

Robotics in Spinal Surgery: The Future is Here

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Surgical procedures of the spine benefit from fine motor coordination, a highly experienced surgeon, and the best available technology. Robotic systems have been used in many surgical disciplines, including spinal surgery. This review will present the advantages and disadvantages of robot-assisted spinal surgery, as well as the most common applications and different types of robots used for spinal surgery. The robotic systems most often used in spinal surgery are master-slave systems and trajectory assistance robots. To date, robotic systems have been used with favorable outcomes in several types of spinal surgery, including posterior instrumentation, tumor resection, and vertebroplasty. Robot-assisted spinal surgery is an ongoing investigational field, and new research directions may lead to the development of very different robotic surgical devices in the future.

Key Words: Navigation, robot, robotic systems, spine, surgery

Abbreviations Used: CSF, cerebrospinal fluid; MIS, minimally invasive surgery; MR, magnetic resonance

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As spinal surgery has evolved, new techniques have been developed to address complex pathologies through smaller anatomical corridors, leading to better outcomes. Surgical procedures of the spine benefit from fine motor coordination, a highly experienced surgeon, and the best available technology,^{5,9,45} and it is clear that surgical robotic systems have established a foothold in medicine as an enabling technology.¹⁵ The rationale for using robotic systems started with the idea that robots would improve surgical dexterity by motion-scaling and tremor-filtering and that they would also eliminate fatigue-related errors.^{39,44} Furthermore, robots should have superior precision and nearly unlimited endurance and should be able to execute repetitive tasks without decreased performance.⁵⁰

In recent years, robotic systems have been used in many surgical disciplines, including gynecology, urology, cardiothoracic surgery, vascular surgery, and general surgery,⁴⁵ whereas robot-assisted spinal procedures have only become commercially available relatively recently.^{7,12}

We present an English-language literature review of articles published in the last 15 years that are related to robotic systems used in spinal surgery; articles related to imaging and diagnostic devices were excluded. The objective of this review is to present the current state of robotic-assisted spinal surgery, including the advantages and disadvantages of robotic systems, most common applications, and different types of robots used.

Advantages of Robotic-Assisted Spinal Surgery

Accuracy and Precision

Accurate image-guidance in spinal surgery can be used to identify the exact position and trajectory during a procedure and is one of the most important tools in the surgeon's armamentarium.^{11,18,19,23,26,27,30,37,43,51,52} Screw misplacement can lead to instability as well as neurological, vascular, and visceral injuries. Misplacement-related complications are reported in 1% to 54% of spinal surgeries,¹⁸ demonstrating a need for surgeons to improve accuracy and consistency in pedicle screw placement. These high complication rates are the main impetus for developing computerized navigation systems and robotic-assisted spinal surgery.⁵⁰ Robots can potentially help spine surgeons improve accuracy by positioning a guide tube over a preplanned target and can improve precision by scaling the surgeon's hand movements and reducing tremor; robots also minimize exposure to radiation.^{16,20,35}

Several retrospective analyses have shown comparable accuracy rates between robotic-assisted and conventional screw insertion techniques.^{18,19,33,48} Pechlivanis et al.³³ analyzed the accuracy of placing 133 percutaneous lumbar pedicle screws using robotic-assisted surgery. In the axial plane, 91.7% were placed exactly within the pedicle, and 6.8% deviated less than 2 mm. In the sagittal plane, 81.2% were exactly within the pedicle, and 9.8% deviated less than 2 mm.¹⁹ Sukovich et al.⁴⁸ successfully instrumented 14 patients using robot-assisted surgery. Screws were placed within 1 mm of the planned trajectory in 96% of the patients.^{18,19} In 2014, Marcus et al.²⁹ presented a systematic review of 5 large studies that included 1,308 placed pedicle screws. Robot-assisted placement was used for 729 screws, and fluoroscopic guidance was used for 579 screws. The authors reported satisfactory accuracy in 94.1% of robot-assisted placements and 92.7% of fluoroscopically guided placements.

Minimal Invasiveness

In theory, robotic systems can improve intraoperative localization, especially in patients with more challenging anatomy,^{18,19} while allowing access through smaller incisions. The development of smaller and smaller robotic manipulators and camera systems that are capable of fitting inside very tight spaces make these capabilities possible. Minimally invasive surgery offers several advantages to the patient: smaller incisions, lower risk of infection, and minimal muscle retraction, which can decrease postoperative pain, opioid use, and the length of hospital stays.^{7,21,22,28,34,36,45}

Radiation Exposure

Another major theoretical advantage is that robotic-assisted spinal surgery, especially minimally invasive surgery, may reduce radiation exposure since robotic placement decreases the need for using intraoperative fluoroscopy. However, the published reports on the amount of radiation exposure are inconsistent.^{3,6,45} Choi et al.,¹⁰ Lieberman et al.²⁶ and Kantelhardt et al.²¹ all reported significantly less radiation exposure with robot-assisted screw placement, while Roser et al.³⁹ and Marcus et al.²⁹ showed only a trend toward less radiation time and dosage with robot-assisted surgery, and Ringel et al.³⁸ and Schizas et al.⁴² noted no difference. It appears that these differences may be related to work flow issues related to the use of intraoperative imaging. Radiation exposure as a health hazard to medical personnel is an ever-increasing concern.^{13,47,49}

Operative Time

Theoretically, if a robot enables easier access with rapid response and holds an accurate and precise surgical trajectory through a less invasive exposure, surgical time could be decreased. However, additional factors regarding operative time require consideration: additional setup time is needed to mount and register a robot, and planning time is needed for the surgeon

to identify the desired trajectory. Current data indicate that the decrease in surgery time due to the performance of the robot is offset by the increased setup and planning time. Most available studies^{21,26,27,29,38} reported no significant time difference between robot-assisted and fluoroscopically guided procedures.

Disadvantages

The main disadvantage of robot-assisted spinal surgery is its technological complexity relative to fluoroscopically guided surgery, which leads to a large increase in potential sources of surgical error. Some of these technological errors may be difficult for the inexperienced surgeon to recognize; therefore, poor outcomes may occur if the technology is relied upon blindly.

A particularly troublesome error that has been documented with robot-assisted techniques is poor accuracy between preoperative three-dimensional images and the real-time anatomy of the patient.⁵⁰ The source of this error can be poor image quality, inaccurate registration, inaccurate or inadequate patient tracking, or a combination of these factors. In some reports, cases of noticeable inaccuracy were dealt with by simply reprogramming the screw trajectory a few millimeters by eye; in other cases, the screws were removed and repositioned by hand.⁴⁰ Devito et al.¹¹ reported their results with the planned robot-assisted insertion of 3,912 pedicle screws. Surgeons were unable to insert 16.4% (641) of the screws with the robotic system because of inaccurate registration, inability to reach the planned trajectory, inability to compensate for respiratory movement, technical issues, or the surgeon's decision to abort the procedure. In 2012, Hu et al.¹⁹ reported results for the planned robot-assisted insertion of 1,085 pedicle screws in 102 patients. In these patients, 949 screws (87.5% of the planned screws) were successfully inserted and 110 screws (10.1%) were placed manually due to poor registration or issues related to deformity, high

body mass index, or poor bone quality. Eleven of the robotically placed screws (1.1%) were misplaced, without any neurological deficit reported. Fifteen screws (1.4%) were not placed due to the intraoperative determination that they were not needed for the stability of the construct.

Some authors have mentioned a possible shift in the entry point and trajectory of screw insertion with robot-assisted systems when the amount of surrounding soft tissue is excessive.⁵⁰ This offset should be considered when planning surgery in obese patients. In addition, some authors have reported a “cannula sliding off” an angled bone surface; this situation typically occurs lateral to the facet joint, leading to inaccuracy.^{38,40}

Other disadvantages of robot-assisted surgery relative to fluoroscopically guided methods include the cost of training the whole surgical team in robotic surgery, the time-consuming learning curve associated with the adoption of new technology, and the high cost of the robotic surgical system itself.⁷

Uses of Robotic Systems in Spinal Surgery

Posterior instrumentation with pedicle screws and rods is by far the most common use for robotic systems in spinal surgery. As discussed previously, some authors have reported that the use of robotic localization to place screws and implants has increased accuracy and precision.^{41,42,45,48}

Robotic systems have also been used successfully for other spinal procedures, such as tumor resections, vertebroplasties, anesthetic blocks, and revision surgery after previous spinal surgery, and for conditions such as spondylolisthesis, stenosis, spondylolysis, ankylosing spondylitis, vertebral fractures, and osteomyelitis.^{6,19,32}

Types of Robots

Two major categories of surgical robots, based on the input that is used

to control movements, are used in spinal surgery: master-slave systems and trajectory assistance robots. Below, we describe one prominent, commercially available example for each of these two types. Robotic systems used for diagnostic or imaging applications were excluded from discussion.

Master-Slave Systems

With master-slave robotic systems, the surgeon fully controls and manipulates the master system and visualizes the operation on a video screen.⁴⁶ The “slave” system consists of mechanical actuators that respond with some amount of computer processing to inputs (typically joystick movements) of the surgeon into the master system.

The daVinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) is the most recognized and used master-slave robotic system. It was approved for general surgery in 2000 and has been used within the past few years in several types of spinal surgery, such as anterior lumbar interbody fusion, thoracolumbar tumor resection, transoral odontoidectomy, and paraspinal tumor removal, and it has been tested under several research protocols with great success.^{6,7,24,25,31,34,38,45} The daVinci robot is comprised of 4 arms: 3 for surgical manipulation and 1 for a camera. Each arm has 6 degrees of freedom and is controlled by 2 hand controls and 2 foot pedals. It provides three-dimensional visual cues, enabling precise dissection and meticulous bleeding control by scaling the surgeon’s hand movement in relation to the robotic arm movement and filtering out tremor. The daVinci robot also has a short learning curve and provides freehand movement and an ergonomic position for the surgeon.^{14,32} Compared with other robotic systems or traditional surgery, it allows excellent visualization.^{7,31,45,53} The increased magnification and illumination of the surgical field allows careful dissection of fine structures such as nerves and blood vessels, substantially improving patient outcomes.^{4,7,17,31,45,53} Conversely, a lack of haptic feedback to the surgeon and

the inability of the surgeon to be stationed at the operating table are two notable limitations.⁴⁶

Trajectory Assistance Robots

Trajectory assistance surgical robots are designed to position an effector over a target for a precise stereotactic insertion procedure. In some systems, the target, insertion site, and trajectory can be virtually planned on preoperative images, which may include plain radiographs, computed tomography, and magnetic resonance imaging. Virtual planning allows the surgeon to safely visualize the trajectory, avoid critical regions, and make changes if necessary. End-effector positioning is registered to a preoperative image and automatically adjusted by a control computer, which directs the robotic motor system based on its interpretation of intraoperative imaging. This robotic control ensures adherence to the virtually planned path. This type of robot is therefore capable of autonomously positioning itself based on image information and is capable of manually or automatically moving into alignment with a fixed trajectory relative to the patient while allowing the surgeon to manually control the surgical instruments.^{1,2}

SpineAssist (Mazor Robotics, Ltd., Caesarea, Israel), a mini-ature robot approved by the U.S. Food and Drug Administration, is used to guide pedicle screw placement and has been evaluated in multiple studies.^{8,11,21,45} SpineAssist is used to guide the surgeon to the desired position relative to a preoperative plan loaded into a workstation preoperatively, leaving the screw insertion entirely to the surgeon.^{1,2} According to Barzilay et al., surgeons need to use SpineAssist in about 5 cases to become fully familiarized with the system and in 10 additional cases to be able to operate the technology independently. These 15 cases should ideally be concentrated in 2 to 4 weeks of intensive use of the system.¹ In 2014, Barzilay et al.³ presented a retrospective analysis of SpineAssist in which 33 patients with 60 vertebral compression fractures un-

derwent robotic-assisted vertebral body augmentation by 2 surgeons simultaneously injecting cement at 2 levels under pulsed fluoroscopy. Accuracy of the robotic system was 98.8%.

Conclusions

Robotic-assisted pedicle screw placement can significantly reduce the screw misplacement rate. Robotic-assisted surgery is especially useful in patients with severe deformity and for minimally invasive and revision surgeries in which anatomical landmarks are obscured. Radiation exposure to the surgical team can be significantly reduced if images can be acquired before surgery.

Surgical robotic systems are a burgeoning field, and new research directions and technological advancements may lead to the development of very different robotic surgical devices in the future. Commercially available master-slave and trajectory robots are gaining acceptance by the surgical community, and technology continues to improve, with the likelihood that robotic-assisted surgery may become the standard of care in the future.

The ideal master-slave robot would give haptic feedback to the surgeon and would allow the surgeon to be stationed at the operating table. The ideal trajectory robot would be autonomously positioned for a given trajectory based on a preoperative or intraoperative plan, would not interrupt surgical work flow, and would integrate seamlessly with image guidance.

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