Review Article

Robotics in spinal surgery

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Abstract: Although the da Vinci robot system has garnered much attention in the realm of surgery over the past few decades, several new surgical robotic systems have been developed for spinal surgery with varying levels of robot autonomy and surgeon-specified input. These devices are currently being considered as potential avenues for increasing the precision of any surgical intervention. The following review will attempt to provide an overview of robotics in modern spine surgery and how these devices will continue to be employed in various sectors across the field.

Keywords: Robotics; da Vinci robot; pedicle screw placement

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Introduction

Over the last three decades, there has been a rise in the rate of robotic surgery across a number of surgical specialties, including gynecology, urology, and general surgery (1-3). The most celebrated robotic system is the da Vinci surgical system, a laparoscopic surgery platform that allows surgeons to remotely control several multipurpose arms and perform complex surgery in a minimally invasive fashion (4). Though less established than the da Vinci robot, several surgical robotic systems have been developed for spinal surgery with varying levels of robot autonomy and surgeon-specified input.

There are 3 main classifications of robots (5) used in surgery today:

(I) The supervisory-controlled interaction allows the surgeon to plan operation and specify motions while the robot performs these motions autonomously under surgeon supervision;
(II) The tele-surgical interaction where the surgeon directly controls the surgical instruments which are held by the robot (e.g., da Vinci);
(III) The shared-control-system where the surgeon and robot control the surgical instrumentation simultaneously.

Current robotics in spine surgery utilize a shared-control-system (5). Driven by the theoretical advantage of improved precision, reduced radiation exposure, and decreased invasiveness, robotic surgery has gained traction within the field. Currently, the market holds three available robotic systems: Mazor Robotics (Medtronic, Israel), ROSA One (Zimmer Biomet, France), and Excelsius GPS (Globus Medica, United States). Being the earliest to develop a robotics platform for the spine and now on its third-generation platform, the majority of published literature evaluating robotic spine surgery is based on outcomes using the Mazor robot. Although newer, ROSA One and the Excelsius GPS robots have also proven to be efficacious in clinical use. All three robots utilize a similar process for preoperative imaging and intraoperative registration with slight differences in the implementation of the technology. This review will highlight the major applications of robotic spine surgery as well as its advantages, drawbacks, and future directions.

Pedicle screw placement

Currently, the primary application of robotics in spine surgery is pedicle screw placement (6). Proper pedicle screw placement is essential for successful outcomes, as misplacement can lead to neurologic, vascular and visceral injuries during procedures and are a major cause of revision surgery (7). With thoracolumbar instrumentation, misplaced pedicle screws using free-hand (FH) or fluoroscopy-assisted (FA) techniques can range widely from 2–31% and are heavily dependent on surgeon, assistant and technician experience (7). By registering intraoperative patient landmarks with a preoperatively obtained computed tomography (CT) scan, robotic-assisted (RA) surgery can theoretically improve the accuracy and precision of pedicle screw placement (8,9).

A number of meta-analyses have compared pedicle screw placement between RA surgery, FH surgery, and FA surgery. While the criteria to determine the accuracy of pedicle screw placement varies by study, RA surgery has generally demonstrated favorable results. In 2010, a meta-analysis performed by Verma *et al.* included data from 23 studies and evaluated the placement of 5,992 pedicle screws in RA and FH surgery. The authors found a significant increase in the accuracy rate of RA surgery compared to FH surgery (10). Two years later, Shin *et al.* performed a meta-analysis that mostly mirrored these results. In evaluating over 7,000 placed pedicle screws, they reported an incidence of misplaced screws in 15% in the FH group and 6% in the RA group (11). This study also subcategorized screws based on cervical, thoracic and lumbar placement, demonstrating an increased accuracy for all three regions of the spine with robot assistance (11). Neither meta-analysis found significant differences in reoperation rate or neurological sequelae (10,11). A meta-analysis by Marcus *et al.* evaluated 5 studies comparing pedicle screw placement in FA and RA surgery. The authors found a 94% satisfactory rate (686/729) for RA surgery and 93% (537/579) satisfactory rate for FA surgery (12). Liu *et al.* included five studies of thoracolumbar and lumbosacral RA and FH surgeries, revealing no difference in accuracy between the two groups at 0 or 2 mm threshold grading criteria (13).

Several recent randomized controlled trials (RCTs) have shown significantly better results with RA surgery using the Gertzbein-Robins scale, which grades screw positions from A (perfect) to E (worst). Zhang *et al.* reported 98.3% of RA screw insertions were clinically acceptable (A or B grade) compared to 93.6% of FA screw insertions (P=0.024) (14). Han *et al.* found the percentage of clinically acceptable screws was 98.7% in the RA to 93.5% in the FA (P<0.01) (15). None of the screws in the RA violated the proximal facet joint while 12 screws (2.1%) in the FA violated the proximal facet joint (15). In a similar study conducted by Schatlo *et al.*, 95 patients with degenerative lumbar disease underwent either RA or FH screw placement. Clinically acceptable screw accuracy was 91.4% in the RA group compared to 87.2% in the FA group (16).

Other studies also utilizing the Gertzbein-Robins scale to evaluate the accuracy of pedicle screw placement have found superior accuracy with RA screw placement (17-20). Hyun *et al.* found an accuracy rate (grade A or B) of 100% in the RA group compared to 98.6% in the FA group (17). In a study evaluating the efficacy of the ROSA system, Lonjon *et al.* reported a 97.3% accuracy rate in the RA group compared to 92% in the FH group (18). In a cohort of lumbar degenerative spondylolisthesis patients, Roser *et al.* reported 99% accuracy in the RA group compared to 97.5% in the FH group (19). A study analyzing pedicle screw placement in open *vs.* percutaneous robotic instrumentation in spondylodiscitis patients reported an accuracy rate of 90% in the RA group versus 74% in the FH group (20).

Radiation exposure

Spine surgery and intraoperative imaging are intimately linked. Exposure to radiation is a major concern for both the patient and the operating room staff during long spinal surgery cases that require intraoperative imaging. Although the acceptable amount of yearly and lifetime exposure to radiation is widely debated, reducing the exposure to patient and staff holds significant value. With most robotic systems, preoperative CT scans allow a drastic reduction of intraoperative radiation exposure. The preoperative CT scan is registered with intraoperative landmarks after surgical exposure using fluoroscopy. This process allows the robot to account for any intraoperative differences in surgical positioning or approach. If a patient does not have a preoperative CT scan, an intraoperative CT scan can be used for registration; in this case additional fluoroscopy is not required. Other robotic systems can utilize fluoroscopy alone without a need for CT scan to complete anatomic registration. Once registration is complete, the robot is able to carry out all instrumentation without need for any further intraoperative imaging, further reducing any radiation exposure to surgeons and operating room staff.

Current literature suggests RA surgery does provide surgeons reduced exposure to radiation in comparison to FA surgery. A study by Smith *et al.* found radiation exposure to the torso of surgeons during pedicle screw placement to be significantly lower in the RA group (0.33 mRem) than in the FA group (4.33 nRem) (21). However, there was no significant difference in radiation exposure to the thyroid. An RCT performed by Villard *et al.* assessed radiation exposure to both surgeons and patients during posterior lumbar instrumentation procedures and showed that radiation exposure to the surgeon was ten times higher in a FA group than in the RA group (22). A cadaveric study performed by Lieberman *et al.* reported a radiation exposure to the surgeon 30× lower in RA surgery than FH procedures (23). Han *et al.* also reported a significant decrease in radiation exposure to the surgeon involved in RA thoracolumbar procedures (15). When comparing conventional FA screw placement to RA procedures, Kantelhardt *et al.* recorded an average exposure time of 77 seconds per screw in FA surgery to 34 seconds per screw in RA surgery (24). Similarly, Keric *et al.* found an average time of 56 seconds per screw in the FA and 24 seconds per screw in the RA group (20). In contrast, Ringel *et al.* found no difference in the intraoperative radiation exposure time between FA and RA groups (25).

Clinical outcomes

While RA surgery may boast higher accuracy during pedicle screw placement, it is important to consider if these improvements actually result in better clinical outcomes. Currently, there is no literature comparing RA surgery to FA or FH surgery for common patient reported outcomes, such as the SF-12 and Oswestry disability index (ODI). However, other clinical outcomes have been measured, specifically length of stay, readmission, revision surgery, and infection rates.

A few studies have demonstrated reduced hospital stays for RA procedures. A single-center clinical outcome analysis in thoracolumbar fusion surgeries comparing RA navigation with FH and FA guidance found a significant decrease in the length of hospital stay (4.72 *vs.* 5.43 days) for RA surgery (26). A study analyzing FH versus RA surgery in spinal pedicle screw instrumentation in spondylodiscitis patients found a decrease in hospital stay from 18.1 days in the FH group *vs.* 13.8 days in the RA group (P=0.012) (20). The study by Xiao *et al.* also showed a decreased spine-related readmission rate (0.8% *vs.* 4.2%) and reoperation rates (5.2% *vs.* 10.9%) in the RA group (27). In a study evaluating 234 patients, Han *et al.* found two patients in the FH group required revisional surgery for foraminal impingement due to misplaced screws while no revisions occurred in the RA group (15). A more recent systematic review and meta-analysis performed by Staartjes *et al.* analyzed data from 37 studies (7,095 patients) comparing RA, FH, and navigation-assisted surgery. The authors found a decrease in the number of revision surgeries required in RA surgery (P=0.04) and navigation-assisted surgery (P<0.001) (28), though RA surgery was no longer significant following subsequent sensitivity analyses.

Due to the high initial cost of a robotic system, these findings suggest that centers with high patient volume and a large number of cases may be more inclined to benefit financially from the integration of a robotic system. Data from multiple studies estimates that 2.1% of patients undergoing a lumbar pedicle screw fixation surgery will require revisional surgery for misplaced screws. Thus, it is reasonable to believe that utilizing RA surgery, which has been shown to reduce the rate of revisional surgery, may decrease health care costs on a widespread scale (29). In a cohort of 70 patients, Solomiichuk *et al.* reported one instance of nerve root injury in FA surgery (n=35) requiring revisional surgery and none in the robotic group (n=35) (30). Schatlo *et al.* also reported one instance of nerve root injury in the FA guided group (n=40) and none in the RA group (n=55) (16).

A few studies have reported postoperative infection rates in robotic-guided cases *vs.* non-robotic cases. Kantelhardt *et al.* found a significantly lower postoperative infection rate of 2.7% in RA procedures *vs.* 10.7% in FA procedures (24). The study by Han *et al.* found no difference in the surgical site infection rate between the robotic and non-robotic group (15). There was also a decrease in intraoperative blood loss when using an RA technique compared to either a FH or FA technique (15,16,31).

Disadvantages

Currently, the most obvious drawback to RA surgery is cost, specifically the costs associated with purchasing the robotic unit, training the surgical team, and overcoming the learning curve of integrating new and evolving technology into surgery (32). The price for these machines can reach up to $850,000–1,000,000, which does not include the annual cost of disposables that range upwards of an additional

$2,000 (33).

Another concern of robotic surgery is the possible intraoperative discrepancy between preoperative CT imaging and intraoperative registration. This error can arise from poor image quality, excessive amounts of soft tissue in the patient hindering proper robotic arm positioning, surgeon error during registration, or a combination of all the above (34). In many cases, these inaccuracies can be fixed prior to screw insertion by simple reprogramming of the screw trajectory by hand (16), in effect turning the robotic assistance into a navigation-assisted technique.

Future applications

The majority of the current literature involving robotics in spinal surgery revolves around outcomes following thoracolumbar fusion. However, RA surgery may provide greater value in surgeries requiring high levels of precision such as cervical spine surgery or with lumbopelvic fixation. For example, the accuracy of screw placement is paramount in S2 alar-iliac (S2AI) spinopelvic fixation procedures. A study performed by Nottmeier *et al.* looked at S2AI screw placement in 20 patients and found that although 5/32 screws placed experienced an anterior breach of the sacrum, none resulted in clinical complications (35). A similar study performed by Ray *et al.* revealed that only 1/22 screws experienced an anterior breach (36), requiring intraoperative readjustment without any subsequent clinical complications. Hu and Lieberman retrospectively evaluated the accuracy and feasibility of placing S2AI screws with RA surgery. They found that of the 35 screws placed in 18 patients, none were misplaced (37), resulting in no intra or post-operative complications. A retrospective study performed by Laratta *et al.* looked at 46 robotic-guided S2AI screws placed in 23 patients. They found an accuracy rate of 95.7% with no intraoperative neurological, vascular or visceral complications (38), concluding spinopelvic fixation using robotic-guided S2AI screw insertion is both safe and accurate. A study performed by Bederman *et al.* analyzing the accuracy of S2AI screw placement in spinal deformity correction procedures found an accuracy rate of 100% (39). More recently, Shillingford *et al.* directly compared the accuracy and safety of S2AI screws placed using RA surgery to FH surgery. The results found that there was no statistically significant difference in the accuracy rates between the two groups and no difference in intraoperative neurological, vascular or visceral complications (40).

Robotics may also have a place in the excision of spinal tumors. Due to the need for resection with close margins to neural elements, RA surgery may increase accuracy of tumor resection and facilitate accurate instrumentation in the setting of compromised bony landmarks. Bederman *et al.* describe using robotic guidance to accurately perform *en bloc* sacrectomy for osteosarcoma, where accurate bony resection of the tumor was performed with negative margins (41). However, to date there is limited literature regarding the use of RA surgery in spine tumor surgery; future prospective studies are needed.

Other potential benefits for RA spine surgery include the possibility of lengthening the careers and increasing performance of aging spine surgeons (42). The use of the robot may also standardize treatment and reduce variability in performance between surgeons, thereby creating uniformity with patient outcomes. In addition, robots are valuable in highly complex cases with distorted anatomy such as complex deformity surgery and could potentially decrease rates of adjacent segment disease. Currently, RA surgery is mostly confined to performing thoracolumbar pedicle instrumentation. However, as the technology and software planning continue to improve, RA surgery be applicable to many different types of surgery including cervical spine instrumentation, bony decompression for stenosis surgery, and other complex tumor reconstruction (43).

Conclusions

Many studies have shown that RA surgery provides increased accuracy of pedicle screws and reduces radiation exposure in comparison to FA surgery. However, to date, clinically meaningful differences between traditional techniques and RA surgery have not been clearly demonstrated. With the ongoing efforts to battle rising healthcare costs and the emphasis on value-based care, RA surgery must demonstrate cost effectiveness. Evidence of significantly reduced reoperation rates, complication rates, and operating time may make widespread utilization of robots more plausible.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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