Chapter

Robotic Guided Minimally Invasive Spine Surgery

Ram Kiran Alluri, Ahilan Sivaganesan, Avani S. Vaishnav and Sheeraz A. Qureshi

Abstract

Minimally invasive spine surgery (MISS) continues to evolve, and the advent of robotic spine technology may play a role in further facilitating MISS techniques, increasing safety, and improving patient outcomes. In this chapter we review early limitations of spinal robotic systems and go over currently available spinal robotic systems. We then summarize the evidence-based advantages of robotic spine surgery, with an emphasis on pedicle screw placement. Additionally, we review some common and expanded clinical applications of robotic spine technology to facilitate MISS. The chapter concludes with a discussion regarding the current limitations and future directions of this relatively novel technology as it applies to MISS.

Keywords: minimally invasive spine surgery, robotic spine surgery, spinal robotics, minimally invasive surgery

1. Introduction

Spine surgery has continued to evolve over the past several decades and significant advancements have been made in operative techniques, biomaterials, implant design, and intraoperative imaging. Many of these advances have been catalyzed by the advent and progression of minimally invasive spine surgery (MISS). MISS allows for less muscle dissection, smaller incisions, decreased post-operative pain, faster recovery, and potentially improved functional outcomes [1–4]. While MISS has evolved from the time of its inception, in part due to advancements in retractors, instruments, and intraoperative imaging, the goals have remained the same: adequate decompression of neural elements with or without vertebral column stabilization, while minimizing soft tissue trauma.

The unique challenge of MISS is that accurate identification of complex three-dimensional landmarks, decompression, and instrumentation all rely substantially on intraoperative imaging, given that anatomic landmarks are often not easily visualized or palpable. The reliance on intraoperative imaging and the resultant occupational radiation exposure to the surgeon and perioperative staff during MISS has been met with concern [5–7], and has contributed to the limited adoption of MISS techniques by some surgeons [8].

Partly in response to these concerns, the use of real-time image guidance and navigation technologies - not dependent on traditional static fluoroscopic imaging - have rapidly evolved over the past two decades. So too have the clinical applications for robotic technology in MISS in an attempt to further improve accuracy, decrease complications, and improve patient-reported outcomes.

2. Robotic spine surgery

Robot-assisted surgery has been performed in multiple surgical sub-specialties including urology, gynecology, and general surgery. Spine surgeons, however, have been relatively late adopters of robotic technology. This may be due to the fact that spine procedures are often technically demanding and rely upon refined fine motor skills when working around neural and vascular elements, all of which can be even more challenging when utilizing small incisions and working corridors with MISS. However, robot-assisted MISS may play a role in allowing surgeons to improve manual dexterity, decrease tremors, and provide stability for instrumentation by providing a fixed working angle that increases accuracy and precision. While there are many purported benefits for robot-assisted spine surgery, many early attempts at integration of this technology into MISS were met with significant challenges.

Early problems with robot-assisted spine surgery involved errors in synchronization of intraoperative fluoroscopic images with preoperative three-dimensional (3D) imaging, deflection of the robotic arm resulting in decreased accuracy of navigation and instrumentation, challenges with the user interface, and software crashes [9]. One early study documented technical or clinical errors in over 50% of spine procedures performed using robotic assistance [10]. In the setting of these early challenges, the lack of initial clinical benefit, significant infrastructure cost, and a steep learning curve, widespread adoption was not initially seen for this potentially beneficial technology [11, 12]. Over recent years, however, the integration of 3D computer-assisted navigation, improvements in the software and user interface, and automation of the robotic arm have driven a resurgence of interest in the use of robotic technology in MISS.

Currently there are three United States (US) Food and Drug Administration (FDA) approved robots for spine surgery. The Mazor X (Medtronic Spine, Memphis, TN, USA) was launched commercially in 2016 and has recently been integrated with Stealth Navigation (Medtronic Navigation Louisville, CO, USA), which allows for real-time instrument tracking intraoperatively. The ExcelsiusGPS (Globus Medical, Inc., Audubon, PA, USA) launched in 2017 and was one of the first robotic spine systems with fully integrated navigation, also allowing for real-time instrument tracking. The ROSA Spine (Zimmer Biomet, Montpellier, France) is the third and final US FDA-approved robot to assist in spine surgery. It was originally approved in 2016, and a recent upgrade - the ROSA ONE - was approved in 2019. Compared to the previously mentioned robots, the ROSA platform allows for navigation and instrumentation across cranial, spine, and total knee arthroplasty procedures, making it a multi-purpose technology with hospital-wide applications. A fourth offering, the TiRobot (TINAVI Medical Technologies, Beijing, China), was approved in China as of 2016, and can also be used for other orthopedic applications outside of spine surgery.

3. Advantages of robotic spine surgery

In MISS, robotic technology is most commonly employed to place percutaneous pedicle screws without direct visualization of anatomic landmarks. The use of robot-assisted pedicle screw placement has been widely researched in terms of accuracy, proximal facet violation rates, radiation, operative time/efficiency, clinical outcomes, and complications as compared to traditional 2D fluoroscopic and 3D navigated pedicle screw placement.

3.1 Pedicle screw placement accuracy

Traditionally placed free-hand pedicle screws have relied on the identification of anatomic landmarks and intraoperative fluoroscopy. Misplaced screws can result in neurovascular complications, continued low back pain, and the potential for earlier-onset adjacent segment disease. In MISS surgery, the absence of directly visualized bony anatomy traditionally mandated even further reliance on fluoroscopic imaging, however 3D intraoperative real-time navigation has improved over the last decade and is readily available for most MISS procedures. While 3D navigation was a significant advancement in MISS, intraoperative navigation is not without its limitations, as it still relies upon surgeons' hand-eye coordination and focus, which can be compromised and fatigued with repetitive tasks (as is the case with multi-level fusion cases). The use of a robotic arm may allow for more accurate, precise, and reproducible pedicle screw placement by minimizing both human error and the mental/physical burden on surgeons [13, 14].

One of the first papers investigating the accuracy of robotic assisted pedicle screw placement demonstrated 91–98% accuracy depending on the plane assessed [15]. Since then, several studies have documented a 94–98% accuracy of pedicle screw placement with robotic systems [16–21]. Specifically comparing robotic-assisted to free-hand pedicle screw placement, two studies demonstrated significantly higher accuracy with robot-assisted placement [22, 23], and a third study demonstrated similar accuracy between the two pedicle screw techniques [21]. However, one prospective study did demonstrate decreased accuracy with robotic-assisted screw placement as compared to fluoroscopic-guided screws [24]. Given the varying results in the literature comparing robotic-assisted versus free-hand or fluoroscopically based pedicle screw placement, three recent high-quality meta-analyses have been performed based on published randomized controlled trials. Two of the meta-analyses demonstrated equivalent accuracy between the two techniques [25, 26], and a third demonstrated more superior accuracy with robotic assistance [27].

Studies comparing robotic-assisted pedicle screw placement versus 3D navigation techniques are fewer in number. Retrospective studies have demonstrated slightly higher accuracy with robotic-assisted screw placement compared to navigation-assisted screw placement. Laudato et al. demonstrated 79% versus 70% accuracy for robotic versus navigated screw placement, respectively [28]. Similarly, Roser et al. demonstrated 99% versus 92% accuracy for robotic versus navigated screw placement, respectively [29]. A recent meta-analysis demonstrated similar reduction in intraoperative and postoperative screw revision risk using robot or navigated screw placement, as compared to freehand techniques [30].

3.2 Proximal facet violation

The use of robotic-assisted pedicle screw placement can allow for precise preoperative or intraoperative planning of pedicle screw trajectories and accurate execution of the planned trajectory with assistance from the robotic arm. The ability to plan pedicle screw placement not only allows for optimization of the size and diameter of pedicle screws, but also allows for trajectories that avoid violation of the superior facet joint at the upper instrumented vertebral level. Violation of this joint can result in an increased risk of adjacent segment disease, which may compromise long-term clinical outcomes [31–33].

To date, three randomized-controlled trials [34–36] and one non-randomized prospective study [37] have demonstrated a reduced risk of superior facet joint violation when using robotic-assisted pedicle screw placement as compared to freehand or fluoroscopically based techniques. Two meta-analyses also demonstrated similarly decreased violation of the superior facet joint when robotic assistance was utilized [27, 38].

3.3 Radiation

Radiation exposure is another area of concern for MISS surgeons, and significant exposure can occur when fluoroscopy is used in the absence of image guidance and navigation. Compared to freehand instrumentation techniques, most studies have demonstrated significantly decreased radiation exposure with robotic-assisted pedicle screw placement [18, 21, 29, 39]. Only two studies have demonstrated no significant difference in radiation exposure between the two instrumentation techniques [24, 28]. When broken down by source of radiation exposure, robotic assistance may result in higher doses to the patient [24], but lower doses to the surgeon [23]. Ultimately, interpretation of these studies is challenging because there can be significant variability in imaging acquisition protocols, surgeon experience, source of radiation detection, and specific freehand instrumentation techniques. Overall, however, the general body of evidence seems to support decreased radiation exposure with robot-assisted instrumentation compared to traditional techniques that rely on fluoroscopy.

3.4 Operative time/efficiency

Several studies have attempted to compare the total operative time and time per screw insertion when using robot-assisted versus freehand techniques [18, 21, 29, 40]. However the comparative results of these studies can be confounded by variables related to approach (open versus percutaneous), the definition of operative time, and surgeon experience. Specific studies applicable to MISS have compared percutaneous pedicle screw placement using a robot versus fluoroscopy-based techniques, but unfortunately they did not report operative time [41, 42]. A cadaveric study by Vaccaro et al. demonstrated that overall surgical time was similar between MISS pedicle screw placement using conventional fluoroscopy versus robot assistance [43]. The actual robot-assisted time per screw was actually lower, but this was offset by a longer setup time [43].

3.5 Impact on clinical outcomes and complications

Studies investigating the additive clinical benefit for robotic assistance in MISS compared to traditional fluoroscopically or 3D navigated MISS are lacking. Most of the literature compares traditional open procedures to robot-assisted MISS, and some of these studies have demonstrated decreased length of stay and faster postoperative recovery with the latter [44, 45]. Other studies comparing open procedures to MISS robot-assisted procedures have demonstrated lower infection rates and dural tear rates in the robot-assisted cohorts, but these studies were not powered to detect a significant difference [18, 23]. A recent study by Menger et al. projected robotic surgery to be more cost-effective secondary, in part, due to fewer revision surgeries and less postoperative complications [46]. As stated previously, none of these studies have specifically compared the additive benefit of robotic-assistance to traditional MISS procedures. If utilizing a robot allows surgeons who traditionally perform open surgery to convert to some MISS surgery with similar or improved instrumentation accuracy, decreased radiation, improved operative time, and potentially lower complications, the previously reported benefits of MISS surgery may become available to a greater number of patients.

4. Minimally invasive spine surgery robotic applications

4.1 Robotic-assisted transforaminal lumbar interbody fusion

Transforaminal lumbar interbody fusion (TLIF) allows for circumferential fusion, restoration of disc space height, and both direct and indirect neural decompression. Open TLIF has been associated with significant early postoperative morbidity secondary to extensive muscle retraction and dissection, which may result in increased postoperative pain, decreased mobility, and impaired overall function [47, 48]. In response to the limitations of open TLIF, the MI-TLIF was developed and has been shown to cause less postoperative pain, faster recovery, shorter hospitalization, and comparable functional outcomes to the open TLIF [49–51].

Traditionally, pedicle screws were placed percutaneously under fluoroscopic guidance for the MI-TLIF, resulting in potentially decreased accuracy and increased radiation exposure, as discussed in previous sections of this chapter. Until recently, the integration of spinal robotics into MI-TLIF has largely been confined to facilitating pedicle screw placement, and previous studies have reported on the feasibility and integration of robotics into the MI-TLIF workflow as well as the high pedicle screw placement accuracy [52–54]. Comparative studies assessing broader benefits of spine robot utilization versus traditional fluoroscopic or 3D navigation are lacking in the literature. De Biase et al., compared robot-assisted versus fluoroscopy-guided MI-TLIF procedures and reported no difference in operative time [55]. The study was limited by lack of comparative radiation, radiographic or functional outcomes between the two treatment groups [55].

A previous limitation of robotic MI-TLIF, as compared to 3D navigation, was that older robotic platforms did not allow for real-time navigation outside of pedicle screw placement. However, newer robotic software platforms now enable pre−/intra-operative planning and navigation for tube placement, interbody cage placement, and disc space preparation (**Figure 1**). Evidence-based benefits of these real-time navigated features have yet to be established in the spinal literature. As robotic integration into MI-TLIF procedures continues to evolve and expand, further research is needed to investigate the possible additive benefit with regards to instrumentation accuracy, operative efficiency, radiation exposure, clinical outcomes, and fusion rates.

4.2 Robotic-assisted lateral and oblique lumbar interbody fusion

Lateral lumbar interbody fusion (LLIF) and oblique lumbar interbody fusion (OLIF) are minimally invasive techniques that can avoid some of the risks associated with anterior or posterior interbody approaches to the spinal column. Traditionally, after the interbody device is placed in LLIF and OLIF procedures in the lateral position, the patient is "flipped" to the prone position for pedicle screw instrumentation and posterior stabilization. Recent studies have begun to investigate the placement of posterior instrumentation in the lateral position, to avoid the "flip," and initial studies have demonstrated improved operative efficiency, less blood loss, and less postoperative ileus with single position lateral circumferential fusions [56].

One of the challenges of performing MISS posterior fixation in the lateral position is pedicle screw instrumentation. Interpreting fluoroscopic imaging, establishing accurate navigation, and the ergonomics of placing the down-sided pedicle screws can be difficult. Placement of robot-assisted pedicle screws in these procedures may offer a significant advantage as the robotic arm acts as a steady holding device, locking the trajectory of the planned pedicle screw, and thereby mitigating

Figure 1.
Intraoperative planning using a spine robot's integrated navigation platform. This particular platform allows for intraoperative planning of pedicle screw trajectories, diameter, and length. Additionally, interbody placement can be planned, and navigated instruments can allow for targeted intraoperative disc preparation prior to interbody cage placement. Lastly, tube trajectories (if applicable) can also be planned.

some of the ergonomic challenges of placing these screws. The accuracy of pedicle screws with robot-assistance in the lateral position has been recently investigated and initial studies demonstrate 98% accuracy [57]. Images demonstrating this technique are shown in **Figure 2**.

As described in the MI-TLIF section, the latest iterations of software in some spinal robotics systems can allow for real-time navigation during tube placement, interbody cage placement, and disc space preparation. An additional benefit in the lateral or oblique position is that the robotic arm can be used to stabilize the retraction system, avoiding the need for a table mounted retractor (**Figure 3**). As these are all relatively recent advancements for robot-assisted LLIF and OLIF procedures, studies demonstrating a clinical benefit have yet to be performed.

4.3 Robotic-assisted MISS deformity correction

The majority of research on MISS has focused on addressing degenerative pathology, but as MISS continues to evolve, the utilization of MISS principals to address adult spinal deformity, without compromising outcomes, continues to be investigated. The traditional goals of adult spinal deformity surgery encompass restoration of sagittal and/or coronal balance, adequate neural element decompression, and achieving a solid arthrodesis. These goals may be achieved through MISS techniques – for example, lordosis can be restored through anterior column realignment procedures such as the LLIF and OLIF or posterior-based procedures such as MI-TLIF. Fixation can of course be achieved through percutaneous pedicle screw placement [58, 59]. In multi-level constructs, robotic assistance may have a cumulative benefit as the time saved at each subsequent level will have an additive benefit in longer deformity constructs. As discussed above, the use of a spinal robot may assist in executing these MISS procedures, just as is the case for patients with primarily degenerative pathology. However, evidence demonstrating the additive benefit of robotic-technology in MISS deformity procedures is sparse.

Figure 2.
Intraoperative placement of pre-planned pedicle screws for a multilevel lateral lumbar interbody fusion. In this image the down-sided pedicle screws are being placed based on the planned trajectory. The stabilized robotic arm facilitates the challenging placement of these screws, eliminates the need for interpretation of fluoroscopic imaging in the lateral position and improves the overall ergonomics and ease of placing these screws.

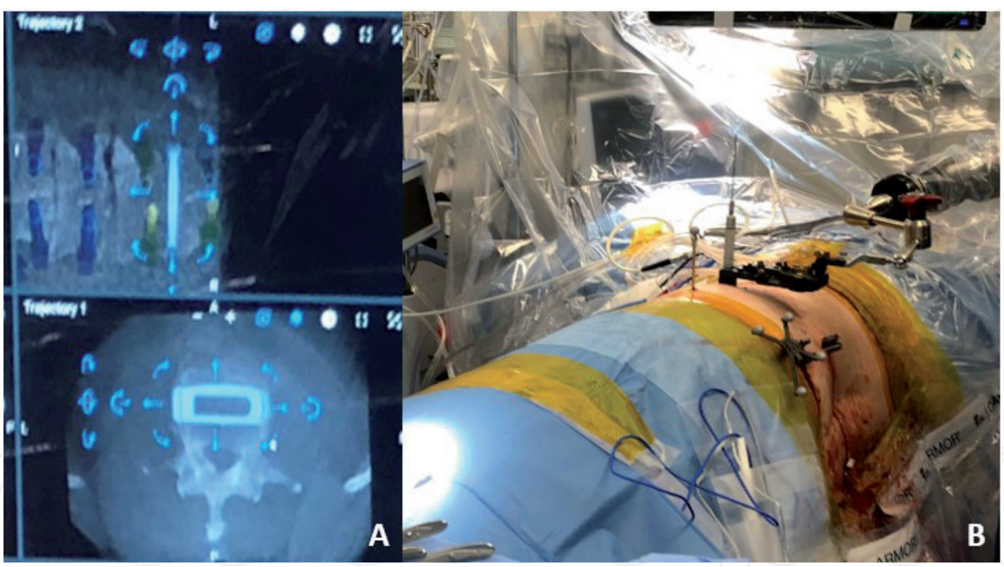

Figure 3.
The intraoperative navigation platform for this spine robot is used to plan the interbody placement in a multilevel lateral lumbar interbody fusion (A). The spine robot arm is then used to localize the trajectory of the planned retractor placement and the stabilized arm can be used to secure the retractor, avoiding the need for a table-mounted retractor (B).

One aspect of area robotic utilization within the field of adult spinal deformity that has received research interest is the safe and accurate placement of pelvic screw fixation. MISS percutaneous pelvic screw fixation using traditional fluoroscopy allows for less soft tissue dissection, as compared to the traditional open technique, which may result in a quicker recovery and less postoperative complications [60]. The additive use of robotic-assistance allows for preoperative planning, may increase accuracy, and decrease the technical difficulty in placing MISS pelvic fixation. A recent study demonstrated high accuracy with no intra- or postoperative complications using robotic-assistance for pelvic screw fixation in adult deformity patients [61].

5. Current limitations of robotic spine surgery

Over the past decade, robot-assisted surgery has played a significant role in the advancement of MISS, but there are limitations preventing its widespread adoption. These hurdles range from technical issues, cost, and operating room efficiency, to the learning curve associated with safely incorporating the robot into the operating room. Initial iterations of spine robots were met with concerns regarding instrument skiving and tool deflection, registration failures, and a lack of real-time navigation. Newer software iterations, as well as advancements in the robotic arm and its associated end-effectors have partly addressed these concerns. With regards to cost, there is no denying the significant capital expenditure required to obtain a spine robot; however, there may be a cost savings stemming from decreased postoperative complications secondary to improved instrumentation accuracy [46]. Further cost-effectiveness studies are needed, however, particularly with regards to MISS [62]. Lastly, there is a learning curve associated with performing safe robotic spinal surgery, but that learning curve may not be as high as previously conceived. One study demonstrated that 30 screws would need to be placed before a noticeable improvement in efficiency was observed [63], and two other studies demonstrated that between 13 and 20 cases may be needed to obtain proficiency in robotic screw placement [64, 65].

6. Future of robotic spine surgery

The safe implementation of robotic-assisted spine surgery in MISS continues to make progress and newer generations of spinal robots with improved software and real-time navigation will allow for the robot to be utilized for more than just pedicle screw instrumentation. Spine robots with real-time navigation currently allow for surgeons to plan tubular retractor trajectories, interbody placement, and navigated disc preparation. As the software continues to improve, magnetic resonance imaging (MRI)-based registration and navigation may allow for robot-assisted disc and ligamentum flavum resection as well as soft tissue tumor resection. Additionally, as burrs become compatible with the spinal robot, pre-operative planning and precise intra-operative execution of bony decompressions may become possible. Even in the domain of instrumentation, there is room for further advancement. While current spine robots only allow for assisted pedicle screw placement, future iterations may allow for fully automated pedicle screw placement. Yet another possibility is the syncing of intra-operative data from multiple robotic systems, which may one day enable machine learning and artificial intelligence algorithms to make real-time, intra-operative suggestions to surgeons based on previous surgeries. These future directions for robot-assisted MISS will likely continue to promote an increased integration and utilization of robotics into MISS.

Author details

Ram Kiran Alluri[1], Ahilan Sivaganesan[1], Avani S. Vaishnav[1] and Sheeraz A. Qureshi[1,2]*

1 Hospital for Special Surgery, New York, NY, USA

2 Weill Cornell Medical College, New York, NY, USA

*Address all correspondence to: sheerazqureshimd@gmail.com

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