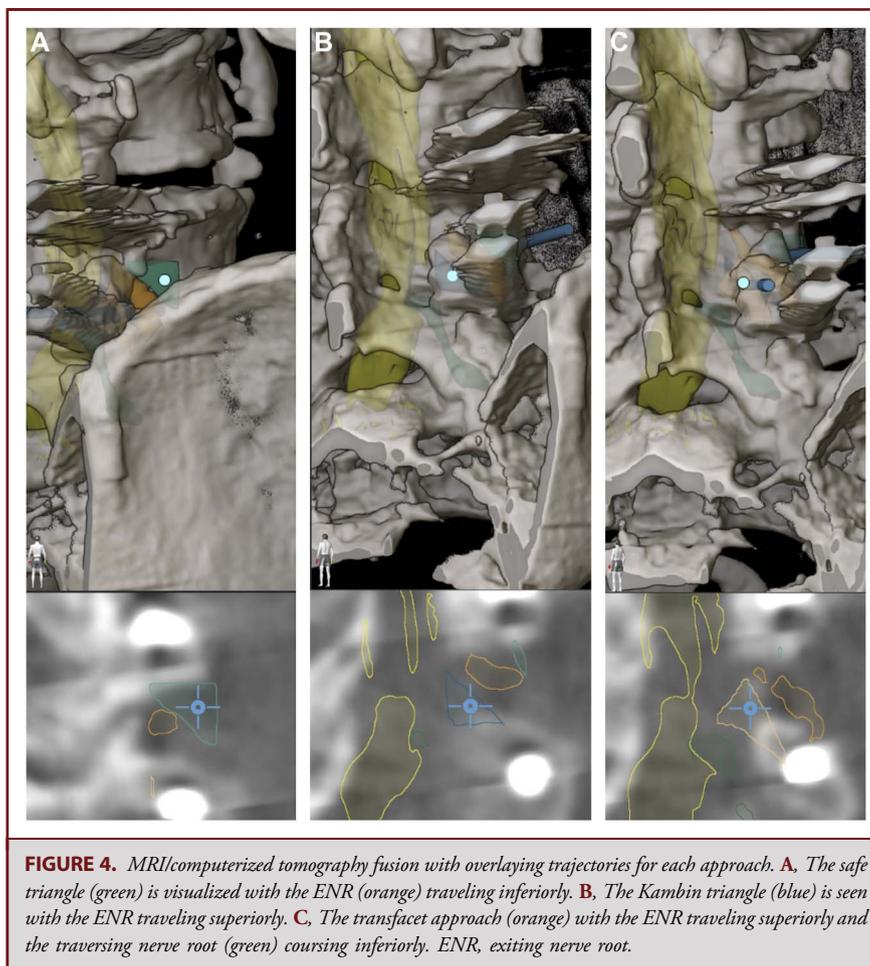


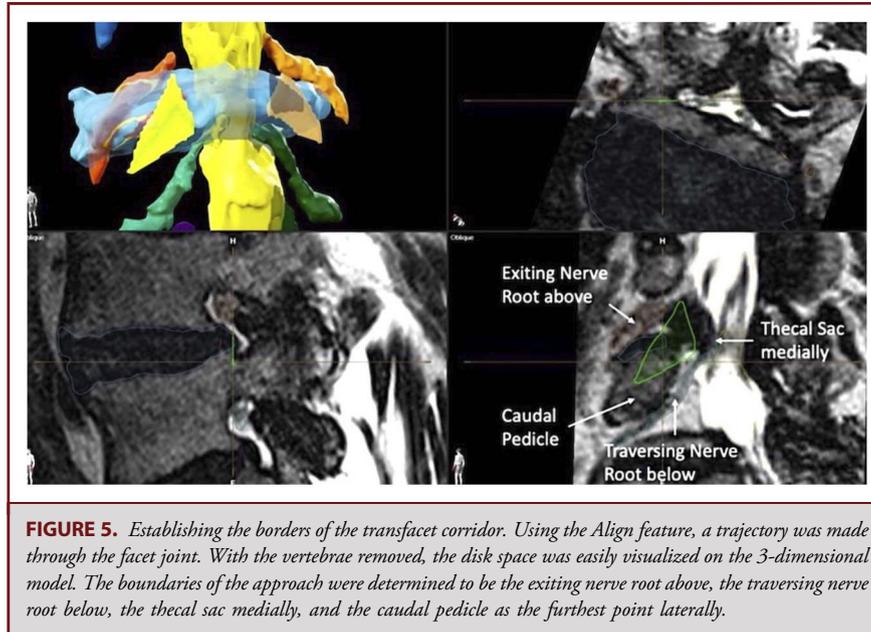
FIGURE 2. Exiting nerve root segmentation. The *Smartbrush* feature with its built-in region growing algorithm was used to segment out the exiting nerve roots bilaterally (left). The *Align* feature was then used to mimic the intraoperative trajectory to maximize the area of each anatomic corridor, with the safe triangle being shown here (right).



As hypothesized, the mean area ($124.1 \pm 19.7 \text{ mm}^2$ vs $83.0 \pm 11.7 \text{ mm}^2$ vs $49.5 \pm 11.4 \text{ mm}^2$) and maximum permissible cannula diameter ($9.9 \pm 0.7 \text{ mm}$ vs $6.8 \pm 0.5 \text{ mm}$ vs $6.05 \pm 0.7 \text{ mm}$) for the transfacet triangles were significantly larger than the Kambin and the

traditional safe triangles, respectively ($P < .001$). In addition, based on Turkey Honestly Significant Difference tests, each group's mean values differed significantly from each pairing, with the safe triangle having the smallest area and maximum cannula diameter (Figure 7).

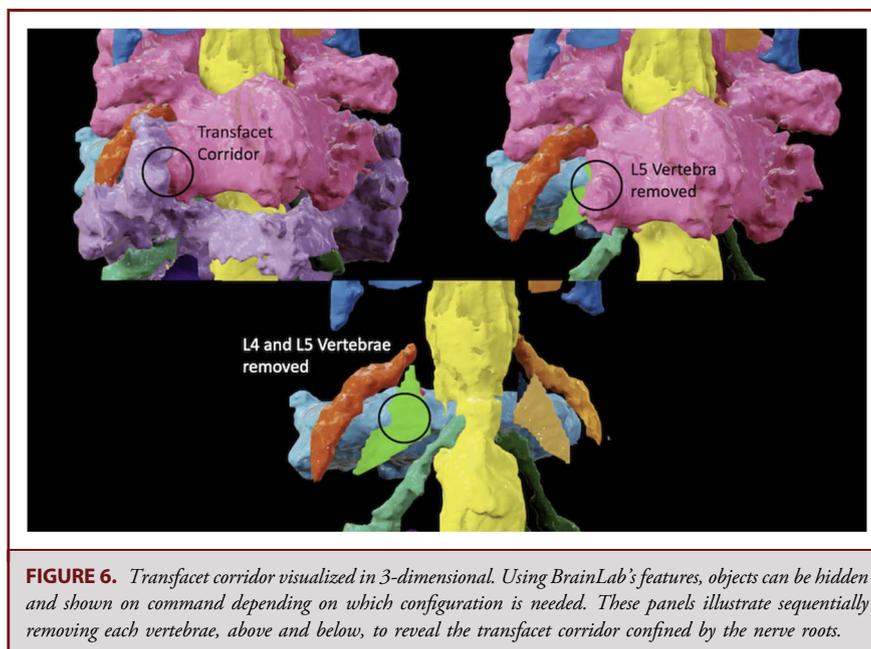




The 95% CI for the mean difference in area between the transfacet and Kambin was 28.1, 53.6; 61.8, 87.3 between the transfacet and safe triangle; and 21.0, 46.5 between the Kambin and safe triangles. The 95% CI for the maximum cannula diameter difference between the transfacet and Kambin was 2.92, 3.24; 3.65, 3.97 between the transfacet and safe triangle; and 0.57, 0.89 between the Kambin and safe triangles. The range of cannula diameters for the safe triangle was 4.7–8.7 mm, 6–8.3 mm for the Kambin triangle, and 8–11 mm for transfacet the approach.

DISCUSSION

With the continuing evolution of imaging modalities, machine-based learning programs, and minimally invasive procedures, segmentation technology will undoubtedly play a growing role in both the preoperative planning and intraoperative execution. Therefore, our study aims to illustrate the feasibility of using commercially available software to help redefine the way surgeons visualize Kambin, safe triangle, and the newer transfacet



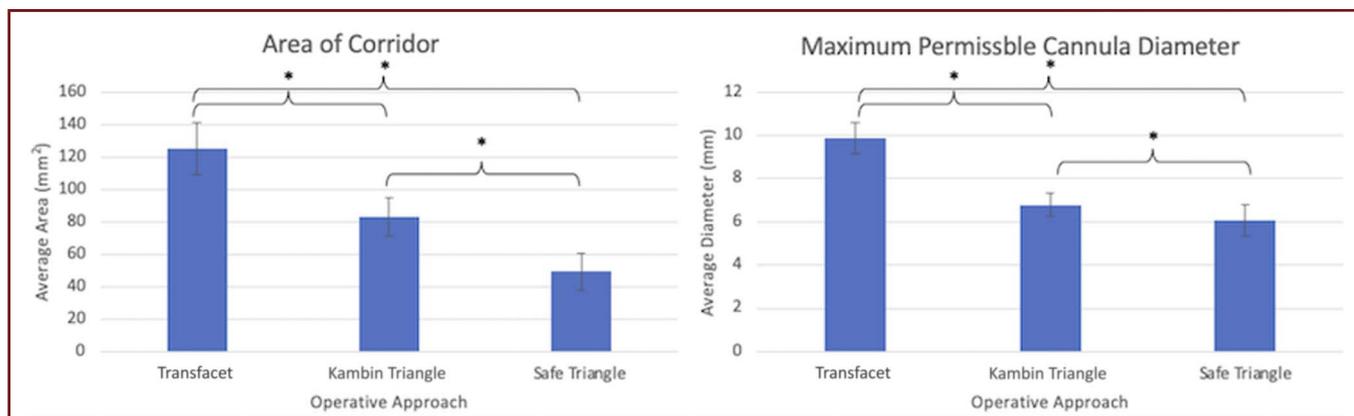


FIGURE 7. Comparing the operative approaches. The transfacet corridor had significantly larger areas compared to both the Kambin and safe triangles (left). Similarly, the transfacet corridor had significantly larger permissible cannula diameters when compared with the other 2 approaches (right). * indicates significance of $P < .05$.

approaches. We show that segmentation not only provides a clear, 3D model to help with trajectory planning but also enables surgeons to decide on the ideal laterality, angle, and type of approach depending on a patient's specific spinal landscape.

Since its coining in 1973, the Kambin triangle has been a point of interest among minimally invasive spine surgeons.^{24,31} It has become one of the most popular approaches for accessing the disk space percutaneously, and for that reason, it has been the target of some initial segmentation work.³² Most notably, Su et al³³ recently reconstructed the Kambin triangle based on automated MRI segmentation using a machine learning protocol. They also used T2-SPACE MRI sequences, given its high-resolution multiplanar reformatted images and thin slice thickness. However, these segments were not reported to have been used in surgery. Taking this technology one step closer to the operating room, Fan et al³⁴ used CT images to reconstruct the Kambin triangle to help plan for epidural spinal injections. The major limitation of their study was the sole use of CT scans, which did not reveal the remaining soft tissues structures as accurately as MRI.³⁵ To build on this previous work, we have implemented both segmentation and MRI/CT fusion to show that when taking nerves and pathology into consideration, the area of the Kambin triangle can decrease substantially leading to more pause for trans-Kambin procedures.²⁷ Given the conglomeration of the current literature, we believe the future of spinal segmentation lies in the field of deep based learning and image fusion; however, it is also important to have these segmentations done manually as a basis for comparison.^{35,36}

Even with segmentation technology, the areas of the Kambin triangle and the safe triangle remain the limiting factor for cage placement in patients needing an interbody fusion.³⁷ Anatomic studies have shown that in more than 400 measured Kambin triangles, only 2% were able to safely accommodate a cannula diameter of 8 mm, which is a common size chosen by surgeons for interbody placement.³⁸ It has also been reported that making 3 or more attempted passes through the Kambin triangle during a TLIF can increase the rate of nerve root irritation.³⁹ For this

reason, the transfacet approach was introduced as an alternative option for patients who require larger cage dimensions or have anatomy which makes accessing the disk space through the other pathways more risky. First described by Khalifeh et al,²³ the proposed transfacet approach was a modification to the standard minimally invasive TLIF for the treatment of lumbar degenerative diseases and low-grade spondylolisthesis. However, its usage in the literature has lagged behind its alternatives. There have been no radiographic or 3D representations published in the literature examining the transfacet approach as we have described in this study. Although the transfacet approach does place the ENR further away from the working corridor, it also brings the TNR into the scope (Figure 8). However, the transfacet approach does boast significant advantages compared with the traditional TLIF. As demonstrated in our work, the maximum permissible diameter size is significantly larger when using the transfacet approach. In cases where more coronal or lordotic change is needed, the transfacet approach may be more appealing than the TLIF because it would allow larger interbody devices to be placed.^{22,23} Of note, the original paper by Khalifeh et al described the transfacet approach as a bony resection of the SAP while leaving the medial IAP, lateral SAP, and rostral pars intact to provide a working corridor that protects the TNR and ENR. Our proposed boundaries extend these borders superiorly to the ENR and inferiorly to the TNR because the use of preoperative segmentation allows surgeons to accurately visualize the full extent of how far they can drill the facet. That being said, although the corridor's borders may be larger than the one described previously, that does not mean the whole area that we outlined needs to be removed when operating. That decision falls on the surgeon based on the size of their preferred interbody cage and the diameter of cannulas needed to place them safely.

Looking forward, the applications of segmentation in spine surgery are vast. Karandikar et al¹¹ provide a summary of the current literature surrounding this technology with a focus on the diagnosis and treatment of various spine disorders ranging from

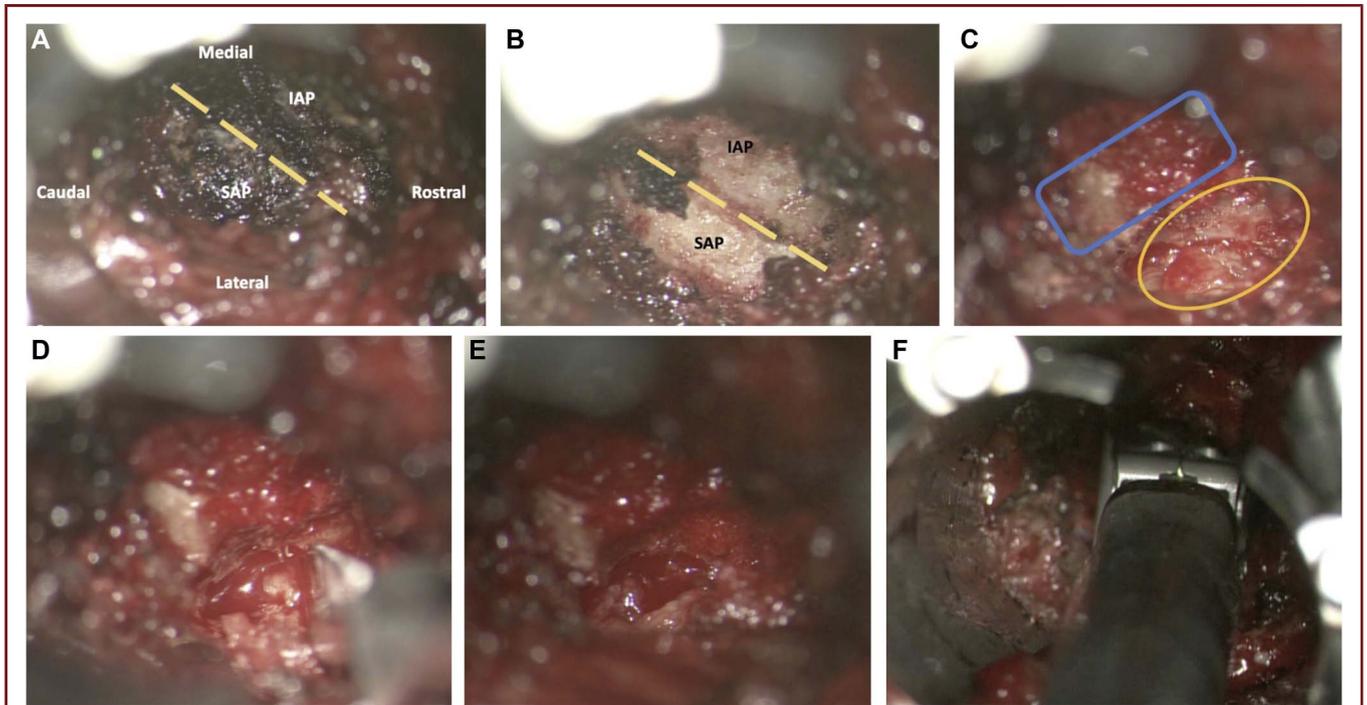


FIGURE 8. Endoscopic view of the transfacet corridor intraoperatively. **A**, L4/5 facet joint after cauterizing and removing the soft tissue and muscle attachment. **B**, After superficial drilling and stripping of the joint capsule with clear demarcation of the joint line (dashed line). **C**, After drilling into the joint and reaching the disk space, the working channel (orange circle) can be seen with the bony boundary laterally (blue rectangle) protecting the theca and traversing nerve root. **D and E**, Initial discectomy. **F**, Introduction of the cage to the disk space. IAP, inferior articulating process; SAP, superior articulating process.

deformity to trauma. Siemionow et al¹² showed that neural networks placed 99% of pedicle screws at Ravi grade 1 and Gertzbein grade A, with no dural breaches noted. Augmented reality headsets can allow real time 3D anatomy to be viewed directly by the surgeon while they look at the patient instead of a monitor.^{13,40-42} Although these technologies are still in their early developmental stages like our nerve segmentation work, it is important to note their potential in aiding surgical accuracy and efficiency. Implementing these various modalities for the other spinal fusion approaches, specifically the lateral interbody techniques, could prove to be useful considering the high rates of postoperative lumbosacral plexus injuries for those procedures.⁴³⁻⁴⁶ For example, if surgeons were able to preoperatively and intraoperatively visualize how the plexus courses from medial to lateral, they would have a better chance of avoiding them during dissection.

Limitations

As with any small retrospective cohort study, there are limitations. Our small patient pool does not illustrate the wide variety of anatomic variances including conjoined nerve roots, pars defects, etc. Larger scale studies using this form of segmentation will be needed before ultimately determining the clinical usefulness of this technique. Similarly, these segmentations were all done manually and confirmed with both a board-certified, fellowship-trained

neurosurgeon and neuroradiologist. However, there is always room for user bias and error when segmenting, outlining, and measuring areas. Future work in automated segmentation may eliminate the source of user error while also reducing the time it takes to segment each level. For the segmentations themselves, MRI does not have the best reliability for identifying bony structures, especially when compared with CT imaging.⁴⁷ For that reason, there is increased risk for user error when determining the limits of the facet joint. One option to avoid this in the future would be to use new technology, like BoneMRI (MRGuidance), which can extrapolate CT data from a preoperative MRI sequence.^{48,49} Practically, the change in anatomy based on patient positioning may be problematic when implementing these segmentations in the operating room. To account for this, we have used commercially available Curvature Correction software (BrainLab) that can adjust for any positional changes after fusing the preoperative MRI with an intraoperative scan.

CONCLUSION

Using commercially available segmentation software, we illustrate the utility of preoperatively segmenting anatomic landmarks, specifically the lumbosacral nerve roots, to help guide clinical decision-making when selecting the optimal operative

approach for each patient. We identified key anatomic borders for the novel transfacet corridor in 3D: the TNR extending until the caudal pedicle as the base, the theca as the height, and the ENR as the hypotenuse. When comparing the safe triangle, Kambin triangle, and transfacet corridors, the area and maximal permissible cannula diameter significantly increased in that order, respectively. To improve time efficiency and cost-effectiveness, we hope that, in the future, manual segmentations can be transitioned to automated models using deep-based machine learning algorithms.

Funding

This study did not receive any funding or financial support.

Disclosures

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article. Christopher I. Shaffrey is a consultant for NuVasive, Medtronic, and SI Bone. Wilson Z. Ray is a consultant for Depuy, Globus, NIH and Corelink. Muhammad M. Abd-El-Barr is a consultant for Spinal Elements, TrackX, and Globus.

REFERENCES

- Bai R, Liu X, Jiang S, Sun H. Deep learning based real-time semantic segmentation of cerebral vessels and cranial nerves in microvascular decompression scenes. *Cells*. 2022;11(11):1830.
- Lin J, Mou L, Yan Q, et al. Automated segmentation of trigeminal nerve and cerebrovasculature in MR-angiography images by deep learning. *Front Neurosci*. 2021;15:744967.
- Bittencourt MA, Sá Mafra PH, Julia RS, et al. Accuracy of computer-aided image analysis in the diagnosis of odontogenic cysts: a systematic review. *Med Oral Patol Oral Cir Bucal*. 2021;26(3):e368-e378.
- Rana M, Modrow D, Keuchel J, et al. Development and evaluation of an automatic tumor segmentation tool: a comparison between automatic, semi-automatic and manual segmentation of mandibular odontogenic cysts and tumors. *J Craniomaxillofac Surg*. 2015;43(3):355-359.
- Su JH, Thomas FT, Kasoff WS, et al. Thalamus Optimized Multi Atlas Segmentation (THOMAS): fast, fully automated segmentation of thalamic nuclei from structural MRI. *Neuroimage*. 2019;194:272-282.
- Zadeh Shirazi A, McDonnell MD, Fornaciari E, et al. A deep convolutional neural network for segmentation of whole-slide pathology images identifies novel tumour cell-perivascular niche interactions that are associated with poor survival in glioblastoma. *Br J Cancer*. 2021;125(3):337-350.
- Meijs M, Pegge SAH, Vos MHE, et al. Cerebral artery and vein segmentation in four-dimensional CT angiography using convolutional neural networks. *Radiol Artif Intell*. 2020;2(4):e190178.
- Hu XP, Tan KK, Levin DN, et al. Three-dimensional magnetic resonance images of the brain: application to neurosurgical planning. *J Neurosurg*. 1990;72(3):433-440.
- Díaz-Pernas FJ, Martínez-Zarzuola M, Antón-Rodríguez M, González-Ortega D. A deep learning approach for brain tumor classification and segmentation using a multiscale convolutional neural network. *Healthcare (Basel)*. 2021;9(2):153.
- Ann CN, Luo N, Pandit AS. Letter: image segmentation in neurosurgery: an undervalued skill set? *Neurosurgery*. 2022;91(1):e31-e32.
- Karandikar P, Massaad E, Hadzipasic M, et al. Machine learning applications of surgical imaging for the diagnosis and treatment of spine disorders: current state of the art. *Neurosurgery*. 2022;90(4):372-382.
- Siemionow KB, Forsthoefel CW, Foy MP, Gawel D, Luciano CJ. Autonomous lumbar spine pedicle screw planning using machine learning: a validation study. *J Craniovertebr Junction Spine*. 2021;12(3):223-227.
- Burström G, Buerger C, Hoppenbrouwers J, et al. Machine learning for automated 3-dimensional segmentation of the spine and suggested placement of pedicle screws based on intraoperative cone-beam computer tomography. *J Neurosurg Spine*. 2019;31(1):147-154.
- McGilvray KC, Easley J, Seim HB, et al. Bony ingrowth potential of 3D-printed porous titanium alloy: a direct comparison of interbody cage materials in an in vivo ovine lumbar fusion model. *Spine J*. 2018;18(7):1250-1260.
- Mcafee PC, Cunningham B, Mullinex K, Dobbs E, Eiserman L. Middle-column gap balancing and middle-column mismatch in spinal reconstructive surgery. *Int J Spine Surg*. 2018;12(2):160-171.
- Reisener MJ, Pumberger M, Shue J, Girardi FP, Hughes AP. Trends in lumbar spinal fusion—a literature review. *J Spine Surg*. 2020;6(4):752-761.
- Smith TG, Joseph SA, Jr., Ditty B, et al. Initial multi-centre clinical experience with prone transpoas lateral interbody fusion: feasibility, perioperative outcomes, and lessons learned. *N Am Spine Soc J*. 2021;6:100056.
- Xu J, Chen E, Wang L, et al. Extreme lateral interbody fusion (XLIF) approach for L5-S1: preliminary experience. *Front Surg*. 2022;9:995662.
- Li R, Li X, Zhou H, Jiang W. Development and application of oblique lumbar interbody fusion. *Orthop Surg*. 2020;12(2):355-365.
- Gil HY, Jeong S, Cho H, et al. Kambin's triangle approach versus traditional safe triangle approach for percutaneous transforaminal epidural adhesiolysis using an inflatable balloon catheter: a pilot study. *J Clin Med*. 2019;8(11):1996.
- Mobbs RJ, Phan K, Malham G, Seex K, Rao PJ. 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.
- Khalifeh JM, Dibble CF, Stecher P, Dorward I, Hawasli AH, Ray WZ. Transfacet minimally invasive transforaminal lumbar interbody fusion with an expandable interbody device—part II: consecutive case series. *Oper Neurosurg*. 2020;19(5):518-529.
- Khalifeh JM, Dibble CF, Stecher P, Dorward I, Hawasli AH, Ray WZ. Transfacet minimally invasive transforaminal lumbar interbody fusion with an expandable interbody device—part I: 2-dimensional operative video and technical report. *Oper Neurosurg*. 2020;19(5):e473-e479.
- Kambin P, Sampson S. Posterolateral percutaneous suction-excision of herniated lumbar intervertebral discs. Report of interim. *Clin Orthop Relat Res*. 1986;207:37-43.
- Corenman DS, Gillard DM, Dorman GJ, Strauch EL. Recombinant human bone morphogenetic protein-2-augmented transforaminal lumbar interbody fusion for the treatment of chronic low back pain secondary to the homogeneous diagnosis of discogenic pain syndrome: two-year outcomes. *Spine*. 2013;38(20):e1269-e1277.
- Epstein NE. More nerve root injuries occur with minimally invasive lumbar surgery: let's tell someone. *Surg Neurol Int*. 2016;7(Suppl 3):s96-s101.
- Tabarestani TQ, Sykes DAW, Kouam RW, et al. Novel approach to percutaneous lumbar surgeries via Kambin's triangle—radiographic and surgical planning analysis with nerve segmentation technology. *World Neurosurg*. 2023;177:e385-e396.
- Tabarestani TQ, Sykes DAW, Maquait G, et al. Novel merging of CT and MRI to allow for safe navigation into Kambin's triangle for percutaneous lumbar interbody fusion-initial case series investigating safety and efficacy. *Oper Neurosurg*. 2023;24(3):331-340.
- Dalton T, Sykes D, Wang TY, et al. Robotic-assisted trajectory into Kambin's triangle during percutaneous transforaminal lumbar interbody fusion-initial case series investigating safety and efficacy. *Oper Neurosurg*. 2021;21(6):400-408.
- Mandell JC, Czuczman GJ, Gaviola GC, Ghazikhanian V, Cho CH. The lumbar neural foramen and transforaminal epidural steroid injections: an anatomic review with key safety considerations in planning the percutaneous approach. *AJR Am J Roentgenol*. 2017;209(1):W26-W35.
- Fanouf AA, Tumialán LM, Wang MY. Kambin's triangle: definition and new classification schema. *J Neurosurg Spine*. 2020;32(3):390-398.
- Tumialán LM, Madhavan K, Godzik J, Wang MY. The history of and controversy over Kambin's triangle: a historical analysis of the lumbar transforaminal corridor for endoscopic and surgical approaches. *World Neurosurg*. 2019;123:402-408.
- Su Z, Liu Z, Wang M, et al. Three-dimensional reconstruction of Kambin's triangle based on automated magnetic resonance image segmentation. *J Orthop Res*. 2022;40(12):2914-2923.
- Fan G, Liu H, Wu Z, et al. Deep learning-based automatic segmentation of lumbosacral nerves on CT for spinal intervention: a translational study. *AJNR Am J Neuroradiol*. 2019;40(6):1074-1081.

35. Tawa N, Rhoda A, Diener I. Accuracy of magnetic resonance imaging in detecting lumbo-sacral nerve root compromise: a systematic literature review. *BMC Musculoskelet Disord.* 2016;17(1):386.
36. Despotović I, Goossens B, Philips W. MRI segmentation of the human brain: challenges, methods, and applications. *Comput Math Methods Med.* 2015;2015:450341.
37. Wang TY, Mehta VA, Gabr M, et al. Percutaneous lumbar interbody fusion with an expandable titanium cage through Kambin's triangle: a case series with initial clinical and radiographic results. *Int J Spine Surg.* 2021;15(6):1133-1141.
38. Pairaiturkar PP, Sudame OS, Pophale CS. Evaluation of dimensions of Kambin's triangle to calculate maximum permissible cannula diameter for percutaneous endoscopic lumbar discectomy: a 3-dimensional magnetic resonance imaging based study. *J Korean Neurosurg Soc.* 2019;62(4):414-421.
39. Abbasi H, Storlie NR, Aya KL. Transfacet oblique lateral lumbar interbody fusion: technical description and early results. *Cureus.* 2022;14(7):e26533.
40. Elmi-Terander A, Burström G, Nachabe R, et al. Pedicle screw placement using augmented reality surgical navigation with intraoperative 3D imaging: a first in-human prospective cohort study. *Spine.* 2019;44(7):517-525.
41. Molina CA, Theodore N, Ahmed AK, et al. Augmented reality-assisted pedicle screw insertion: a cadaveric proof-of-concept study. *J Neurosurg Spine.* 2019;31(1):139-146.
42. Auloge P, Cazzato RL, Ramamurthy N, et al. Augmented reality and artificial intelligence-based navigation during percutaneous vertebroplasty: a pilot randomised clinical trial. *Eur Spine J.* 2020;29(7):1580-1589.
43. Grunert P, Drazin D, Iwanaga J, et al. Injury to the lumbar plexus and its branches after lateral fusion procedures: a cadaver study. *World Neurosurg.* 2017;105:519-525.
44. Pimenta L, Pokorny G, Amaral R, et al. Single-position prone transposas lateral interbody fusion including L4L5: early postoperative outcomes. *World Neurosurg.* 2021;149:e664-e668.
45. Abel NA, Januszewski J, Vivas AC, Uribe JS. Femoral nerve and lumbar plexus injury after minimally invasive lateral retroperitoneal transposas approach: electrodiagnostic prognostic indicators and a roadmap to recovery. *Neurosurg Rev.* 2018;41(2):457-464.
46. Mousafeiris VK, Tsekouras V, Korovessis P. Simultaneous combined major arterial and lumbar plexus injury during primary extra lateral interbody fusion: case report and review of the literature. *Cureus.* 2021;13(3):e13701.
47. Chang G, Boone S, Martel D, et al. MRI assessment of bone structure and microarchitecture. *J Magn Reson Imaging.* 2017;46(2):323-337.
48. Staartjes VE, Seevinck PR, Vandertop WP, van Stralen M, Schröder ML. Magnetic resonance imaging-based synthetic computed tomography of the lumbar spine for surgical planning: a clinical proof-of-concept. *Neurosurg Focus.* 2021;50(1):e13.
49. Davidar AD, Judy BF, Hersh AM, et al. Robot-assisted screw fixation in a cadaver utilizing magnetic resonance imaging-based synthetic computed tomography: toward radiation-free spine surgery. Illustrative case. *J Neurosurg Case Lessons.* 2023; 6(2):CASE23120.

Acknowledgments

We would like to thank the Duke Department of Statistics for their help with the analysis. Author Contribution Statements: Troy Q. Tabarestani contributed to the data collection, manuscript writing, editing, study design, and analysis. David S. Salven contributed to the data collection, manuscript editing, and analysis. David A.W. Sykes contributed to the data collection, manuscript editing, and analysis. Anas M. Bardeesi contributed to the data collection, manuscript editing, and analysis. Alyssa Bartlett contributed to the data collection, manuscript editing, and analysis. Timothy Y. Wang contributed to the manuscript editing and analysis. Mounica R. Paturu contributed to the manuscript editing and analysis. Christopher F. Dibble contributed to the manuscript editing and analysis. Christopher I. Shaffrey contributed the manuscript editing and analysis. Wilson Z. Ray contributed to the manuscript editing and analysis. John H. Chi, contributed to the data collection, manuscript editing, and analysis. Walter F. Wiggins, contributed to the data collection, manuscript editing, study design, and analysis. Muhammad M. Abd-El-Barr contributed to the data collection, manuscript editing, writing, study design, and analysis. All authors approved of the final manuscript before submission.