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Robotics planning in minimally invasive surgery for adult degenerative scoliosis: illustrative case

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BACKGROUND Minimally invasive surgical techniques are changing the landscape in adult spinal deformity (ASD) surgery, enabling surgical correction to be achievable in increasingly medically complex patients. Spinal robotics are one technology that have helped facilitate this. Here the authors present an illustrative case of the utility of robotics planning workflow for minimally invasive correction of ASD.

OBSERVATIONS A 60-year-old female presented with persistent and debilitating low back and leg pain limiting her function and quality of life. Standing scoliosis radiographs demonstrated adult degenerative scoliosis (ADS), with a lumbar scoliosis of 53°, a pelvic incidence–lumbar lordosis mismatch of 44°, and pelvic tilt of 39°. Robotics planning software was utilized for preoperative planning of the multiple rod and 4-point pelvic fixation in the posterior construct.

LESSONS To the authors' knowledge, this is the first report detailing the use of spinal robotics for complex 11-level minimally invasive correction of ADS. Although additional experiences adapting spinal robotics to complex spinal deformities are necessary, the present case represents a proof-of-concept demonstrating the feasibility of applying this technology to minimally invasive correction of ASD.

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KEYWORDS adult spinal deformity; ASD; robotics; adult degenerative scoliosis; minimally invasive; minimally invasive surgery

Adult spinal deformity (ASD) is one of the most challenging clinical entities in spine surgery, affecting 32%–68% of people over the age of 65 years. While not all patients require surgical intervention, when surgery is pursued it is often highly morbid, with significant intraoperative blood loss and soft tissue dissection.[1] For this reason, many efforts have been made to identify minimally invasive surgical (MIS) approaches for adult spinal deformity,[2–4] including the use of percutaneous instrumentation, lateral and oblique lumbar interbody fusion, and more recently, the incorporation of spinal robotics.[5]

Although best known for their utilization for the accurate placement of pedicle screws, spine robots and their accompanying planning software have a potentially expanding role to play in the management of ASD.[6] This planning software provides surgeons with a three-dimensional (3D) representation of the spinal anatomy.[7] Planning software (e.g., Surgimap)[8] has also previously been suggested as a useful clinical tool for guiding bone work (e.g., osteotomy location) and in situ rod maneuvers by providing the surgeon with multiplanar reconstructions showing projected patient postoperative alignment based on the proposed surgical plan. To this end, some groups, including that of Langella et al.,[9] have demonstrated that planning software such as Surgimap can predict postoperative alignment with a high degree of accuracy (κ 0.466–0.496). Kisinde et al. reported similarly good results using the X-Align (Medtronic), wherein the planning software was able to predict the postoperative

ABBREVIATIONS ADS = adult degenerative scoliosis; ASD = adult spinal deformity; BMI = body mass index; cMIS = circumferential minimally invasive surgery; CT = computed tomography; LLIF = lateral lumbar interbody fusion; MIS = minimally invasive surgical; MISDEF2 = minimally invasive spinal deformity surgery algorithm; MRC = multiple rod construct; OLIF = oblique lumbar interbody fusion; PI-LL = pelvic incidence–lumbar lordosis; PSO = pedicle subtraction osteotomy; PT = pelvic tilt; SVA = sagittal vertical axis; TK = thoracic kyphosis; 3D = three-dimensional.

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coronal Cobb angle within 6° and the postoperative sagittal Cobb angle within 9°.[10–13] As previously suggested by the senior author, spine robots have the potential to combine the above surgical strategies and technologies to greatly advance the ability to perform MIS correction of ASD.[7] Despite this, the literature documenting the application of robotics to MIS spinal deformity correction has been limited. The majority of the extant literature on spinal robotics has merely focused on the accuracy of pedicle screw instrumentation or on short-term outcomes (e.g., hospital length of stay, intraoperative blood loss) in short segment fusion for degenerative disease.[14]

The objective of the present report is to highlight the application of spinal robotics to the MIS correction of a patient with adult degenerative scoliosis (ADS). While it has been demonstrated that MIS deformity correction is associated with less pain, reduced narcotics usage, and shorter hospital stay,[5] the present case is, to our knowledge, the first description of the application of spinal robotics and planning for complex 11-level MIS ADS correction utilizing a multiple rod construct (MRC) with multipelvic fixation.

Illustrative Case

Patient Presentation

A 60-year-old woman presented with persistent and debilitating low back and leg pain limiting her function and quality of life. Standing scoliosis radiographs demonstrated ADS with a lumbar scoliosis of 53°, sagittal vertical axis (SVA) of 3.7 cm, a pelvic incidence–lumbar lordosis (PI-LL) mismatch of 44°, pelvic tilt (PT) of 39°, and thoracic kyphosis (TK) of 5° (Fig. 1). The patient was classified as class III according to the minimally invasive spinal deformity surgery algorithm (MISDEF2) criteria (flexible spine, no prior fusion, utilization of expandable cage technology for her procedure). Due to her body mass index (BMI) of 38.4 kg/m^2, a minimally invasive approach was offered with a first stage T12–S1 oblique lumbar interbody fusion (OLIF) followed by a second-stage percutaneous T9–ilium multiple rod posterior spinal fixation and fusion. Robotics planning software (Mazor X Robotics Planning Software with X-Align, Medtronic Sofamor Danek) was utilized for preoperative planning to simulate correction of her scoliosis and design of the multiple-rod 4-point pelvic fixation posterior construct.

FIG. 1. Anteroposterior (**left**) and lateral (**right**) radiographs demonstrating adult degenerative scoliosis with associated sagittal imbalance.

First Stage: T12–S1 Preoperative Planning and Intraoperative Technique

The placement of 6 interbodies from T12–S1 was simulated within the robotics software from a preoperatively obtained computed tomography (CT) scan with predictive coronal and sagittal correction as an assessment of an appropriate surgical plan. The software allows for an "ideal" correction, assuming that there is full movement and apposition of the endplates to the cage geometry chosen, which notably may not always be clinically achieved due to facet hypertrophy or a rigid deformity. The patient then underwent an MIS T12–S1 OLIF as her first stage with the placement of 4 lateral expandable titanium cages at T12–L4 and 2 lateral anterior lumbar interbody fusion (ALIF)-type titanium cages at L4–S1 (Fig. 2). Standing radiographs were then obtained to determine if any further coronal or sagittal correction was needed or if her second stage could proceed with purely percutaneous placement of instrumentation (Fig. 3). Because of the achievement of her predicted correction, the second stage was planned to be percutaneous without any additional active correction beyond her prone positioning.

Second Stage: T9-Ilium Preoperative Planning and Intraoperative Technique

A minimally invasive MRC and fusion from T9-ilium was then planned with the robotics software utilizing a preoperative CT obtained after her first stage (Fig. 4A). Due to her BMI and the known risk of lumbosacral pseudarthrosis and implant failure after correction of ADS,

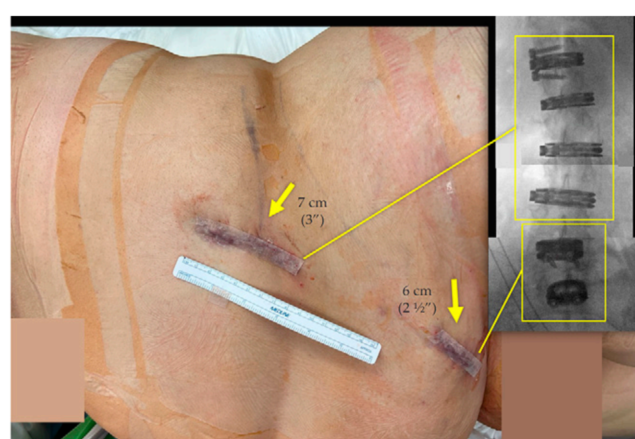

FIG. 2. Intraoperative image of the lateral incisions used for the first stage T12–S1 oblique lumbar interbody fusion. Insets demonstrate the intraoperative fluoroscopy image with all 6 interbodies with the T12–L4 cages placed through the proximal 7-cm incision and the L4–S1 cages placed through the distal 6-cm incision.

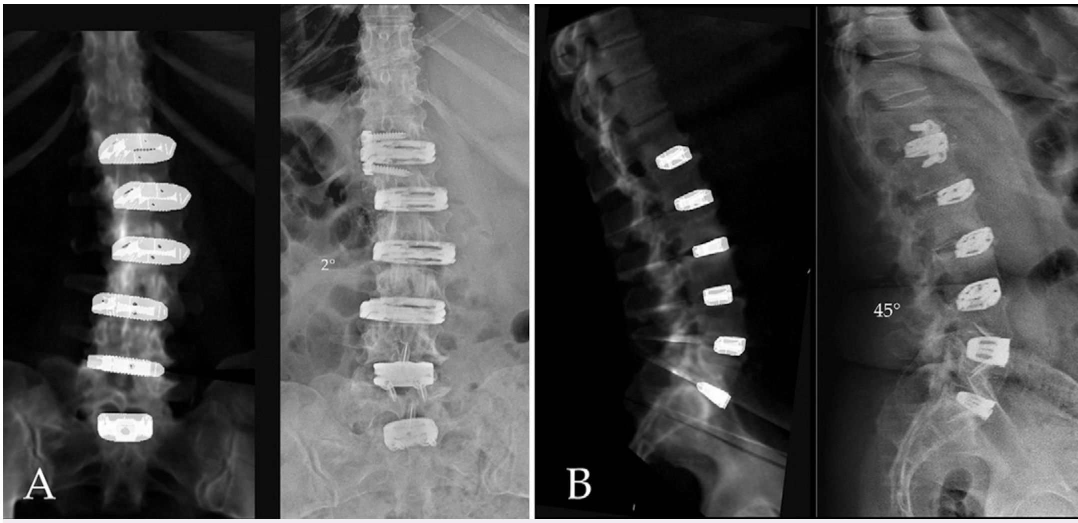

FIG. 3. A: Predictive software plan compared with standing anteroposterior lumbar radiograph after the first-stage T12–S1 oblique lumbar interbody fusions. **B:** Predictive software plan compared with standing lateral lumbar radiograph after the first-stage T12–S1 oblique lumbar interbody fusions.

multiple rods and pelvic fixation points were designed. A simulated rod appears after the sequential placement of each pedicle and iliac screw to ensure appropriate planar alignment. Satellite accessory rods were planned through the placement of screw trajectories more lateral-to-medial outside the main rod (left T12, right L2 and L3); while satellite rods can be placed in open cases through the use of dual-headed screws or domino connectors, these options are prohibitive in MIS and so these rods were placed without direct connection to the main rod. Great attention is placed to the extension towers from L4 to S2 due to their convergence (Fig. 4B), and minor adjustments to pedicle screw trajectory can be made in the sagittal plane to still ensure both a transpedicular screw without tower collections through the skin. Two patient-specific rods are made for the main rods that correlate to her planned and targeted alignment.

The patient then underwent MIS percutaneous placement of pedicle screws from T9-ilium with robotic assistance (Mazor X Stealth Edition, Medtronic Sofamor Danek). Screws are placed proximal (T9) to distal (S1) with all iliac screws placed last. An intraoperative CT scan is obtained to confirm appropriate screw placement, and a navigated burr is then used to decorticate and drill out

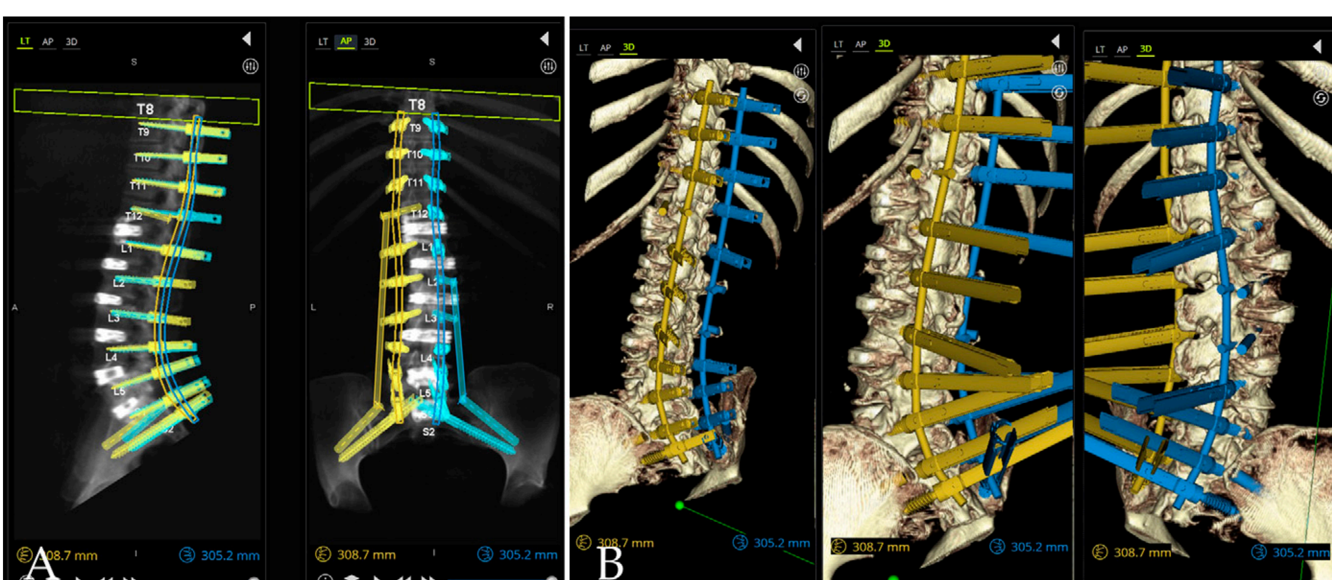

FIG. 4. A: Lateral and anteroposterior software plan showing 2 planar main rods from T9–S2 with a left T12 satellite rod and a right L2 and L3 satellite rod, both of which have separate connections to additional iliac screws. **B:** A 3D reconstruction of the plan with percutaneous towers for additional granular planning to ensure there are no tower collisions at L4–S2 due to convergence at the expected lumbar lordosis.

the proximal levels' facet joints through the percutaneous incisions (pedicle subtraction osteotomy [PSO]) that are then packed with bone graft with a funnel. Rods are then passed using percutaneous technique, which, despite the number of levels, was not prohibitive due to the precision of the preoperative planning. The satellite rods are secured first so their towers can be removed from the workspace, followed by the main rods; a long-film radiograph is then obtained to confirm appropriate and acceptable alignment (Fig. 5). All towers are then removed, set screws final tightened, and closure proceeds in the usual fashion.

Postoperative Course

The patient recovered as an inpatient in the intermediate care unit without the need for an intensive care unit stay. There were no blood transfusions needed. Standing radiographs were obtained, which showed good apposition to the expected preoperative plan

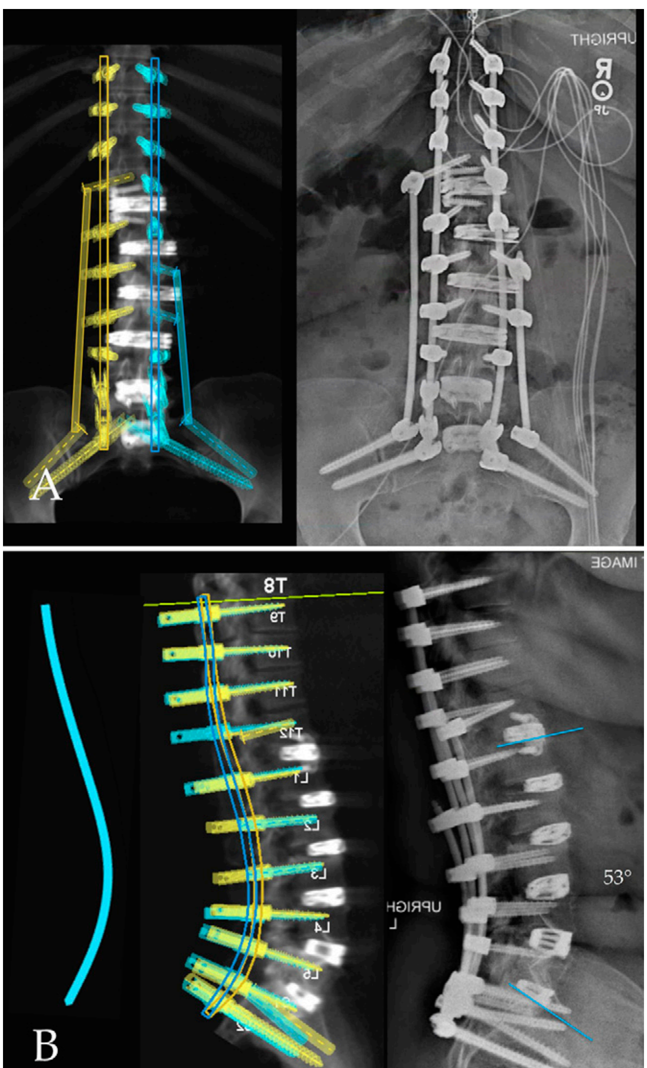

FIG. 5. A: Intraoperative long-film radiograph showing percutaneous placement of all screws with the screw towers connecting the satellite rods already removed. **B:** Intraoperative image showing minimally invasive percutaneous placement of screws and 3 rod passers in view.

and patient-specific rods (Supplementary Fig. 1). Standing scoliosis radiographs obtained at the follow-up showed improvement in her radiographic parameters with a lumbar scoliosis of 2°, SVA of 4.3 cm, PI-LL mismatch of 3°, PT of 22°, and TK of 32° (Supplementary Figs. 2 and 3). At the last follow-up of 9 months, she was walking independently with near resolution of her back pain and complete resolution of her leg pain.

Discussion

Observations

Both open and minimally invasive (MIS) approaches can be applied to the correction of ASD, and several groups, notably the International Spine Study Group,[15] have published decision-making aids to help guide the selection of technique based on a patient's underlying deformity. However, in general, these have yet to incorporate spinal robotics and planning software, which have demonstrated significant advancement over the past several years. Although still undergoing continued improvement, these tools offer the ability to maximize instrumentation placement accuracy and improve consistency in care delivered across patients, and in so doing minimize the complications of ASD correction surgery.[16] While much of spinal robotics research and development has focused on advancements in hardware, the greatest utility to spine surgeons is provided by the surgical planning software, which continues to accumulate advancements at a rapid pace. We attempt to highlight the application of these technologies to ASD correction through illustration of a case involving ADS.

For patients undergoing ASD correction, the goals of surgery are restoration of age-normalized sagittal and coronal alignment, and, where present, decompression of the neural element(s). Open surgery has been the mainstream approach since the adoption of modern spine surgery; however, it is associated with significant intraoperative blood loss and a high perioperative complication profile. It consequently is not a feasible option for many patients, especially those with multiple medical comorbidities, as ADS is common among the steadily increasing segment of the US population over 65 years of age. For this reason, MIS techniques have been developed to facilitate adequate correction while affording an acceptable risk profile for ASD correction surgery, with the hope of reducing intraoperative blood loss as well as postoperative hospital length of stay and recovery times.

For these reasons, MIS techniques have become widely adopted for ASD correction surgery and have evolved to feature numerous variations and subcategories that can be tailored to the severity of the deformity and patient symptoms: (1) MIS decompression only or with fusion of listhetic level; (2) multilevel MIS surgery with or without decompression and interbody fusion; (3) circumferential MIS (cMIS) involving 360° deformity corrrection, PSO, and expandable cage technology, or hybrid-open approaches; and (4) open surgery with osteotomies and possible extension of fusion to the thoracic spine.

In many instances, MIS decompression (with or without fusion) alone will not suffice when greater correction and stabilization is needed. Accordingly, the cMIS approach often involves lateral lumbar interbody fusion (LLIF) followed by posterior percutaneous pedicle screw fixation for further long-segment correction and stabilization of the deformity. The advantages of LLIF as a workhorse correction tool in cMIS include its robust applications for both sagittal and coronal deformity correction that also effectively restore disc height and thus indirectly decompress the neural elements in a manner that preserves the anterior and posterior longitudinal ligaments and thereby maintains the stability of the spinal column.

While these 4 main approaches (outlined by the MISDEF2) to MIS ASD correction—a rapidly evolving field within spine surgery—have gained popularity for their applications in ADS correction, these applications have been limited to mild-to-moderate cases of ADS. However, our case demonstrates that the same tenets upon which cMIS and hybrid approaches have been based can be extrapolated to the most complex deformity cases, including that which we describe herein: an 11-level MIS ADS correction surgery featuring MRC with multipelvic fixation that was planned with great precision utilizing the robotics planning software for a patient with class III degenerative ASD.

For the patient described in this report, several different considerations were taken into account in preparation for the robotics surgical planning phase. Clinically, the patient reported both back and lower extremity pain refractory to medical management, meaning that surgery was strongly indicated. Ultimately, as previously mentioned, the patient was categorized as MISDEF2 class III based on her flexible, unfused spine and alignment parameters.

With recent innovations in spinal robotics and robotics planning, the way in which surgeons approach MIS deformity correction is continuously advancing. This has necessitated the development of new algorithms that can determine the appropriate surgical approach for ASD correction based on radiographic parameters such as PI-LL mismatch, SVA, and PT—the measurements that have been linked to pain and functional outcomes. Previously, in 2014, Mummaneni and colleagues[17] developed the MIS deformity (MISDEF) algorithm that utilized sagittal parameters to identify the most appropriate MIS technique for patients with ASD. The group then subsequently released a new and improved algorithm, the MISDEF2, in 2020. While the initial focus of the original MISDEF was SVA, the MISDEF2 algorithm for adult degenerative spinal deformity performs initial allocation based on whether or not the patient has a fused and/or rigid spine. If they do not, they will ultimately be grouped into class I (MIS decompression ± fusion), class II (multilevel MIS surgery ± decompression ± LIF), or class III (cMIS with ACR, pedicle subtraction osteotomy, expandable cage implantation, or hybrid open approach). However, to qualify for class IV status, the patient must have had prior fusion or rigid spine along with preexisting multilevel instrumentation or $>$ 10 segments requiring treatment.

OLIF was suitable for the extensive 11-level case because, similar to LLIF, this approach allows for minimally invasive placement of interbody cages that allow for correction of sagittal and coronal imbalance including the L5–S1 level. Subsequently, percutaneous T9-ilium posterior spinal fixation and fusion were performed with the assistance of preoperative robotics planning software to allow for the design of the multiple-rod 4-point pelvic fixation posterior construct. One of the difficulties associated with MIS ASD correction is the need to place pedicle screw instrumentation without direct visualization in such a fashion that a rod/longitudinal member can be placed to connect all segmental members. Such 3D planning is difficult, but as demonstrated here, surgical planning software can assist with this to allow for proper screw entry points. Additionally, pedicles contained within the concavity of the deformity can be hypoplastic or atrophic, which further complicates the placement of segmental instrumentation.[18] Again, spinal robotics and planning software can assist with identification of a suitable entry point and trajectory that will allow for adequate purchase while ensuring the screw can be captured.

A previous example of the successful application of spinal robotics to the management of ADS was recently published by Pham et al. In that study the authors present the results of a series of 6 complex cases of ASD that were treated using robotics planning software (X-Align) and robot-assisted transfascial placement of pedicle screws. All patients experienced significant improvement in their preoperative pain and in all cases there was correction of the underlying deformity to within age-specific alignment goals.[19]

In the present case, robotics planning was used for a more complex ADS pathology. This is, to our knowledge, the first reported MIS correction of 11-level ADS using robotics planning in the current literature. Ultimately, this case adds further evidence that MIS is gaining momentum in spinal surgeries and that the addition of robotics planning will pave the way for correction of more complex pathologies.

The present case demonstrates effective incorporation of surgical planning software into the management of ASD. As this application of robotics in spinal deformity surgery represents a new frontier, future studies are needed for further evaluation of the accuracy of this navigation software and whether guided correction is superior to correction obtained by conventional methods. Furthermore, new technology enabling correction through combined software planning and customized implants adds a further layer of complexity that must be evaluated. Ultimately, although these technologies appear to hold great potential, it still remains to be seen whether custom implants and advanced planning software are cost-effective.

Lessons

Minimally invasive approaches to ASD correction are becoming increasingly popular; they reduce the morbidity of surgery and in so doing may make surgery feasible for a greater proportion of patients. Surgical planning software and spinal robotics seem well poised to allow the wider-spread adoption of these MIS techniques. In the present study we demonstrate the application of both to the management of ADS. This highlights the feasibility and safety of applying spinal robotics and planning software to MIS correction and additionally underlines the need for further investigations regarding the efficacy and cost-effectiveness of this approach.

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Disclosures

Dr. Pham reported personal fees from Medtronic, Globus, and Thompson Surgical outside the submitted work.

Author Contributions

Conception and design: Pham. Acquisition of data: Pham, Brown, Quadri. Analysis and interpretation of data: Pham, Brown, Quadri, Pishva. Drafting of the article: all authors. Critically revising the article: all authors. Reviewed submitted version of the manuscript: all authors. Administrative/technical/material support: Pishva. Study supervision: Pham.

Supplemental Information

Online-Only Content

Supplemental material is available with the online version of the article.
Supplementary Figs. 1–3. https://thejns.org/doi/suppl/CASE22520.

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