Robotic-assisted Spine Surgery: A Review of its Development, Outcomes, and Economics on Practice

Cameron Kia, MD* and Sean Esmende, MD†

Purpose: Improper pedicle screw placement can lead to increased complications and the need for revision surgery. The purpose of this article is to review the history of robotic assistance in spine surgery, along with the current data on its clinical outcomes, potential advantages, and economics on practice.

Methods: Review of the literature.

Results: A review of the current literature demonstrated that intrapedicular accuracy has shown to be either superior or equivalent to a free-hand technique. Radiation exposure with robotic assistance is generally similar to free-hand, with a trend toward a lesser exposure following increased experience. Operative times, outcomes, and complication rates have been variable between prospective and retrospective studies, with mostly equivalent results when compared with free-hand screw placement.

Conclusions: Higher-level studies (level I and II) have demonstrated similar clinical outcomes and pedicle screw accuracy when compared with the free-hand technique. As with most new technology, a learning curve is apparent, with the potential for a decrease in radiation exposure and economic benefit over time.

Key Words: robotic—device outcome—spine surgery—minimally invasive.

(Tech Orthop 2021;36: 272–276)

The use of robotic assistance has been utilized in several surgical fields, allowing for more minimally invasive techniques, while demonstrating promising clinical outcomes.1–3 More recently, this has become popular in the field of orthopedic surgery, especially in the spine.4–6 As accurate intrapedicular screw placement known to be critical for stability as well as clinical outcomes during thoracolumbar instrumentation, understanding the potential benefits and pitfalls of robotic assistance is essential before investing in the technology.

In general, 3 types of robotic systems are available for surgical assistance: telesurgical, supervisory controlled, and a shared-controlled model.5–9 In the telecommunication model, the surgeon controls all motions and operates remotely from the robot at a distance. This was the first seen by the da Vinci Surgical System (Intuitive Surgical Inc., Sunnyvale, CA), which became the first Food and Drug Administration (FDA) approved robot for laparoscopic surgery.1 In a supervisory controlled model, the robot performs actions based on preprogrammed settings created by the physician. However, the shared-controlled model has become the most utilized design for robotic assistance in spine surgery, requiring both robotic and surgeon motion control.

Utilizing this shared-controlled model, the SpineAssist (Mazor Robotics Ltd, Caesarea, Israel), became the first FDA approved robot to be used for spinal surgery.10 Early clinical studies demonstrated accurate pedicle screw placement with the potential to be superior to the free-hand technique.10 Since its recent introduction, other competing devices, as well as multiple studies examining its efficacy in spinal surgery, have been published. The purpose of this article was to review the evolution and current use of robotic assistance in spine surgery, as well comparing its results to conventional free-hand technique.

EVOlUTION OF ROBOTIC ASSISTANCE IN SPINE

The concept of computer-assisted navigation systems along with robotics relies on similar principles of stereotaxis to provide accurate trajectory in spine surgery. Stereotaxis, first described by Horsely and Clarke,11 utilized a Cartesian coordinate system to locate points within the brain in an animal model. Early robotic models using stereotaxis were originally used for neurosurgical biopsy12 as well as in the orthopedic world for total hip arthroplasty.13 In 2002, the Georgetown Robot14 was introduced as a telesurgical system that could be used to accurately perform spinal blocks. However, it was not until 2004 that the FDA approved the first robotic assistance device for thoracolumbar screw fixation; the SpineAssist (Mazor Robotics Ltd). This shared-control model system consisted of a miniature robot, a framework robotic arm, a mounting system, as well as guide-sleeves for pedicle screw placement.10 Mounted to bony landmarks on the patient, the robotic arm allowed for 6 df, controlled from a workstation to match preoperative and intraoperative imaging. After registering each vertebra independently and allowing for robotic and surgeon verification (Fig. 1), the arm places the trajectory over the specific pedicle determined by the physician.15 In 2015, it was reported to have been used in over 3000 spine procedures annually in the United States.16

Since its arrival, several modifications, as well as competitor systems, have arrived to the market. Other robotic options examined in the literature have included the Renaissance (Mazor Robotics Ltd), ROSA spine (Zimmer-Biomet, Warsaw, IN), ExelsiusGPS (Globus Medical Inc., Audubon, PA), and Mazor X (Mazor Robotics Ltd) robot. Each robotic device utilizes a patent algorithm in matching preoperative computed tomography imaging with intraoperative fluoroscopy, with advances in the Mazor X and ExelsiusGPS to allow for intraoperative navigation.

Pedicle Screw Accuracy

Pedicle screw accuracy has become of great concern, as misplacement can result in neurological or structural compromise.17,18 In 2010, Devito et al.10 retrospectively examined the accuracy of pedicle screw placement from over 840 robotic-assisted cases and
found clinically acceptable screw placement in 98% of screws. Hyun et al\(^{19}\) then performed a randomized control trial comparing robotic guidance compared with the free-hand technique. Using the Gertzbein-Robbins classification to analyze screw placement, they found 100% accuracy using robotic assistance compared with 98% using the free-hand technique.\(^{19}\) Although these and others have shown promising results, Ringel et al\(^{20}\) found that only 85% of patients had acceptable screw placement compared with 93% using the free-hand technique in their randomized control trial. The authors noted skidding of the wire cannula occurred with enlarged degenerative facets,\(^{20}\) highlighting the importance of preoperative and intraoperative examination during screw placement. Keric et al\(^{21}\) compared the use of minimally invasive robotic assistance compared with open surgical free-hand technique and found that percutaneous fixation was significantly more accurate than free-hand (90% vs. 73.5%). Urakov et al\(^{22}\) then compared open robotic to percutaneous and found that an open approach was significantly better at improving screw accuracy than percutaneous. Overall, as demonstrated in a meta-analysis by Gao et al,\(^{23}\) randomized controlled studies have shown that robotic assistance is equivalent to free-hand technique, with fewer proximal facet joint violations (Table 1).

### Operative Time and Radiation Exposure

Similar to accuracy, operative time, and radiation exposure for robotic assistance has been variable. Lonjon et al\(^{26}\) found in their prospective study a significantly longer average operating time using robotic assistance (336 min) compared with open free-hand technique (226 min, \(P<0.001\)). Kantelhardt et al\(^{27}\) compared percutaneous and open robotic assistant pedicle screw to standard free-hand technique (226 min, \(P<0.001\)). Solomiichuk et al\(^{28}\) performed a retrospective matched cohort study on patients with metastatic spine disease and found robotic assistance on average was faster (226 min), compared with fluoroscopic assisted screws (264 min), although this was not considered statistically significant. Tian et al\(^{25}\) also found no significant difference when looking at total (skin to skin) operating time, however, they did find instrumentation time to be shorter with free-hand technique (\(P=0.04\)).

The possibility of reducing the radiation exposure for both the patient and surgeon during spine surgery has garnered recent interest. Keric et al\(^{21}\) found in their retrospective study that radiation time per screw for robotic percutaneous technique (0.4 min/screw) was significantly less than the open free-hand cohort (0.94 min/screw) (\(P<0.001\)). This was similarly reported in a prospective randomized controlled study by Hyun et al,\(^{19}\) which found robotic assistance (3.5 s/screw) had significantly less radiation time than free-hand (13.3 s/screw, Table 1). Gao et al\(^{23}\) recent meta-analysis also confirmed that of the 3 randomized controlled trials that reported radiation exposure, robotic assistance significantly reduce radiation time (mean difference = 12.38 s/screw).

### Patient Outcomes and Length of Stay

Along with pedicle screw placement accuracy, patient-reported outcomes and length of stay are important factors that should be considered when deciding to use robotic assistance. Park et al\(^{29}\) found at 2 years, patients with lumbar robotic pedicle screw fixation had significant improvement compared with the preoperative Visual Analogue Scale and Oswestry Disability Index score, with no significant difference when compared with conventional free-hand technique. Keric et al\(^{21}\)

---

### TABLE 1. Randomized Control Trials of Robotic-assistance Compared With Free-hand

| References       | Type of Study | Pedicle Accuracy | Radiation Time (s/screw) | Operating Time (min) |
|------------------|---------------|------------------|--------------------------|----------------------|
| Hyun et al\(^{19}\) | Prospective RCT | 100% RA vs. 98.6% FH | 3.5 RA vs. 13.3 FH | 208.5 RA vs. 208.5 FH |
| Kim et al\(^{24}\)  | Prospective RCT | 99.4% RA vs. 99.4% FH | Not compared | 220.1 RA vs. 189.8 FH |
| Ringel et al\(^{20}\) | Prospective RCT | 93% RA vs. 85% FH | 3.8 RA vs. 3.8 FH | 151 RA vs. 132 FH |
| Roser et al\(^{13}\) | Prospective RCT | 99% RA vs. 97.5% FH | 16 RA vs. 31.5 FH | 140.8 RA vs. 111.2 FH |
| Tian et al\(^{25}\)  | Prospective RCT | 100% RA vs. 98.9% FH | Not compared | 138.9 RA vs. 118.2 FH |

FH indicates free-hand; RA, robotic assistance; RCT, randomized control trial.
found similar outcomes between groups even at a mean of only 8.4-month follow-up. There has also been no significant difference found in time to ambulation after surgery between groups (39 h free-hand vs. 36 h for robotic assistance). With regard to the length of stay, studies have favored the use of percutaneous screw fixation with robotic assistance over open free-hand technique. Kantelhardt et al. found robotic-assisted fusion resulted in an average decrease of 4 days hospitalization compared with conventional technique ($P < 0.05$). Similarly, Hyun et al. found the length of the hospital stay significantly shorter (~3 d) using robotic assistance ($P = 0.02$). However, Ringel et al. found no significant difference in hospital stay in their randomized control trial (6 robot vs. 7 free-hand days, $P = 0.29$).

Complications
Avoiding injury to the nerves and dura can be critically important for an optimal outcome. Although, the majority of studies reported no complication using robotic assistance, technical software issues, cannula skidding, or skiving from soft tissue can occur. Devito et al. only found a 0.7% rate of neural injury, but all were reversible without the need for revision. Hyun et al. reported no dural tears or neurovascular injury with percutaneous robotic screw placement compared with only 1 patient in the free-hand group who required revision surgery for medial violation of the pedicle screw causing the neurological deficit. In a retrospective review by Keric et al., the authors reported a revision rate of 4.95% in the free-hand group compared with 0.58% in the robot-assisted group for misplaced hardware. In addition, the authors found adverse event rate was 12.5% in the free-hand group compared with 6.1% using robotic assistance ($P = 0.14$). Limited studies have reported on infection rate, with robotic involvement ranging from 0% to 12.6%.

Economics on Practice
The current high price of spinal fusion places the pressure of weighing cost-effectiveness in relation to patient satisfaction on the surgeon. Studies looking at cost-effectiveness have been limited, with several using length of stay as a marker for health care value. Watkins et al. estimated that operating room (OR) costs for spinal surgery were roughly $93 per minute, making any potential decrease in operating time a chance for substantial cost savings.

In a recent study by Menger et al., the authors analyzed the cost-effectiveness of adding a robotic technology in an academic practice over the course of a year. They found that utilizing a robot would on average resulted in a time savings of 3.4 minutes per 1-level with an minimally invasive surgery procedure, resulting in a potential annual savings of $5713 from OR time alone. In addition, their results predicted that robotic use would have resulted in 140 fewer total hospital admission days, avoided 2.3 infections, as well as 9 revisions for hardware.

FIGURE 2. Demonstrates preoperative (A) lumbar template for L1-L5 spinal fusion before interbody placement. Intraoperative segmentation (B) and verification are still able to be performed using a robotic device (Mazor X; Medtronic) even with a change in preoperative alignment after multilevel interbody device placement.
misplacement.35 Over the course of 557 cases in 1 year, the authors estimated cost savings of roughly $608,546 with the implementation of robotic assistance.35 However, their model did not take into account the initial cost of the robot and the learning curve that vary between surgeons.32,36 This was highlighted in a study by Hu and Lieberman,36 which found that the rate of successful pedicle placement significantly increased with experience. The authors found that a roughly 17% conversion to manual placement in the group of surgeons with minimal robotic experience.36

With regard to the initial cost and maintenance of the robot, the majority of the literature has focused on Mazor technology. The Renaissance system setup has been reported as an upfront cost of roughly $550,000 USD, along with an additional yearly 10% maintenance cost that is not included in the initial price.37,38 This also does not take into account the disposable equipment that is required for each procedure.37

Future Directions of Robotic Assistance

Although robotics in spine surgery is currently in its infancy, there is potential for a greater role than isolated thoracolumbar pedicle screw placement. One drawback to current devices the ability to truly measure screw depth, unlike computer-assisted navigation, which provides improved visualization and feedback during placement. This has limited the robot for use in the cervical spine. Fan et al39 recently compared the use of the O-arm navigation system to robotic assistance and found that while there was similar pedicle screw accuracy, the robot still significantly reduced fluoroscopy and time per screw. This has led to the development of the Mazor X Stealth Edition (Mazor Robotics Ltd) which combines the use of robotics with intraoperative navigation. However, further biomechanical and clinical data is needed with this technology before its use in the cervical spine.

In addition to pedicle screw placement, robotic assistance may garner interest during tumor resection and osteotomies in spinal deformity. Implementing robotics with tools such as a burr or saw could allow for a safer decompression or osteotomy. With potential intraoperative navigation, the system may provide improved visualization and feedback during placement. This has limited the robot for use in the cervical spine. Fan et al39 recently compared the use of the O-arm navigation system to robotic assistance and found that while there was similar pedicle screw accuracy, the robot still significantly reduced fluoroscopy and time per screw. This has led to the development of the Mazor X Stealth Edition (Mazor Robotics Ltd) which combines the use of robotics with intraoperative navigation. However, further biomechanical and clinical data is needed with this technology before its use in the cervical spine.

In addition to pedicle screw placement, robotic assistance may garner interest during tumor resection and osteotomies in spinal deformity. Implementing robotics with tools such as a burr or saw could allow for a safer decompression or osteotomy. With potential integration of navigation with preoperative magnetic resonance imaging, there may be a role for even disectomy or mobilization of neural elements to be performed with a robot. Similar to the development of the robotic arm in total joint arthroplasty, the authors feel that as robotics become more routinely used in practice, this will drive further software development, as well as high-quality studies demonstrating its effectiveness.

CONCLUSIONS

Robotics in spine surgery is rapidly increasing, with several reports anticipating significant health care accessibility in the near future.37 Although new technology is enticing, understanding its impact on health care quality is essential. Several studies seem to favor the accuracy of robotic fixation, however, surgeons should understand the potential pitfalls that could lead to misplacement. Cannula skiving can occur from the pressure of the soft tissues or from enlarged, degenerative facet joints. In addition, hardware issues may misplace the trajectory, which should be recognized by the surgeon with proper intraoperative x-rays before leaving the OR. Robotic assistance may be especially useful in cases of deformity or following placement of multiple interbody devices, which can change alignment before instrumentation (Fig. 2). With regard to the economic benefit, the surgeon should understand that there is a learning curve to using robotic assistance and that the potential efficiency of conventional technique has not been proven in the literature. Going forward, greater biomechanical and clinical outcomes research is needed. In addition, examining the exact cost-effectiveness should be evaluated. With the drive for health care value becoming increasingly pertinent for reimbursement, the benefit of robotic assistance needs to be better analyzed in both the intraoperative costs, as well as its relation to patient-reported outcomes.

REFERENCES

1. Beutler WJ, Peppelman WC Jr, DiMarco LA. The da Vinci robotic surgical assisted anterior lumbar interbody fusion: technical development and case report. Spine. 2013;38:356–363.
2. Dogangil G, Davies BL, Rodriguez y Baena F. A review of medical robotics for minimally invasive soft tissue surgery. Proc Inst Mech Eng H. 2010;224:653–679.
3. Illgen RL, Bukowski BR, Abiola R, et al. Robotic assisted total hip arthroplasty: outcomes at minimum two-year follow-up. Surg Technol Int. 2017;30:365–372.
4. Zheng G, Nolte LP. Computer-assisted orthopedic surgery: current state and future perspective. Front Surg. 2015;2:292–299.
5. Karthik K, Colegate-Stone T, Dasgupta P, et al. Robotic surgery in trauma and orthopaedics: a systematic review. Bone Joint J. 2015;97-B:292–299.
6. Nathoo N, Cavusoglu MC, Vogelbaum MA, et al. In touch with robotics: neurosurgery for the future. Neurosurgery. 2005;56:421–433.
7. Dreval ON, Rynkov IP, Kasparova KA, et al. Results of using spine assist Mazor in surgical treatment of spine disorders. Zh Vopr Neirokhir Im N N Bardenko. 2014;78:14–20.
8. Taylor RH, Stoianovici D. Medical robotics in computer-integrated surgery. IEEE Trans Robot Autom. 2003;19:765–781.
9. Roberts DW, Strobbehn JW, Hatch JF, et al. A frameless stereotactic integration of computerized tomographic imaging and the operating microscope. J Neurosurg. 1986;65:545–549.
10. Devito DP, Kaplan L, Dietl R, et al. Clinical acceptance and accuracy assessment of spinal implants guided with SpineAssist surgical robot: retrospective study. Spine. 2010;35:2109–2115.
11. Horsley V, Clarke RH. The structure and functions of the cerebellum examined by a new method. Brain. 1908;31:45–124.
12. Bann S, Khan M, Hernandez J, et al. Robotic assistance in surgery. J Am Coll Surg. 2003;196:784–795.
13. Unger SW, Unger HM, Bass RT. AESOP robotic arm. Surg Endosc. 1994;8:1131.
14. Cleary K, Watson V, Lindisch D, et al. Precision placement of instruments for minimally invasive procedures using a “needle driver” robot. Int J Med Robot. 2005;1:40–47.
15. Roser F, Tatagiba M, Maier G. Spinal robotics: current applications and future perspectives. Neurosurgery. 2013;72:A12–A18.
16. Patel V. Future of robotics in spine surgery. Spine. 2018;43(7S):S28.
17. Longstein JE, Denis F, Perra JH, et al. Complications associated with pedicle screws. J Bone Joint Surg Am. 1999;81:1519–1528.
18. Aciibas SC, Arslan FY, Tuncer MR. The effect of transpedicular screw misplacement on late spinal stability. Acta Neurochir (Wien). 2003;145:949–955.
19. Hyun SJ, Fleischhammer J, Molligai G, et al. Minimally invasive robotic versus open fluoroscopic-guided spinal instrumented fusions. Spine. 2017;42:353–358.
20. Ringel F, Stuer C, Reinke A, et al. Accuracy of robot-assisted placement of lumbar and sacral pedicle screws. Spine. 2012;37:E496–E501.
21. Kerin N, Eum DJ, Afgan F, et al. Evaluation of surgical strategy of conventional vs. percutaneous robot-assisted spinal trans-pedicular instrumentation in spondyloolisthesis. J Robot Surg. 2016;11:17–25.
22. Urakov TM, Chang KH, Burks SS, et al. Initial academic experience and learning curve with robotic spine instrumentation. *Neurosurg Focus*. 2017;42:E4.

23. Gao S, Lv Z, Fang H. Robotic-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis of randomized controlled trials. *Eur Spine J*. 2018;27:921–930.

24. Kim HJ, Jung WI, Chang BS, et al. A prospective, randomized, controlled trial of robot-assisted vs freehand pedicle screw fixation in spine surgery. *J Int J Med Robot*. 2016;13:1–7.

25. Tian W, Fan MX, Han XG, et al. Pedicle screw insertion in spine: a randomized comparison study of robot-assisted surgery and fluoroscopy-guided techniques. *J Clin Orthop Relat Res*. 2011;20:860–868.

26. Schatlo B, Martinez R, Alaid A, et al. Unskilled unawareness and the learning curve in robotic spine surgery. *Acta Neurochir (Wien)*. 2015;157:1819–1823.

27. Schroder ML, Staartjes VE. Revisions for screw malposition and clinical outcomes after robot-guided lumbar fusion for spondylolisthesis. *Neurosurg Focus*. 2017;42:E12.

28. Goz V, Rane A, Abtahi AM, et al. Geographic variations in the cost of spine surgery. *Spine*. 2015;40:1380–1389.

29. Watkins RG, Gupta A, Watkins RG. Cost-effectiveness of image-guided spine surgery. *Orthop Open J*. 2010;4:228–233.

30. Fiani B, Quadri SA, Farooqui M, et al. Impact of robot-assisted spine surgery on health care quality and neurosurgical economics: a systematic review. *Neurospine*. 2018;15:216–224.

31. Watkins RG, Gupta A, Watkins RG. Cost-effectiveness of image-guided spine surgery. *Orthop Open J*. 2010;4:228–233.

32. Menger RP, Savardekar AR, Farokhi F, et al. A cost-effectiveness analysis of the integration of robotic spine technology in spine surgery. *Neurosurg*. 2018;15:216–224.