The Importance of Planning Ahead: A Three-Dimensional Analysis of the Novel Trans-Facet Corridor for Posterior Lumbar Interbody Fusion Using Segmentation Technology

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BACKGROUND: **The rise of minimally invasive lumbar fusions and advanced imaging technologies has facilitated the introduction of novel surgical techniques with the trans-facet approach being one of the newest additions. We aimed to quantify any pathology-driven anatomic changes to the trans-facet corridor, which could thereby alter the ideal laterality of approach to the disc space.**

METHODS: **In this retrospective cohort study, we measured the areas and maximum permissible cannula diameters of the trans-facet corridor using commercially available software (BrainLab, Munich, Germany). Exiting and traversing nerve roots, thecal sacs, and lumbar vertebrae were manually segmented on T2-SPACE magnetic resonance imaging. Spondylolisthesis, disc protrusions, and disc space heights were recorded.**

RESULTS: **A total of 118 trans-facet corridors were segmented bilaterally in 16 patients (65.6 ± 12.1 years, 43.8% female, body mass index 29.2 ± 5.1 kg/m^2). The mean areas at L1–L2, L2–L3, L3–L4, and L4–L5 were 89.4 ± 24.9 mm^2, 124 ± 39.4 mm^2, 123 ± 26.6 mm^2, and 159 ± 42.7 mm^2, respectively. The mean permissible cannula diameter at the same levels were 7.85 ± 1.43 mm, 8.98 ± 1.72 mm, 8.93 ± 1.26 mm, and 10.2 ± 1.94 mm, respectively. Both parameters increased caudally. Higher degrees for spondylolisthesis were associated with larger areas and maximum cannula diameters on regression analysis ($P < 0.001$).**

CONCLUSIONS: **Our results illustrate that pathology, like spondylolisthesis, can increase the area of the trans-facet corridor. By understanding this effect, surgeons can better decide on the optimal approach to the disc while taking into consideration a patient's unique anatomy.**

INTRODUCTION

The overlap of advanced preoperative planning technologies, endoscopic techniques, and the general shift toward less invasive procedures has played a key role in the investigation of operative lumbar spinal corridors. In parallel, as the population ages, the resultant higher incidence of concomitant comorbidities and the inability of a greater number of patients to safely tolerate general anesthesia for extended periods causes significant challenges in the surgical management of symptomatic

Key words
- Endoscopic
- Exiting nerve root
- Interbody fusion
- Minimally invasive
- Percutaneous
- Segmentation
- Trans-facet

Abbreviations and Acronyms

3D: Three-dimensional
ADH: Anterior disc height
IAP: Inferior articular process
MIS-TLIF: Minimally invasive transforaminal lumbar interbody fusion
MRI: Magnetic resonance imaging
PDH: Posterior disc height
percLIF: Percutaneous lumbar interbody fusion
SAP: Superior articular process
TF-LIF: Trans-facet corridor lumbar interbody fusion

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lumbar spine patients.[1-4] For these reasons, recently minimally invasive surgery (MIS) approaches to lumbar fusion are being compared to their open counterparts more frequently. Several large studies have revealed MIS results in decreased blood loss, shorter length of stay, and shorter operative time while maintaining a commendable safety profile and outcomes.[5-7] Of the MIS approaches, the traditional minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) and the trans-Kambin percutaneous lumbar interbody fusion (percLIF) have been the most well described.[8-10] Most recently, the trans-facet corridor lumbar interbody fusion (TF-LIF) has garnered increased attention.[11-13]

The cornerstone MIS-TLIF achieves definitive correction by way of a hemilaminectomy and medial facetectomy to access the disc space for ultimate cage placement. Notably, this technique requires retraction of the exiting nerve root to access the disc via the "safe triangle."[14,15] Accordingly, to mitigate iatrogenic nerve root injury and further reduce the surgical footprint, the fully endoscopic percutaneous posterolateral approach emerged, eliminating the requirements of neural manipulation and excessive bony work. The percLIF has been coined as a facet-sparing procedure, given that the trajectory of the portal avoids the superior articular process (SAP) medially and does not require any drilling. While both techniques have their advantages over the open TLIF such as limited tissue disruption, lower blood loss, less perioperative opioid consumption, and shorter lengths of stay, the disadvantages of percutaneous and endoscopic fusion have also been documented.[16-18] Concerns surrounding the limited amount of spinal deformity correction, nerve root injury, and achieving bony fusion have all been highlighted for the percLIF.[19] To further optimize the endoscopic MIS approach, Khalifeh et al. developed the TF-LIF, which accesses the disc space completely within the bony confines of the facet joint.[12] Not only does this technique theoretically reduce the risk of iatrogenic nerve injury since the inferior articular process (IAP) protects the surgeon medially from the traversing nerve root and thecal sac, but it also provides a larger corridor for interbody delivery compared to the percLIF. In a follow-up study, Khalifeh et al. revealed a fusion rate of 90% after 1 year with significant short- and long-term postoperative improvements on the Oswestry Disability Index for low back pain.[13] Afforded by advancements in preoperative planning with advanced imaging, spinal fusions are becoming much more patient-specific depending on their unique spinal and neurovascular landscape.[20,21] Despite these advances, there remains a paucity of studies examining the pathology-specific anatomic constraints of various spinal pathologies on the trans-facet corridor size. Thus, using segmentation technology, the goals for this study were to 1) characterize the novel TF-LIF corridor in the lumbar spine by level, 2) illustrate the effect of specific pathology on this corridor, and 3) evaluate the resultant effect on maximum permissible cannula to treat patients with spondylolisthesis or degenerative disease through the TF corridor.

MATERIAL AND METHODS

Study Design and Data Collection

The authors performed a single-center retrospective cohort study of patients who underwent TF-LIF and percLIF from September 2021 to August 2023 at a major academic research institution. Patients were selected for surgery according to the established indications of each respective procedure in the literature.[12,22] Informed consent was obtained before every procedure. Patient permission to publish deidentified data were not necessary, as this study fell under the university's Institutional Review Board's (IRB) guidelines for "exempt" patient research (IRB Protocol ID: Pro00090408). Demographic data was collected via electronic health record review. Spondylolisthesis, anterior disc height, and posterior disc height (PDH) were measured using preoperative full-length standing radiographs. Severe, unilateral disc protrusions were recorded based on preoperative magnetic resonance imaging (MRI) and the official radiology report. Specifically, for the PDH, the height was measured in alignment with the TF corridor pathway instead of the mid-sagittal plane. This gave a more relevant measurement since the marked asymmetric morphology of the vertebral bodies can change going further lateral from midline.[23,24] We also assessed all the normal, nonpathologic levels in each patient to use as internal controls, which included sixteen L1—L2, thirteen L2—-L3, twelve L3—L4, and 2 L4—L5 levels. Levels were excluded if the MRI quality at that specific level was not sufficient to clearly identify the anatomical structures.

Segmentation Protocol

Three-dimensional (3D) isotropic T2-weighted MRI sequences acquired at 1-mm slice thickness were used for the segmentations. As described previously, the exiting and traversing nerve roots at each lumbar level were manually "drawn out" with the *Smartbrush* feature in BrainLab (BrainLab, Munich, Germany) by a single investigator with 3 years of experience.[11] This tool uses a region-growing model to connect outlined anatomy from different MRI planes to create a single 3D object (**Figure 1**). When visible on imaging, the traversing nerve roots were identified within the thecal sac rostrally and traced laterally as far as possible after exiting the dura. After the nerve roots were identified, all lumbar vertebrae were segmented. The thecal sac, given its hyperintensity on T2-weighted imaging, was segmented using the Threshold feature, which automatically highlights objects based on their intensity measurements. BrainLab then generates a 3D model of all segmented objects to enhance relative spatial proximity of each element (**Figure 2**).

Trans-Facet Corridor Segmentation and Measurement

For each level, the Align feature was used to orient the axial image to pass straight through the facet joint space. This also altered the orientation of both the sagittal and coronal corresponding views to mimic the ideal pathway into the disc through the facet capsule. Using the already segmented anatomy, the key anatomic borders for the TF corridor were identified: the traversing nerve root extending until the caudal pedicle as the base, the thecal sac as the height, and the exiting nerve root as the hypotenuse (**Figure 3**).[11] After outlining the corridor, we used an approximation of the largest triangle that contained every part of the safe zone and calculated the area using the formula: 0.5 × base × height. For cannula diameter, we drew the largest circle confined to the outlined TF corridor and measured its diameter, ensuring no overlap between the adjacent neural elements and proposed

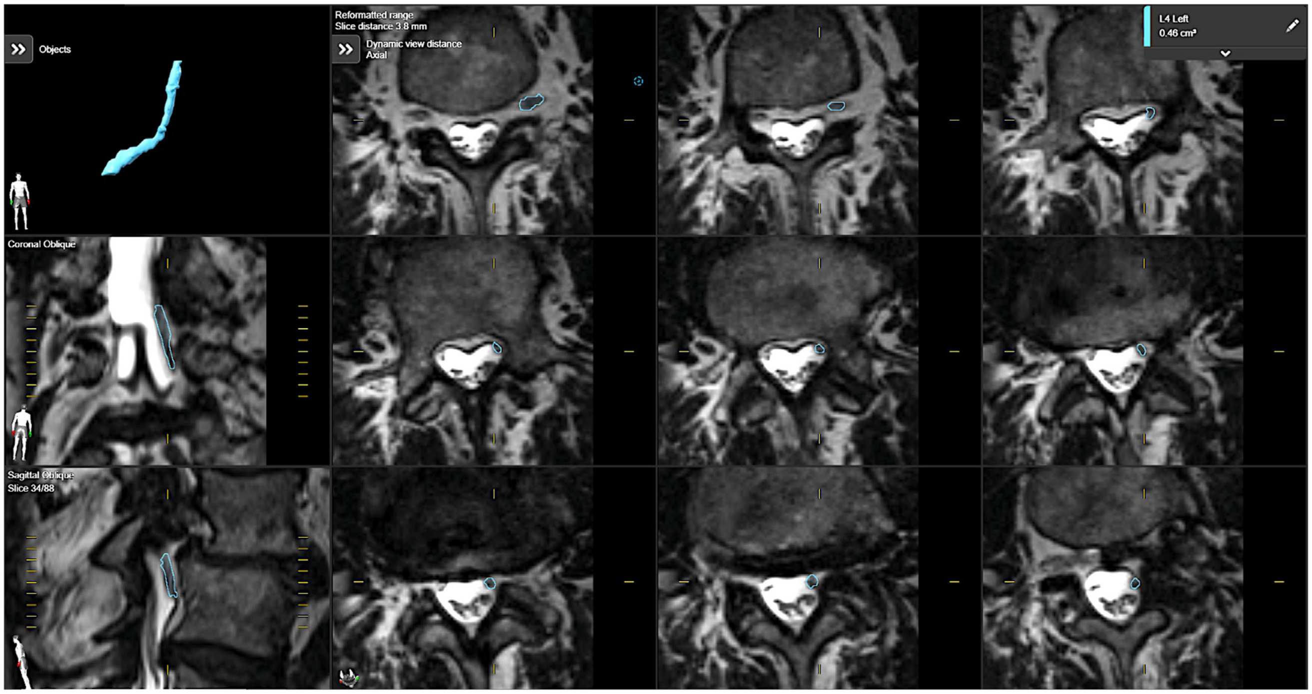

Figure 1. Individual nerve roots (*blue*) were identified in the axial, sagittal, and coronal planes using the Smartbrush feature. Each nerve root was segmented bilaterally starting from within the thecal sac until as far lateral as possibly visualized on imaging.

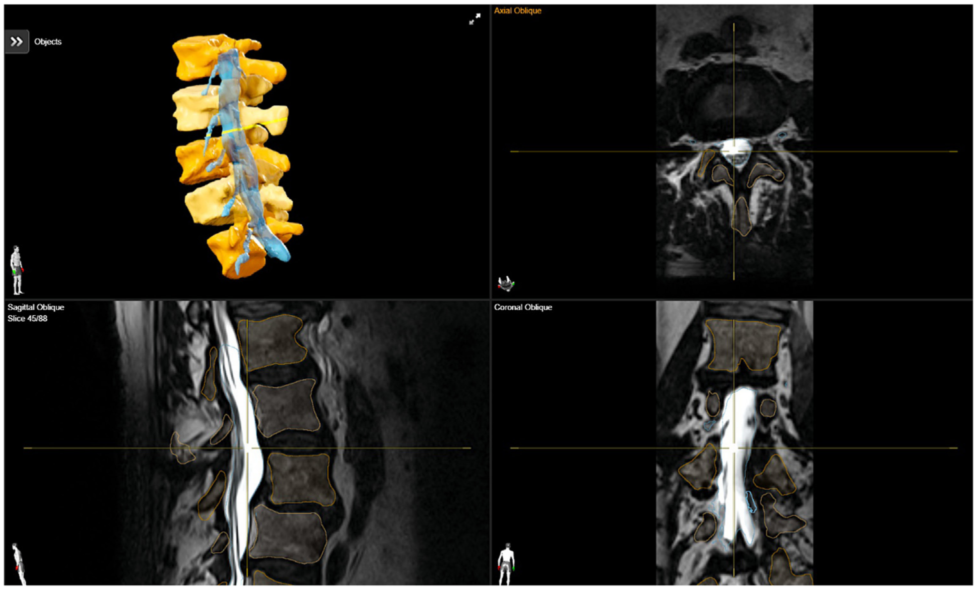

Figure 2. The vertebral bodies from L1 to L5 (*orange*) and thecal sac (*blue*) were then segmented after the nerve roots were seen using the Smartbrush feature. 3D models were created based on a region-growing algorithm.

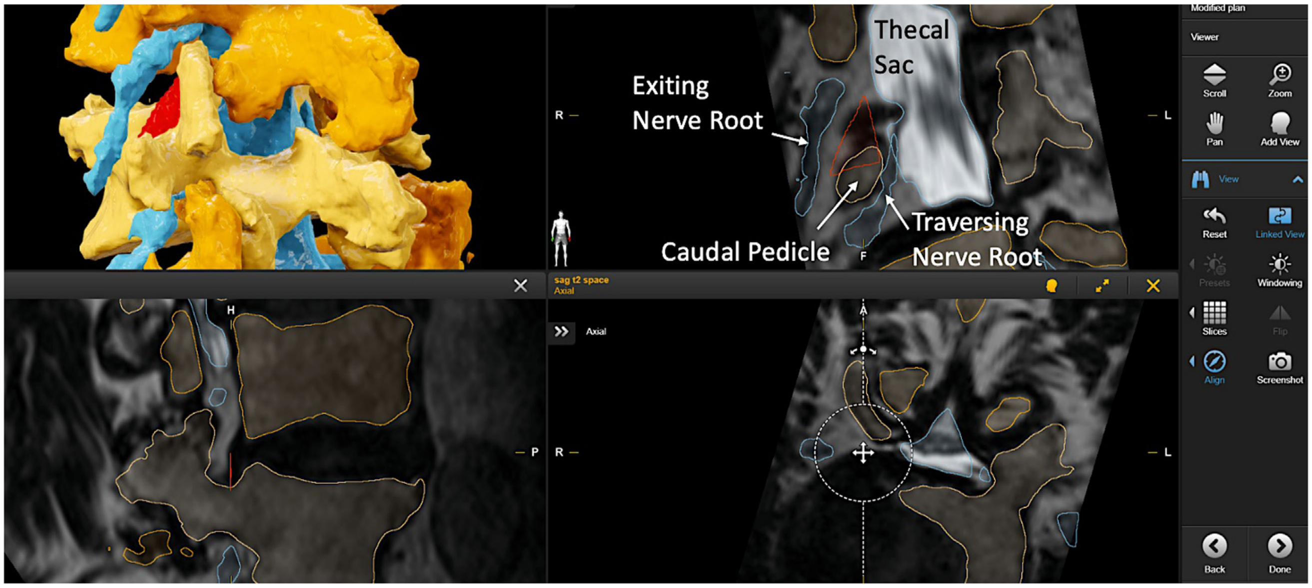

Figure 3. Using the *Align* feature (*bottom right panel*), the axial image was oriented to pass straight through the facet joint. The remaining images were then automatically altered to match that trajectory. The trans-facet corridor (*red*) was outlined as each level bilaterally based on its known anatomic boundaries: the traversing nerve root extending until the caudal pedicle as the base, the thecal sac as the height, and the exiting nerve root as the hypotenuse.

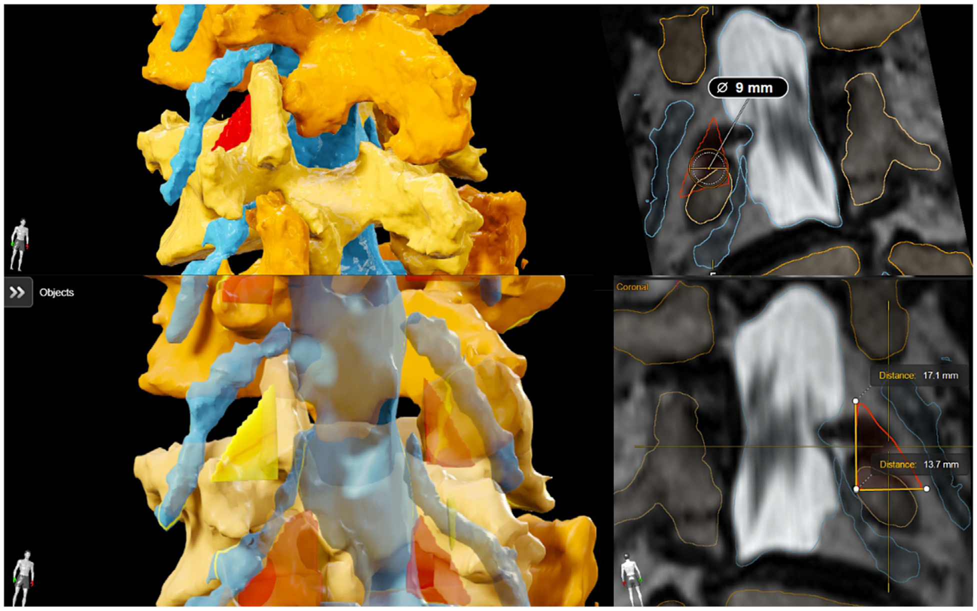

Figure 4. Using the Measure features, the area and maximum cannula diameter were recorded for each of the trans-facet approaches at all lumbar levels. No overlap of the corridors with either the exiting or traversing nerve roots was noted on the 3D transparent segmentations.

cannula (Figure 4). A board-certified neuroradiologist with 5 years of experience interpreting lumbar spine MRI and fellowship-trained neurosurgeon edited and confirmed each segmentation before analysis was conducted.

Statistics

For all continuous variables, a two-sample t-test was conducted. For all linear regressions, analysis was done with the built-in Excel (Redmond, Washington) data analysis tool pack using an analysis of variance model. For categorical variables, a two-proportion Z-test was used. For all statistical calculations, a P-value $\leq$0.05 was used to determine significance.

RESULTS

Trans-facet Corridor Trends in the Lumbar Spine

Sixteen patients (65.6 ± 12.1 years, 43.8% female, body mass index 29.2 ± 5.1 kg/m^2) were included and 118 TF corridors were segmented (Figure 5). The mean areas at L1–L2, L2–L3, L3–L4, and L4–L5 were 89.4 ± 24.9 mm^2, 124 ± 39.4 mm^2, 123 ± 26.6 mm^2, and 159 ± 42.7 mm^2, respectively. The mean maximum permissible cannula diameter at L1–L2, L2–L3, L3–L4, and L4–L5 were 7.85 ± 1.43 mm, 8.98 ± 1.72 mm, 8.93 ± 1.26 mm, and 10.2 ± 1.94 mm, respectively. The dimensional trends of the area ($P = 0.05$, $R^2 = 0.89$) and maximum cannula diameter ($P = 0.05$, $R^2 = 0.88$) each followed linear regression models, revealing a significant increase in both parameters moving caudally (Figure 6). Of note, the L5-S1 lumbosacral joints were not included in the analysis since the anatomic boundaries of the TF approach are not as easily identifiable at that level given that the sacrum is involved and the iliac crest can obstruct the view. Additionally, 10 (7.8%) of individual TF corridors were excluded from analysis due to poor MRI quality at those specific levels.

Pathology's Effect on the Trans-Facet Corridor

Among the 16 patients, 11 (68.8%) had a radiographic diagnosis of Grade 1 spondylolisthesis, 5 (31.3%) had Grade 2 spondylolisthesis, and 4 (25%) had severe disc protrusion. L4–L5 was the most commonly diseased, with 14 (87.5%) patients having at least a diagnosis of Grade 1 spondylolisthesis at that level. When any of these pathologies were present, both measured parameters of the TF corridor significantly increased at L2-L3 ($P = 0.002$ for area, $P = 0.003$ for cannula diameter) and L3–L4 ($P = 0.018$ for area, $P = 0.019$ for cannula diameter) when compared to healthy control levels (Table 1). L1–L2 was not analyzed for pathologic effect given that none of the patients had any disease at this level. L4-L5 did not reach significance due to high values of standard deviation for that specific level. At each diseased level, both individual TF corridors were compared to discern whether there was a difference between laterality allowing for the largest cannula diameter. There were significant differences in laterality at the pathologic levels for both mean area (180 ± 40.5 mm^2 vs. 147 ± 40.9 mm^2, $P = 0.029$) and cannula diameter (11.1 ± 1.84 mm vs. 9.46 ± 1.93 mm, $P = 0.018$), respectively (Table 2).

Next, when plotting the radiographic variables against the area and maximum cannula diameters, linear regression analysis revealed 2 key findings: higher grades of spondylolisthesis were significantly associated with 1) larger areas of the TF corridor ($R^2 = 0.25$, $P < 0.001$) and 2) larger maximum permissible cannula diameters ($R^2 = 0.25$, $P < 0.001$) (Figure 7). PDH and anterior

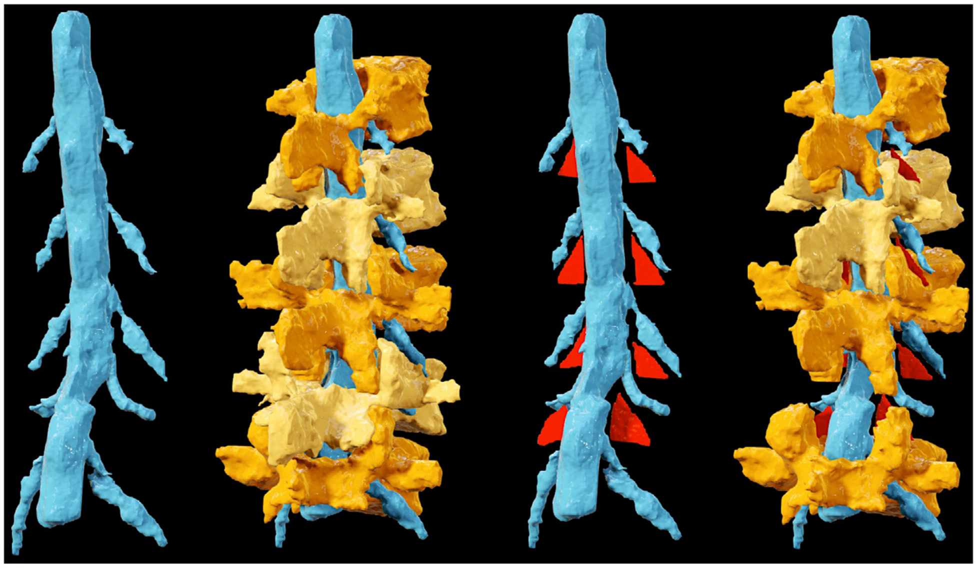

Figure 5. Representative images showing a full patient's lumbar spine segmented including the vertebrae (*orange*), neural structures (*blue*), and trans-facet corridors (*red*) bilaterally.

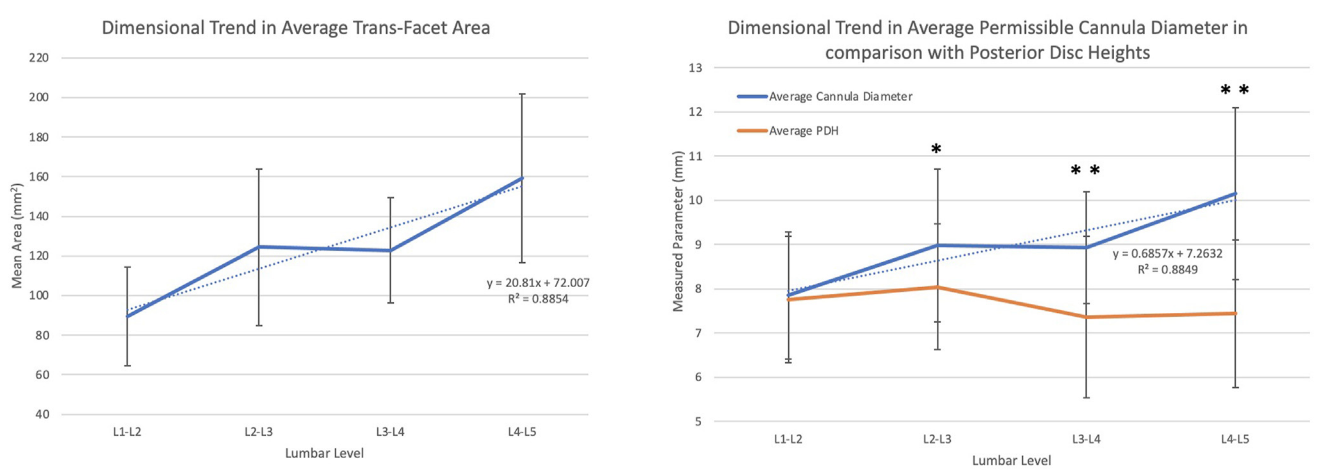

Figure 6. Line graphs depicting an increase in both mean trans-facet area (*left*) and the mean maximum permissible cannula diameters (*right*) extending inferiorly in the lumbar spine. Both models were significantly correlated based on linear regression analysis and ANOVA modeling. The right panel also shows the comparison between the cannula sizes with the posterior disc heights (PDH) at each corresponding level, further emphasizing that on average, the limiting factor for the interbody cage is no longer the surgical approach, but rather the disc height when performing a TF-LIF. * indicates $P \leq 0.05$ and ** indicates $P < 0.001$. ANOVA, analysis of variance; PDH, posterior disc height; TF-LIF, trans-facet corridor lumbar interbody fusion.

disc height did not show any linear association with the TF area ($P = 0.829$, 0.751) or cannula size ($P = 0.489$, 0.799). However, upon comparing the corresponding bilateral PDH values to the maximum cannula diameter that would fit through the TF corridor safely at each respective level, we found that out of the 118 corridors measured, 80 (67.8%) had permissible diameters larger than the PDH value ($P < 0.001$). When comparing the cannula diameters to their respective level PDH values, the cannula diameters were significantly larger at all the pathologic levels including L2–L3 (8.98 + 1.72 mm vs. 8.04 ± 1.43 mm, $P = 0.023$), L3-L4 (8.93 ± 1.26 mm vs. 7.36 ± 1.83 mm, $P < 0.001$), and L4–L5 (10.2 ± 1.94 mm vs. 7.44 ± 1.67 mm, $P < 0.001$). When a severe unilateral disc protrusion was present, there was a significant increase in the difference of TF areas between diseased and healthy levels (47.7 ± 24.1 mm² vs. 7.5 ± 10 mm², respectively; $P = 0.006$) (**Figure 8**).

DISCUSSION

Dating back to the 1970s, endoscopic and percutaneous spinal surgeries have undergone significant changes owed primarily to technical innovations such as more accurate preoperative planning, instruments that can deliver interbody devices through smaller portals, and cages that can be expanded once in the disc space.[25] MIS fusions have attempted to solve many of the disadvantages associated with more conventional open techniques. This most notably includes the widespread damage to posterior anatomical structures from tissue disruption and retraction associated with increased blood loss, longer inpatient hospital length of stay, and longer recovery periods.[26] However, while attempting to overcome these issues, endoscopic surgery has its own unique challenges including the potentially higher rates of cage subsidence and nerve root/dural tears given the lack of clear visualization.[27,28] To minimize these risks, the endoscopic TLIF has undergone multiple iterations beginning

Table 1. Comparing the Mean Area and Cannula Diameter of the Trans-facet Corridor Between Diseased and Healthy Lumbar Levels

Levels:	Mean Pathological Area (mm²)	Mean Non pathological Area (mm²)	*P* Values
L2-L3	178 ± 48.1	116 ± 31.5	0.002*
L3-L4	165 ± 33.5	120 ± 24.1	0.018*
L4-L5	163 ± 44.2	135 ± 21.5	0.219
Levels:	**Mean pathologic cannula diameter (mm)**	**Mean non-pathological cannula diameter (mm)**	***P* values**
L2-L3	11.3 ± 1.82	8.63 ± 1.44	0.003*
L3-L4	10.9 ± 1.27	8.79 ± 1.16	0.019*
L4-L5	10.2 ± 2.09	9.68 ± 0.43	0.604

*$P < 0.05$.

Table 2. Comparing the Laterality of Approach to the Trans-Facet Corridor at Diseased Levels

Measured Values:	Larger Trans-Facet Corridor	Smaller Trans-Facet Corridor	*P* Value
Pathologic area	180 ± 40.5	147 ± 40.9	0.029*
Pathologic cannula diameter	11.1 ± 1.84	9.46 ± 1.93	0.018*

*$P < 0.05$.

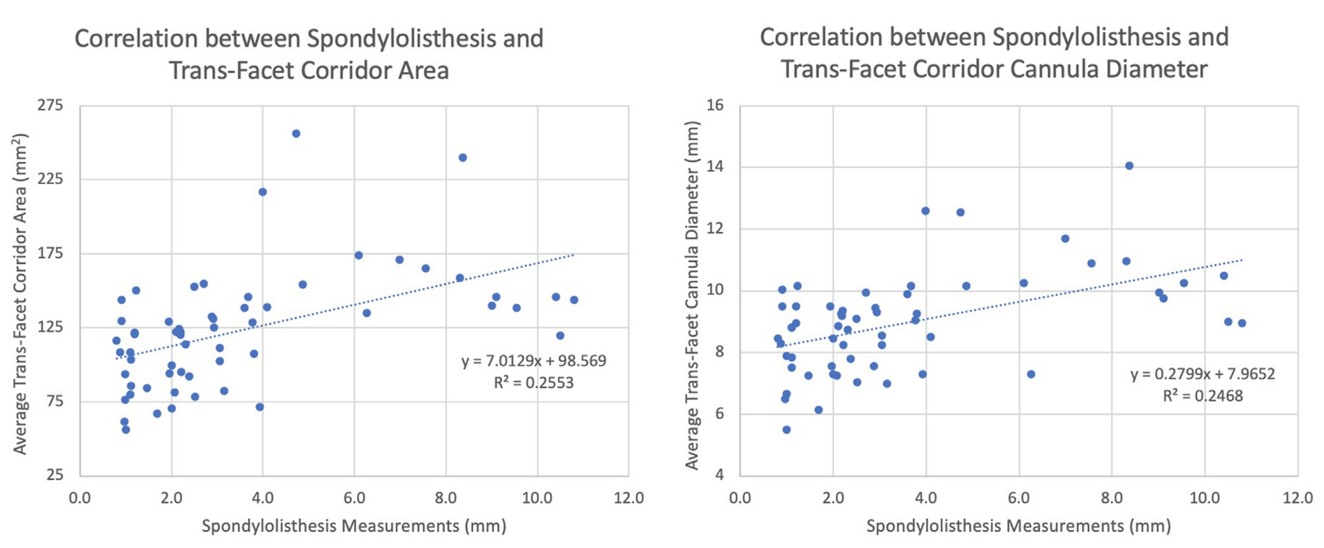

Figure 7. Scatter plots depicting a linear increase in both the trans-facet area (*left*) and maximum cannula diameter (*right*) measurements as spondylolisthesis values increased. Using ANOVA modeling, both of the linear regressions had an $R^2 = 0.25$ with *P* values <0.001. ANOVA, analysis of variance.

with the MIS-TLIF, morphing to the percLIF, and now to the modified TF-LIF. As described previously, the TF approach strikes a compromise between a larger corridor than Kambin's Triangle but also a safer approach than the MIS-TLIF in regard to the exiting and traversing nerve roots since the IAP remains intact.[11,13]

To our knowledge, there have been only 3 articles to date that have described the TF-LIF in detail. The first 2 by Khalifeh et al. showed the operative steps and displayed the positive outcomes for the procedure on 68 patients.[12,13] The third study by Tabarestani et al. used novel segmentation technology to analyze the corridor in 3D, clearly define the extent of its borders, and compare its dimensions to both the trans-Kambin and traditional "Safe Triangle" approach.[11] However, no prior studies have described the overall relative size of the TF corridor in the lumbar spine or analyzed how pathology can affect its dimensions. This study sought to answer these questions.

Pathology Can Increase the Trans-Facet Corridor

We recently demonstrated the ability to radiographically segment a patient's lumbosacral nerves prior to surgery and delineate key anatomy including the nerve roots, Kambin's Triangle, and adjacent structures.[29] By doing so, surgeons can enter the disc space through a corridor that allows for the largest cannula while providing the greatest distance from the coursing nerve root.[30] We also revealed that higher values of vertebral slippage and smaller PDHs decreased the safe zone of the percLIF. Compared to Kambin's Triangle, which has been shown to significantly decrease when any form of pathology is present, the TF corridor has the opposite result.[29] Instead of decreasing the safe area to access the disc space, higher values of spondylolisthesis increased both the measured area of the corridor and the maximum permissible cannula diameter that would fit within the confines of the borders. Mechanistically, these findings are expected. First, with diastasis of the facet joint potentially worsened from fluid buildup in degenerative disease, the SAP and IAP are more separated compared to a healthy level.[31] Given the inferior border of the TF corridor is the distance from the traversing nerve root to the lateral extent of the caudal pedicle, the increased joint space directly impacts the safe area that a surgeon has to access the disc space. Second, Katikar et al. demonstrated that in patients with spondylolisthesis, the angle of the exiting nerve root leaving the foramen is more oblique compared to healthy-level counterparts.[32] In other words, healthy patients have nerve roots that exit more vertically and travel parallel to the posterior border of the vertebra. This directly affects the superior border of the TF corridor — if the exiting nerve root travels more obliquely versus vertically, that provides a larger safe zone and thereby a larger cannula diameter to fit without requiring any additional nerve root retraction.

More specifically, for patients with severe disc protrusions, the area of the TF corridor on the side of the herniation was significantly larger than the contralateral side. We hypothesize that the larger size is due to medial displacement of the thecal sac (**Figure 8**). Once again, the medial border of the TF window is the thecal sac/traversing nerve root, so if a disc is pushing either of those structures toward the contralateral side, the surgeon will have a larger safe zone to place their portal. Not only would they have more area to access the disc but would also have the advantage of doing a formal discectomy on that same herniated side during their entrance or after. Our dimensional analysis further corroborated this finding, given that there was a significant difference in corridor size and cannula diameter when comparing the laterality of approach at the pathological levels (**Table 2**).

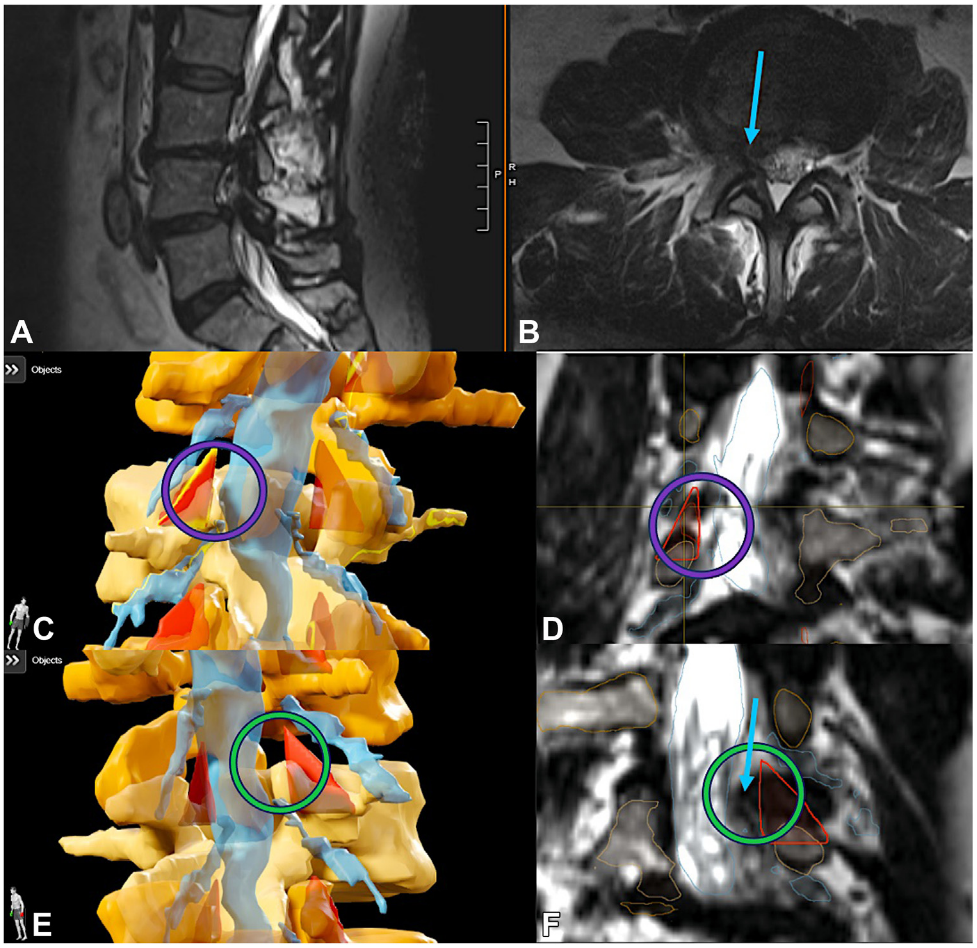

Figure 8. Representative bilateral segmentations at L3—L4 with a severe right disc protrusion seen on the sagittal (**A**) and axial (**B**) T2 SPACE MRI of the top panel. As seen in panels **C** and **D**, the thecal sac and traversing nerve root are being pushed laterally secondary to the disc herniation (*purple circles*), which reduced the area (98.5 mm^2) and cannula diameter (6.8 mm) of the left corridor. Conversely, in panels **E** and **F**, the right trans-facet corridor increased in both area (180 mm^2) and diameter (10.2 mm) since the diseased disc (*blue arrows*) moved the medial border (thecal sac/traversing nerve root) towards the contralateral side (*green circles*). MRI, magnetic resonance imaging.

TF-LIF Versus percLIF

Understanding the effect of pathology on each corridor is valuable information during pre-operative planning, especially when deciding the type of approach and optimal laterality to best treat a specific patient. For example, the literature has shown that the implanted interbody's shape, size, and placement all play a key role in the risk of device subsidence while also highlighting that wider cages significantly reduce subsidence risk.[33] Therefore, depending on the severity of spondylolisthesis and/or the presence of a disc protrusion, a surgeon may elect to enter from the larger TF corridor instead of attempting a percLIF. This is even more important given that prior studies have shown that in more than 400 Kambin's Triangles, only 2% could accommodate a maximum cannula diameter of 8 mm, which is a common size chosen by surgeons for interbody placement.[34] However, for a patient with lower values of spondylolisthesis, the percLIF approach may be better suited to minimize removal of the facet joint. We have also shown that patients who undergo percLIF use fewer opioids in the perioperative period than those who underwent MIS-TLIF.[35] Tangentially, if the need for drilling in the transforaminal space can be avoided, that may also reduce the risk of any type of dural tear or nerve root injury. From a clinical standpoint, Kim and Wu et al. discussed in their narrative review that both the facet-preserving percLIF and facet-sacrificing Endo-LIF showed promising clinical outcomes.[36] Both techniques have been studied long term and have demonstrated high rates of fusion, low patient-reported pain scores, and significant spinal parameter correction.[17,37-39]

Unfortunately, the novelty of the TF-LIF precludes large-scale study at this time. Although promising, there is only 1 description of the clinical and radiographic TF-LIF outcomes, meaning that future large cohort studies are required before any direct comparisons of efficacy or complication rates can be made between the 3 techniques.[13]

Using Segmentation to Enhance Preoperative Planning and Clinical Applications

Once the operative team has decided on performing a TF-LIF, they can then use the preoperative segmentation technology to visualize exactly how much of the IAP or endplate of the caudal vertebral body they would need to remove to make sufficient space for their desired cannula diameter. Although there have been some reports that drilling the endplate may assist with overall fusion rates, the majority of the current literature shows that disrupting the cortical endplate bone could potentially increase rates of cage subsidence.[40-42] Therefore, it is crucial to plan a course into the disc that maximizes distance from the nerve roots while also minimizing the amount of endplate resected to implant their interbody of choice.[43,44] As illustrated, the extent of bony resection can depend on the laterality of entrance, which again emphasizes the importance of accurate spatial awareness between the nerve roots and IAP (**Figure 9**). Similarly, our results show that when using the TF corridor, there was a significantly higher proportion of levels (80 vs. 38, $P < 0.001$) in which the maximum permissible cannula diameter was larger than the PDH. This is valuable information for the surgical team when planning their approach and deciding on what size interbody to implant. If the cannula diameter is larger than the distance between the superior and inferior endplates, that provides the surgeon an even greater amount of flexibility to place a larger cage since the limiting factor is no longer the approach, but rather the disc height itself. Further work analyzing this specific finding on a larger scale and comparing it to the percLIF technique is warranted.

Another potential overlap between segmentation and endoscopic procedures may fall on the relatively novel trans-SAP) approach for decompression of lateral recess pathology, first described by Hofstetter et al.[45] In their work, they describe a very similar approach to the TF technique, since the extent of bone resection is confined solely to the SAP. Using different size dilators and bone trephines under endoscopic guidance, they remove part of the SAP to create a window toward the lateral recess for traversing nerve root decompression. Although their first study revealed very positive clinical outcomes for 40 patients, they still expressed some limitations about their technique which could be solved with preoperative segmentation. Mainly, they describe that when planning their approach, the amount of SAP and caudal pedicle removal was only estimated since the traversing nerve root was difficult to visualize preoperatively. By combining the enhanced preoperative neuroanatomical visualization provided by segmentation with the superior intraoperative view of the endoscopic camera, surgeons can feel even more confident in their trajectories when approaching either the disc space for fusions or the nerve roots for decompressions.

Looking further down the line, this planning technology could be used in conjunction with robotics in the operating room. As described throughout the literature, the use of both semi-autonomous and fully-autonomous robots is slowly gaining traction, especially for sacroiliac fusions, deformity screw placement, and percLIF cases through Kambin's Triangle, to name a few.[46-49] Similar to work done by Satin et al., one could imagine a robot being fed the planned trajectory through the TF corridor created using the preoperative segmentation models.[50] Then, the robotic arm could dock straight onto the facet joint, drill down to the disc following the alimented, and create a window with the desired diameter to fit a portal. While the current and future applications of the TF-LIF in conjunction with advanced navigation techniques are promising, it should be duly noted that the TF-LIF is still a novel approach compared to its more established counterparts including the MIS-TLIF and open surgeries. For that reason, the learning curve of this procedure warrants further analysis, especially considering that the facet joint is generally removed in its entirety for both open and traditional MIS surgeries to allow for better disc space exposure. Until this technique and its training become more readily available, it is still always recommended that the surgeons elect the proper type of approach based on both the patient's pathology and the surgeon's skill set.

Limitations

As with any small retrospective cohort study, there are limitations. Our small patient size does not exhibit the wide breadth of anatomic variances including conjoined nerve roots, pars defects, disease at the L1—L2 level, etc. Likewise, a cohort of 16 patients limits the generalizability of our findings to the broader population. The L5—S1 level was also excluded from analysis since the anatomic boundaries of the TF corridor at the lumbosacral joint were more difficult to fully visualize on imaging compared to the other lumbar levels. Given that this spinal level also has a very high incidence of disease, future work looking specifically at the lumbosacral joint to compare various surgical approaches including the TF, other posterior, and anterior lumbar interbody fusions is warranted.[51] Similarly, these segmentations were all done manually and confirmed with both a board-certified, fellowship-trained neurosurgeon and neuroradiologist. However, there is always a chance for bias and error when segmenting, outlining, and measuring areas. MRI is also not the imaging modality of choice for viewing the osseous structures of the spine. Therefore, there is an increased risk of error when determining the limits of the facet joint, caudal pedicle, and endplates. As seen in our study, 10 TF corridors were omitted from analysis since the poor image quality of the MRI at those levels precluded accurate identification of the anatomic borders for measurement. This again highlights the imaging modality's importance and the limitation that a poor image can have on pre-operative planning. It is also important to note that position change, from supine during the MRI to prone during surgery, may affect the positions of the nerve roots and adjacent structures. Additionally, spondylolisthesis was calculated on standing radiographs, but some of the

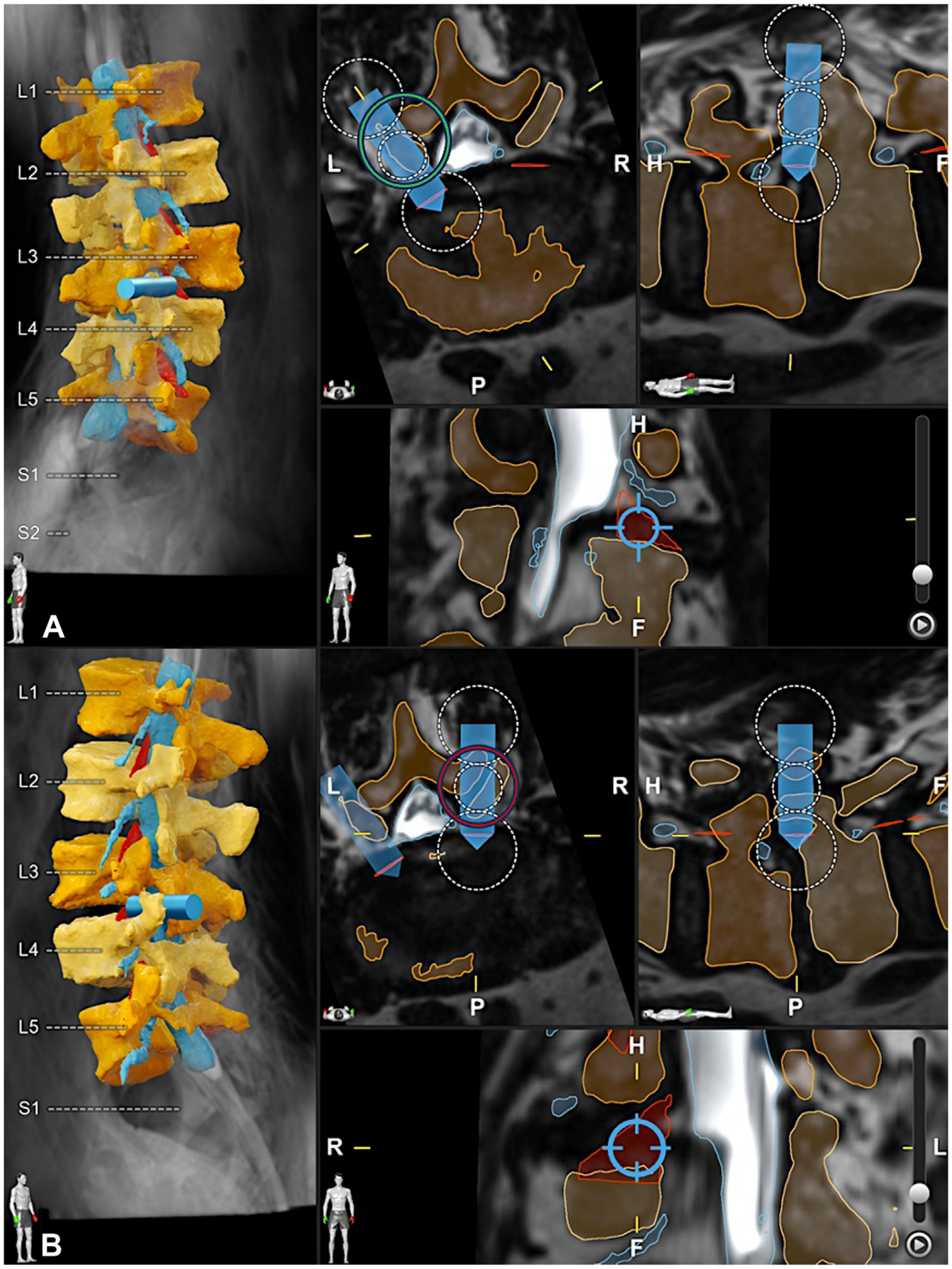

Figure 9. Representative preoperatively planned trajectories to safely maximize disc entry. Using the Spinal Planning feature, maximum diameter portal trajectories through the trans-facet corridors bilaterally at the L3–L4 level are depicted safely avoiding the segmented traversing nerve roots. (**A**), The top panel shows a 10 mm portal, which would require very minimal IAP (*green circle*) and endplate resection. (**B**), The contralateral side can fit an 11 mm portal safely, but this would also require a greater extent of the IAP removal (*red circle*). Depending on the preferred cannula size for the desired interbody cage, the surgeon can utilize the segmented pathways to help guide their decision-making and laterality of entrance. IAP, inferior articular process.

patients may have had dynamic instability when lying supine for the MRI.

CONCLUSION

Using segmentation technology, we were able to characterize the trends of the TF corridor across healthy and diseased lumbar levels. Similar to that of Kambin's Triangle, the areas and cannula diameters for the TF corridor increase caudally. However, unlike the percLIF, we found that higher values of spondylolisthesis were significantly associated with both larger working areas and maximum permissible cannula diameters. Taken together, surgeons can make a more precise and patient-specific decision when electing to perform either a facet-sparing or facet-sacrificing procedure. Likewise, this technology could help reduce the risk of nerve root injuries by customizing the trajectory into the disc space and avoiding overlap with the surrounding neural structures. Further larger scale, prospective studies are required to corroborate these preliminary findings, assess the clinical outcomes of the TF-LIF procedure, and provide a foundation for future techniques using segmentation-based trajectories.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Troy Q. Tabarestani: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Peter N. Drossopoulos:** Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Chuan-Ching Huang:** Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. **Alyssa M. Bartlett:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Mounica R. Paturu:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Christopher I. Shaffrey:** Conceptualization, Data curation, Supervision, Validation, Writing – review & editing. **John H. Chi:** Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. **Wilson Z. Ray:** Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. **C. Rory Goodwin:** Conceptualization, Supervision, Validation, Visualization, Writing – review & editing. **Timothy J. Amrhein:** Conceptualization, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Muhammad M. Abd-El-Barr:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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