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Case Series

Novel Applications of Robot-Assisted Navigation in the Treatment of Lumbar Adjacent Segment Disease: A Case Series

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Abstract

Objective: The treatment of adjacent segment disease (ASD) following lumbar fusion is common and often requires reoperation. Traditionally, reoperation requires revision and exposure of prior instrumentation, and removal of this hardware increases operative time and perioperative risks. The authors report on the use of robot-assisted navigation (RAN) to accomplish minimally-invasive posterior pedicle screw fixation, including pedicle re-instrumentation when needed, to treat ASD and avoid revision and exposure of prior hardware.

Methods: A retrospective review of five patients treated for lumbar ASD with posterior fixation was conducted. All screw trajectories were planned preoperatively using the robotic software. All patients underwent minimally-invasive decompression and transforaminal lumbar interbody fusion followed by robot-assisted pedicle screw placement for fixation. Basic demographics, operative indications, pre-operative planning data, perioperative outcomes and short-term clinical outcomes were evaluated.

Results: The mean age was 71.2 years, mean total operative time was 117.6 minutes (range: 98 - 140 minutes), mean operative time per screw was 27.2 minutes, mean estimated blood loss was 30mL (range: 25 - 50 mL), mean body mass index was 36.64 (range: 26.7 - 46.9), and mean length of stay was 1.2 days (range: 1-2 days). A total of six screws were placed in previously instrumented pedicles without removing prior hardware, four in a cortical bone trajectory and two in a transpedicular trajectory (TPT). In one patient with both distal and proximal ASD, pedicle re-instrumentation was avoided altogether, creating a construct caudal, rostral and medial to index fusion. Patients were successfully treated for both single- and multi-level ASD. There were no perioperative complications. One patient was lost to follow-up. The remaining four patients had acceptable outcomes at short-term clinical follow-up.

Conclusion: The authors present a novel application of RAN for the treatment of ASD which obviates the need for revision of prior hardware. To our knowledge, this is the first report of multilevel ASD treatment that avoided revision, as well as the first report of pedicle re-instrumentation in a TPT adjacent to a prior transpedicular screw. This method maintained low operative time and acceptable perioperative outcomes. RAN may offer a minimally-invasive and effective treatment option for patients with ASD that avoids revision of prior hardware and reduces perioperative risk. Long-term clinical outcomes are warranted to ensure clinical and biomechanical durability.

Keywords: Robot-Assisted Navigation; Adjacent Segment Disease; Lumbar Spine; Degenerative Spine Disease; Robotics

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Abbreviations

ASD: Adjacent Segment Disease; RAN: Robot-Assisted Navigation; TLIF: Transforaminal Interbody Fusion; TPT: Transpedicular Trajectory; CBT: Cortical Bone Trajectory; BMI: Body Mass Index; EBL: Estimated Blood Loss; CT: Comuted Tomography

Introduction

Adjacent segment disease (ASD) is relatively common following lumbar fusion. ASD is a broad term that refers to a spectrum of degenerative conditions that occur adjacent to an index spinal fusion such as degenerative disc disease, stenosis, and listhesis [1]. Some authors suggest that an increase in biomechanical forces adjacent to a fusion level accelerates degeneration while others believe ASD to be natural progression of the degenerative process dictated by biological and environmental influences [1].

As the number of individuals undergoing lumbar spinal fusion has dramatically increased in recent decades, so too has the incidence of ASD [2-4]. The incidence is estimated to be between 2 to 4% per year in both the lumbar and cervical spine [1]. Based on meta-analysis, it is reported that 8% of patients will require reoperation secondary to ASD following spinal fusion over an average follow-up period of 6.4 years [2].

However, reoperation rates vary considerably with studies reporting up to 36% of ASD patients undergoing reoperation at 10 years [5].

Various surgical techniques have been utilized to address lumbar ASD, including both open and minimally-invasive approaches. Minimally-invasive surgery provides the advantage of reducing tissue dissection, blood loss, length of hospital stay and morbidity in patients undergoing reoperation for ASD. ASD reoperations, however, are commonly performed open in order to expose the prior hardware for either its revision or extension. Such procedures are commonly associated with an increase in operative time and risk for peri-operative complications, such as excess blood loss, infection and neurovascular injury secondary to the presence of scar tissue and distorted anatomy [3,6-8,9,10]. Thus, a minimally-invasive approach which avoids the need to expose or revise prior hardware is an attractive surgical option.

Robot-assisted navigation (RAN) has demonstrated utility in increasingly complex spinal procedures and may enable a minimally-invasive approach to ASD re-operation procedures that avoids the need for revision or extension of prior hardware. Here, we present a case series of five patients who underwent a minimally-invasive transforaminal lumbar interbody fusion (TLIF) followed by robot-assisted posterior screw fixation for treatment of ASD. Utilizing preoperative planning software and intraoperative RAN, the surgeon was able to avoid exposure and revision of prior hardware in all patients. These reports are critical to the growing literature of ASD treatment, as such an approach can potentially avoid the need for hardware revision, minimize complications, and provide favorable clinical outcomes.

Materials and Methods

Data collection

The study was approved by Institutional Review Board at HCA Ocala Regional Hospital. Retrospective review of five patients who underwent lumbar fusion for ASD by a single surgeon at a single institution was conducted. Data on basic demographic information, surgical indications, pre-operative planning, perioperative outcomes, and clinical outcomes were collected. The latest follow-up data from time of data collection was obtained. All patients had radiographic evidence of ASD with new onset of back pain or radicular symptoms that failed conservative management. All patients were candidates for lumbar fusion, decompression, and posterior fixation.

Surgical procedure

At least one day prior to the operation, each patient underwent CT imaging according to the Mazor CT protocol. CT imaging was used to create virtual 2-dimensional (2D) and 3-dimensional (3D) anatomical reconstructions of the patient's spine for preoperative planning. On the day of surgery, all patients first underwent a minimally-invasive TLIF using a microscopic tubular approach. A small unilateral vertical skin incision centered over the pedicle screw entry points was made. Dilators of increasing diameter were then sequentially inserted within the paraspinal muscles directed toward the lateral lamina. A working channel was docked and secured to the operative table with a metal arm. The surgical microscope was then introduced and the following steps performed. The bottom of the superior lamina, top of inferior lamina and complete facet were drilled on one side. A Kerrison punch was used to do laminotomy and medial facetectomy. With the thecal sac displaced, central lateral recess decompression was completed on both sides followed by discectomy and appropriate endplate preparation. An expandable interbody cage was placed in the interspace along with allograft, demineralized bone matrix and bone morphogenic protein. Interbody cage placement was confirmed with fluoroscopy.

Following decompression and interbody cage placement, the Mazor X Stealth Edition™ Robot was introduced into the operative field. A navigation reference pin was attached to the posterior superior iliac spine and the robotic platform was mounted to the pin. Intraoperative fluoroscopy imaging was obtained and matched with preoperative CT imaging, independently registering each vertebra. After satisfactory registration was achieved, a 2D and 3D reconstruction of the patient's anatomy was registered for intraoperative navigation. Percutaneous screws were placed using RAN in the steps as follows. The robotic arm was sent to the appropriate spinal level and skin incision was made at the site if not already created by prior TLIF. In sequential order, a navigation-guided dilator, drill with a 30mm positive stop, tap and screw were inserted percutaneously through the robotic arm. The screw dimensions and trajectories were planned preoperatively and adjusted intraoperatively as needed. Following placement of the screw, the robotic arm was sent to the next site. After all screws were placed, intraoperative O-arm scan (Medtronic) was performed to confirm screws were in appropriate position. Percutaneous connecting rods were then passed, set screws applied and torqued off. Following surgery, patients were discharged once they were cleared by physical therapy and were able to eat, void, and pass flatus.

Results

Demographics and perioperative outcomes

Our case series resulted in 1 female and 4 males undergoing operative intervention for symptomatic ASD in the lumbar spine. All patients had previously undergone one- or two-level lumbar fusion with posterior fixation, except for one patient who had previously undergone two-level LLIF with placement of lateral screws and plate. All prior screws were placed in a traditional transpedicular trajectory (TPT) except for the one patient with a prior LLIF. All patients were candidates for posterior fixation based on preoperative imaging. Indications for surgery included symptomatic ASD with radiographic signs of stenosis, spondylolisthesis, disc space collapse or herniation. Three patients had proximal ASD, one patient had distal ASD, and one patient had both proximal and distal ASD.

In this cohort of patients, the mean age was 71.2 years, mean total operative time was 117.6 minutes (range: 98 - 140 minutes), mean operative time per screw was 27.2 minutes, mean estimated blood loss (EBL) was 30mL (range: 25 - 50 mL), mean body mass index (BMI) was 36.64 (range: 26.7 - 46.9), and mean length of stay (LOS) was 1.2 days (range: 1-2 days) (Table 1). Of note, operative time accounted for time from skin injection to the time patient was transferred off the operating table. All patients remained in the hospital for 1 day postoperatively, except for one patient who stayed for 2 days and had undergone anterior cervical discectomy and fusion the day prior to lumbar surgery.

Instrumentation

A total of 22 screws were placed with RAN (Table 1). Of these, 8 screws were placed in already instrumented vertebral levels without removing the index instrumentation. Of these eight screw, 4 were placed in a cortical bone trajectory (CBT) and 4 in a TPT (Table 1). Of those instrumented in TPT, two were carefully inserted adjacent to an index traditional pedicle screws while the other two were guided through non-instrumented pedicles, superiorly to laterally traversing screws within the vertebral body from a prior LLIF. The remaining screws were placed in a traditional TPT in adjacent non-instrumented spinal levels, including one patient with distal and proximal ASD. Here, screw orientations were carefully planned so that rods would run medially to index rods. All screws were accurately placed on primary insertion except for two screws in one patient which were instrumented in a TPT in previously un-instrumented pedicles. They were noted to be slightly lateral breach following O-arm scan and replaced with Stealth Navigation™.

Clinical outcomes

There were no perioperative complications. On follow-up, one patient had resolution of symptoms at 2 weeks. Two patients had improving symptoms at 2-week and 4-week follow-up, respectively. One patient had persistent symptoms at 6 weeks of follow-up, and we were unable to obtain follow-up on one patient.

Case descriptions

Case 1

A 66-year-old female with prior L4-5 fusion with posterior fixation and laminectomies from L3-4 to L4-5 presented with new onset axial back pain, neurogenic claudication, and radiculopathy. Preoperative myelogram demonstrated ASD at L2-3 with moderate spinal canal stenosis and grade 1-2 anterolisthesis of L3 on

Case Number	Age	Gender	Index fusion procedure	Revision Procedure	Screw Placement and Trajectory	Total Number of Screws	BMI	Total Operative Time (minutes)	Operative Time/ screw (minutes)	EBL (mL)	Length of Stay (days)
1	66	F	L4-5 fusion and posterior fixation	L2-4	L2: TPT bilaterally L4: CBT bilaterally	4	33.3	131	32.75	50	1
2	74	M	L3-4 and L4-5 fusion and posterior fixation	L2-5	L2: TPT bilaterally L4: unilateral CBT on left side L5: unilateral CBT on right side	4	46.9	98	24.5	25	1
3	59	M	L1-L3 fusion and lateral fixation	L3-5	L3, L4 and L5 bilaterally in TPT	6	26.7	119	19.83	25	1
4	82	M	L4-5 fusion and posterior fixation	L3-4	L3: TPT bilaterally L4: TPT bilaterally	4	42.7	100	24	25	1
5	75	M	L4-5 fusion and posterior fixation	L3-S1	L3: TPT bilaterally S1: TPT bilaterally	4	33.6	140	35	25	2

Table 1

L4. The patient underwent a minimally-invasive TLIF from L2 to L4 followed by robot-assisted posterior screw fixation. Using RAN, screws were guided into the previously instrumented L4 pedicles in a CBT bilaterally (Figure 1). Screws were then guided into L2 and L3 levels bilaterally in a TPT. Following O-arm scan, L4 screws were appreciated to be in good position. However, both L2 screws were noted to be lateral breach. At this point, O-arm registration was completed, L2 screws were removed and replaced using Stealth Navigation™. The patient was discharged on post-operative day 1. At 2-week follow-up, the patient reported improving symptoms.

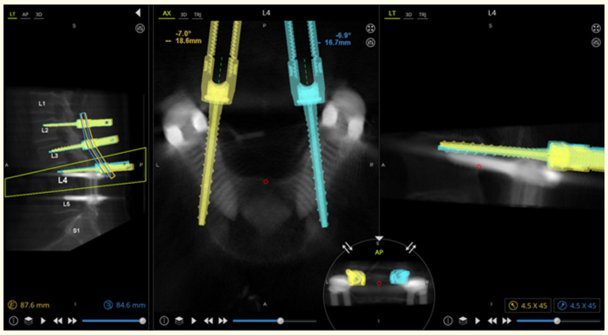

Figure 1: Preoperative planning of cortical bone screws in L4 pedicles bilaterally.

Case 2

A 74-year-old male with 2 prior lumbar fusions, L3-4 and L4-5, and posterior fixation presented with new onset axial back pain, right lower extremity numbness and inability to walk. Preoperative MRI demonstrates ASD at L2-3 with spinal canal stenosis. The patient underwent a minimally-invasive TLIF from L2 to L5 followed by robot-assisted posterior screw fixation. Using RAN, screws were guided into L2 pedicles bilaterally and unilaterally at L4 and L5. L2 screws were placed in a TPT in non-instrumented pedicles. The L4 and L5 screws were fixated unilaterally on the left and right, respectively, within previously instrumented pedicles. They were placed in a CBT, terminating cephalad to index screws (Figure 2). Screw alignment and position were confirmed with intra-operative O-arm. The patient was discharged on post-operative day 1. Follow up data was unable to be obtained for this patient.

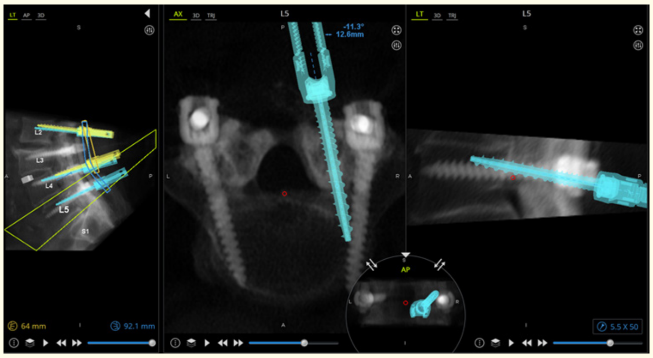

Figure 2: Preoperative planning for cortical bone pedicle screw of right L5 pedicle in lateral and axial views. Of note, the image depicts two pedicle screws in the L4 vertebra, one of which was not inserted intraoperatively.

Case 3

A 59-year-old male with prior L1-3 LLIF with lateral instrumentation presented with new onset axial back pain and radiculopathy. Preoperative MRI demonstrated ASD at L3-4 and L4-5 with disc herniation and moderate spinal stenosis at L3-4 and grade 1 anterolisthesis, disc herniation and severe spinal canal stenosis at L4-5. The patient underwent a minimally-invasive TLIF from L3 to L5 followed by robot-assisted posterior screw fixation. Using RAN, screws were guided into the L3, L4 and L5 pedicles bilaterally in TPT. At the previously instrumented L3 vertebra, pedicle screws were guided into the vertebral body superior to laterally traversing index screws (Figure 3,4). Screw alignment and position were confirmed with intra-operative O-arm. The patient was discharged on post-operative day 1. At 4 week follow up, the patient reported improving symptoms.

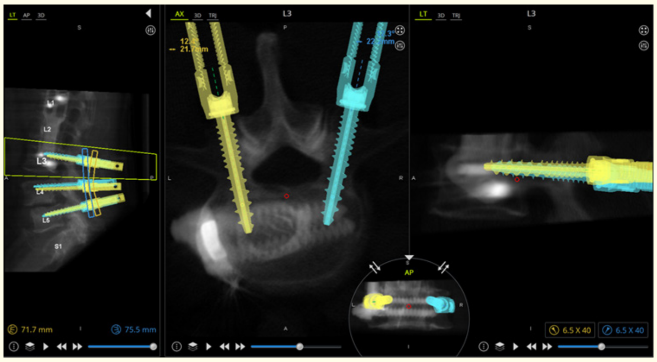

Figure 3: Preoperative planning for L3 pedicle screws bilaterally in a traditional transpedicle trajectory. Screws were planned so that they would traverse the vertebral body superior to laterally traversing index screws from prior LLIF.

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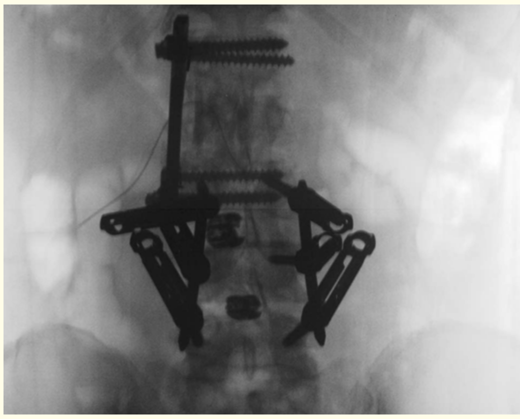

Figure 4: Intraoperative X-ray.

Case 4

An 82-year-old male with a history of prior L4-5 fusion with posterior fixation presented with new onset axial back pain, radiculopathy and frequent falls. Preoperative MRI imaging revealed ASD at L3-4 with mild to moderate spinal canal stenosis and disc bulge. The patient underwent a minimally-invasive TLIF at L3-4 followed by robot-assisted posterior screw fixation. Using RAN, screws were guided into L3 and L4 pedicles bilaterally in TPT. L4 screws were guided adjacent to existing pedicle screws (Figure 5). Screw alignment and position were confirmed with intra-operative O-arm. The patient was discharged on post-operative day 1. At 2-week follow-up the patient reported resolution of symptoms.

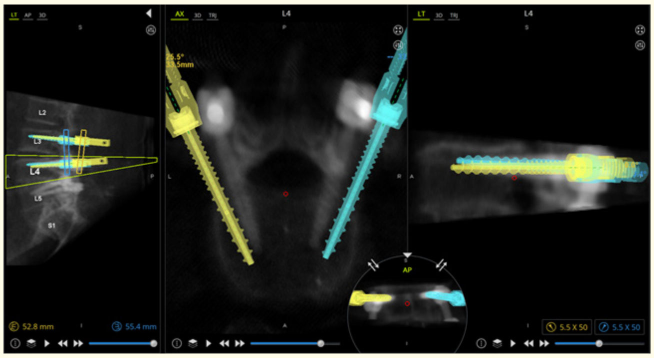

Figure 5: Preoperative planning for bilateral L4 pedicle screws. The pedicle screws were carefully instrumented in a TPT, adjacent to existing pedicle screws.

Case 5

A 75-year-old male with a history of prior L4-5 fusion with posterior fixation presented with new onset axial back and neck pain and radiculopathy in all four extremities. Preoperative lumbar MRI imaging revealed ASD at L3-4 and L5-S1 with moderate to severe spinal canal stenosis, as well as moderate to severe canal stenosis and neural foraminal narrowing at L4-5. One day following anterior cervical discectomy and fusion, the patient underwent a minimally-invasive TLIF from L3 to S1 followed by robot-assisted posterior screw fixation. Using RAN, screws were guided into non-instrumented pedicles of L3 and S1 bilaterally in an orientation that enabled rod fixation medial to existing construct (Figure 6). Screw alignment and position were confirmed with intra-operative O-arm. The patient was discharged on post-operative day 2. At 6-week follow-up the patient reported persistent symptoms.

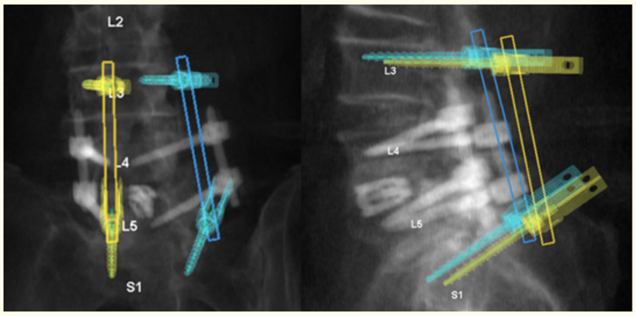

Figure 6: Preoperative planning bilateral L3 and S1 pedicle screws. Pedicle screws were guided into non-instrumented pedicles in an orientation that enabled rod fixation medial to existing construct.

Discussion

Surgical robotics has continued to advance spinal surgery, with utilization in increasingly complex procedures [11-13]. Although neurosurgery has been slower to adopt robotic systems as compared to other surgical specialties, its use in spinal surgery has undergone substantial evolution since its introduction for pedicle screw fixation in 2004 [14]. Despite controversy, literature suggests RAN can offer greater precision and accuracy of pedicle screw placement as compared to free-handed or navigation-guided techniques alone [15-19]. We believe this increase in precision and accuracy can enable instrumentation techniques needed to avoid revision and removal of index hardware in reoperations for lumbar ASD. In addition, RAN may facilitate minimally-invasive approaches, reduce complications, and improve operative efficiency for these procedures.

Here, we describe a case series of five patients with symptomatic lumbar ASD in the setting of prior instrumentation who were successfully treated with a minimally-invasive TLIF and robot-assisted posterior screw fixation without exposure or removal of prior hardware. The use of RAN in these procedures enabled execution of screw trajectories that may have otherwise been difficult to instrument freehand or with neuronavigation or fluoroscopic guidance alone. These procedures were also completed with little morbidity and with low operative time.

There are currently few reports in the literature documenting surgical management of ASD requiring posterior screw fixation that avoids revision. Current reports that exist, limited to two case reports and one case series, utilize CBTs to guide screws into previously instrumented pedicles [20-22]. These authors employed minimally invasive approaches with StealthStation Navigation™, fluoroscopic guidance and, in one case report, RAN. Engaging cortical bone, a CBT traverses the pedicle from medial to lateral in the transverse plane and caudocephadally in the sagittal plane, thereby avoiding intersection with the traditional pedicle screw already in place. Similarly, in our case series, 4 screws were placed in a CBT within previously instrumented pedicles without removal of the prior hardware.

However, not all patients are candidates for CBTs due to small pedicle size or orientation of the existing screw which may preclude the addition of a second pedicle screw. Thus, alternative, and potentially more complex, trajectories are required to accomplish posterior instrumentation without hardware revision. In our series, one patient underwent bilateral pedicle instrumentation using a TPT screw guided adjacent to the index screws which were likewise placed in a traditional TPT. To our knowledge, this is the first report of pedicle re-instrumentation in a TPT in the setting of an existing traditional pedicle screw. Moreover, in a patient with both distal and proximal ASD, pedicle re-instrumentation was avoided altogether. Using the pre-operative planning software, the surgeon was able to instrument screws at vertebral levels superior and inferior to index fusion site in an orientation that enabled rods to run medial to index rods. Furthermore, in one patient with a prior LLIF, pedicle screws were guided into the vertebral body so that they entered superiorly to existing screws. Finally, three patients in our series were treated for multilevel ASD. To the best of our knowledge, this is the first report of reoperation for multilevel ASD treatment that avoided the need for revision of prior hardware.

Altogether, in this series, careful preoperative planning with anatomical reconstructions enabled the surgeon to assess whether an already instrumented pedicle possessed sufficient residual bone to accommodate a new screw and, if so, create the most ideal trajectory. Intraoperatively, RAN was able to execute these trajectories, accomplishing fixation that may have been technically challenging to accomplish free-hand or with neuronavigation and fluoroscopic-guidance alone [15,16,19]. Further, when the surgeon determined it was most advantageous to avoid additional hardware within the pedicle, pre-operative planning software and RAN enabled execution of screw orientations that created constructs which avoided interference with the index fusion.

In terms of follow up, all patients had acceptable outcomes. Our follow up data, however, is limited in duration and long-term follow-up is critical to ensure clinical and biomechanical durability. A prior cadaveric study in osteoporotic spines has suggested durability of double pedicle screw instrumentation techniques [23]. Similar in theory to one of our cases, this technique involved the insertion of two smaller diameter pedicle screws adjacent to each other. Compared to a single screw, the double-screw technique led to greater stiffness and axial load to failure, suggesting strength and durability [23]. However, additional biomechanical studies are needed to assess the durability of double pedicle screws when one is placed in a TPT and another in a CBT, as seen in two patients in this study. Prior reports which may suggest durability for such a technique include one prior case series which reported good long-term outcomes at 10-15 months following ASD reoperations which avoided revision of prior hardware by utilizing cortical bone screws in the setting of a prior traditional pedicle screw [22]. Nonetheless, our follow-up period is currently limited and additional follow up is imperative. In particular, there is currently no biomechanical or long-term clinical data on such techniques for the treatment of multilevel ASD and further study is warranted before such a technique should be implemented.

Another important advantage of robot-assisted spinal surgery illustrated in by our series is the potential for reduced operative time [24-26]. Presently, the literature is inconsistent secondary to reports of both reduced and increased operative time with robot-assisted spine surgery [12,24,26]. In our series, the operative time per screw - which accounted for time of skin injection to patient transfer off the operating table - was 27.2 minutes. This operative time is lower compared to literature on conventional freehand procedures and robot-assisted primary fusions, which range between 52.9 to 264.2 minutes and 59.1 to 226.1 minutes per screw, respectively [12]. With revision procedures, these operative times are likely to increase further [6]. Prior research has suggested that operative time for robot-assisted spinal surgeries significantly decreased with time and accrual of surgical experience [24-26]. It has thus been argued that once the learning curve is overcome, RAN has a potential to improve operative efficiency. Our findings are in agreement with this literature, and we likewise believe that RAN can lead to a reduction in operative time as learning curves are conquered and technologies continue to improve.

Furthermore, with robotics we can perform increasingly complex procedures in a less invasive manner, enabling decreased incision sizes, reduced tissue dissection and faster recovery [12,25,27]. Several studies have demonstrated decreased hospital stays with RAN [18,28,29]. For example, in a study by Hyun and colleagues, minimally-invasive robot-assisted surgery for spinal fusion was associated with a 6.8 day length of stay as compared to 9.4 days in the open fluoroscopy arm [29]. In our series, the average length of stay was 1.2 days, further strengthening the potential for reductions in recovery time.

Finally, the advantages of minimal dissection and shorter operative time make this an ideal procedure for high-risk patients, such as those who are obese, diabetic, elderly or with comorbidities. These patient populations are at greater risk for infection and complications related to extended anesthesia times [30-32]. In particular, individuals over age of 65 make up a significant portion of patients undergoing ASD reoperation [3,33,34]. This patient population is at especially greater risk for perioperative complications associated with extended anesthesia time and are also more likely to have comorbidities that further increase morbidity and mortality [35,36].

Limitations

There are limitations to our study that are important to address. Foremost, this series is a retrospective, observational study and there is a high risk of selection bias. Our series also has a small sample size, and the absence of a control group precludes our ability to make a reliable comparison to the standard of care in each case. We also did not objectively quantify the post-operative change the symptoms, which we aim to do in a future study.

Our series had two intraoperative screw revisions. This occurred in one patient and were two traditional pedicle screws that were noted to be slightly lateral breach following O-arm scan. They were placed in previously un-instrumented pedicles at a single vertebral level and were replaced with neuronavigation. Although we believe that the increase in accuracy and precision that is offered by RAN is critical to effectively accomplish the complex instrumentation in our series, we also recognize that these technologies are not free from fault, even for more simple instrumentation. As such, alternative means of instrumentation may be necessary and suitable depending on the case and surgeon experience. In this context, pedicle re-instrumentation for ASD operations for the purpose of avoiding removal of prior hardware has been accomplished without the use of RAN in two prior reports [20,22]. Although alternative methods are feasible, we ultimately believe that RAN may be most efficient and accurate in the setting of these more complex ASD procedures and may also be suitable for a broader range of anatomy.

Finally, and importantly, we have limited follow up on these patients. Despite the occasional use of this procedure in the literature there remains little *in vitro* biomechanical data on such instrumentation techniques. Long-term clinical and radiographic follow up for such techniques is likewise limited. In particular, there are currently no biomechanical studies or long-term data on these techniques for treatment of multilevel ASD. Although the short-term clinical outcomes in our series were acceptable, one patient, who was treated for multilevel ASD, did not experience improvement in symptoms post-operatively and the reason for this is unclear. Thus, continued follow-up on these patients and further biomechanical studies are essential to confirm safety and durability of this procedure. In the future, we would like to report on long-term outcomes and collect this data prospectively.

Conclusion

As robot-assisted technologies for spinal surgery continue to advance there is potential for expanded indications in increasingly complex procedures, while also enabling minimally-invasive approaches and maintaining operative efficiency. Here, we demonstrated that RAN can enable pedicle screw instrumentation for ASD in a minimally-invasive manner which avoids revision, exposure and removal of prior hardware. These procedures were accomplished efficiently, safely and with minimal recovery time for patients. However, long-term clinical and radiographic outcomes are limited. Longer follow-up periods and further investigation of this technique in the form of biomechanical studies is essential.

Altogether, ASD is an important and common sequela of lumbar fusions and will continue to increase in incidence as more lumbar fusions are performed each year. Thus, it is essential to develop the most effective and efficient method to treat this disease. As supported by this series, RAN has potential to enable ASD reoperations in a minimally-invasive manner that avoids removal or revision of prior hardware and may be a valuable treatment option with continued study.

Conflict of Interest

There are no conflicts of interests.

Disclaimer

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