Robotics in Spine Surgery - Is it going to be the Future ?

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Introduction

Spine surgery requires fine motor skills to manipulate neural elements and a steady hand to work in challenging corridors utilising exposures that reduce collateral damage. Long and arduous procedures may predispose a spine surgeon to mental and physical fatigue. Hence, there was a need to integrate robotic assistance in spine surgery. Robotics was commonly used in other arenas, but remained in its infancy in spine surgery, until recently, there has been growing evidence to suggest that robotics may be a part of our everyday spine surgery practice.

Screw placement remains a critical step in spine surgery instrumentation as malpostioning leads to drastic complication of neural tissue injury and vascular injuries.

postoperative CT-based Gertzbein and Robbins system (GRS) to classify pedicle screw accuracy[7,25]. In the GRS, screws completely within the pedicle are Grade A;a breach of < 2mmis GradeB;a breach of 2 to <4 mm is Grade C; a breach of 4 to <6 mm is Grade D; and a breach of > 6 mm is Grade E. In this system, both Grades A and B are deemed acceptable.

Historically, free handed pedicle screw placement has resulted in relatively high inaccuracy, and while the addition of fluoroscopy has improved accuracy rates, the risk of nerve and vascular injury continues to exist [3]. Intra-operative fluoroscopy also brings the risk of increased radiation exposure for the surgeon and staff [4]. This risk is especially increased in minimally invasive spinal procedures. (Ghasem 2018)

types of robots (Overley et al)

One of the pioneers and by far the most studied of these robotic-assisted surgical devices for spine surgery is the Spine-Assist/Renaissance robot (MAZOR Robotics IncR , Orlando, Florida). This device operates under a shared-control model, with 6^0 of freedom of motion positioning surgical instruments for spinal procedures (Figure 5). It utilizes 3 different outrigger arms, each accommodating a drill guide sleeve. The robotic software, in sync with a CAN, determines which arm produces the most accurate pathway for pedicle instrumentation based on the chosen implant and relative location of the SpineAssist robot to the predetermined entry point and screw trajectory. The robot may be attached directly to a spinous process in the case of open surgery, or attached to a frame triangulated by percutaneously placed guide wires (1 Kirschner wire at a spinous process and 2 Steinmann pins in the posterior superior iliac spines) for MIS procedures. The first step of the process is to obtain and register CT images of the desired spinal levels with the SpineAssist software to create a virtual spinal map for the robot. However, unlike intraoperative real-time navigation, these images may be obtained preoperatively for preoperative templating. The second step involves the templating of desired screw entry point, trajectory, and screw size. This may be done in the OR or even preoperatively based on the 3-D spinal map constructed by the software and transferred to the intraoperative Spine Assist workstation. Once the virtual template for instrumentation has been created, a short verification procedure is performed intraoperatively, which utilizes tracked Kirschner wires that are inserted into the mounted robot, verifying accuracy of the system. This process assures accuracy to the set specifications, less than 1.5-mm deviation of the actual implant from the preoperative template. The final registration involves obtaining 6 still fluoroscopic images for calibration and intraoperative registration purposes. The SpineAssist software then determines the optimal position of the selected arm for insertion of the drill sleeve and a cannulated drill guide is placed in the arm, which is now aligned along the predetermined implant trajectory. The drill is then used to create a cortical punch at the desired entry point; a guide wire is inserted into the vertebral body so a screw pilot hole may be drilled along the guide wire. The appropriate length and diameter screw is then inserted into the pilot hole after pedicle probing and surgeon confirmation of accuracy [83].

Cadaver studies first verified the accuracy of this novel robotic- assisted technique, reporting an average deviation of 1 mm or less of actual implant position compared to preoperative template.83 , 84 Soon thereafter, several clinical studies sought to expand upon the translational accuracy and efficacy of the Spine- Assist robot (MAZOR Robotics IncR) in Vivo [85 - 88]. Roser et al [85] found a 99% accuracy rate of lumbosacral pedicle instrumen- tation using the SpineAssist robot compared to 98% utilizing fluoroscopy guided, and 92% using navigation techniques. Shizas et al [86] reported a 95% accuracy rate vs 92% for robot-assisted vs fluoroscopic-guided lumbosacral pedicle screw instrumentation, and Kantelhardt et al [87] similarly showed 95% accuracy vs 92% using SpineAssist and conventional fluoroscopy, respec- tively. Interestingly, the only study to date demonstrating a reduced accuracy of screw placement came from Ringel et al [88] in a randomized controlled trial that demonstrated a significantly reduced accuracy rate of lumbosacral pedicle screw instrumentation with the SpineAssist robot (85%) compared to fluoroscopic-guided screws (93%, P = .019). The authors also reported that 10 of the 146 screws placed with robotic assistance necessitated intraoperative removal and FH reimplantation. The authors utilized a percutaneous means of affixation of the robot to the spine using the hover T method

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Table 1: Summary of 25 articles included in systematic literature review related to robotics in spine

Authors & year	Data Collection	Study Type	Comparison Group	Robot Type	Instrumentation	No. of Pts	No. of Screws Placed	Accuracy (%)
Barzilay et al, 2006	Prospective	Case series	None	Mazor	Pedicle Screw	15.0	-	-
Bederman et al, 2016	Retrospective	Case series	None	Mazor	S2-alar-iliac screw	14.0	31.0	100.0
Devito et al. 2010	Retrospective	Case series	None	Mazor	Pedicle Screw	635.0	3,271.0	98.3
Devito et al. 2014	Retrospective	Case series	None	Mazor	GO-LIF & Pedicle Screw	50.0	-	-
Hu et al, 2013	Retrospective	Case series	None	Mazor	Pedicle Screw	102.0	1,085.0	98.9
Hu & Lieberman, 2014	Retrospective	Case series	None	Mazor	Pedicle Screw	162.0	-	-
Hu et al, 2015	Retrospective	Case series	None	Mazor	Pedicle Screw	9.0	-	-
Hyun et al, 2016	Prospective	RCT	Freehand	Mazor	Pedicle Screw	30.0	130.0	100.0
Kantelhardt et al, 2011	Retrospective	Case series	Freehand	Mazor	Pedicle Screw	55.0	250.0	94.5
Keric et al, 2017	Retrospective	Comparative	Freehand	Mazor	Pedicle Screw	66.0	341.0	90.0
Kim et al, 2016	Prospective	RCT	Freehand	Mazor	Pedicle Screw	37.0	158.0	99.4
Kuo et al, 2016	Retrospective	Case series	None	Mazor	Pedicle Screw	64.0	317.0	98.7
Lonjon et al, 2016	Prospective	Matched cohort	Freehand	ROSA	Pedicle Screw	10.0	40.0	97.2
Macke et al, 2016	Retrospective	Case series	None	Mazor	Pedicle Screw	50.0	662.0	92.7
onen et al. 2014	Retrospective	Case series	None	Mazor	Pedicle Screw	27.0	136.0	98.6
Pechlivanis et al, 2009	Retrospective	Case series	None	Mazor	Pedicle Screw	31.0	133.0	99.2
Ringel et al, 2012	Prospective	RCT	Freehand	Mazor	Pedicle Screw	30.0	146.0	85.0
Roser et al, 2013	Prospective	RCT	Freehand, standard navigation	Mazor	Pedicle Screw	18.0	72.0	99.0
Schatio et al, 2014	Retrospective	Matched cohort	Freehand	Mazor	Pedicle Screw	55.0	244.0	91.4
Schatio et al, 2015	Retrospective	Case series	None	Mazor	Pedicle Screw	258.0	1,265.0	96.2
Schatio et al, 2012	Prospective	Matched cohort	Freehand	Mazor	Pedicle Screw	11.0	64.0	95.3
Sensakovic et al, 2016	Retrospective	Matched cohort	None	Mazor	Pedicle Screw	34.0	-	-
Sukovich et al, 2006	Retrospective	Case series	None	Mazor	Pedicle Screw	14.0	98.0	96.0
Tsai et al, 2016	Retrospective	Case series	None	Mazor	Pedicle Screw	35.0	176.0	98.9
Van Dijk et al, 2015	Retrospective	Case series	None	Mazor	Pedicle Screw	112.0	494.0	97.9

Pts = Patients

The blank column in the last two columns de note that those values were not reported in the studies cited.

(1 K-wire attached to the spinous process and 2 Steinmann pins in the posterior superior iliac spines), and noted instability in the Kirschner wire leading to malposition of the drill sleeves. They also noted skidding of the drill cannula, which they attributed to skidding of the sleeve lateral to the facet joints. They postulated that these errors might be corrected by use of superior fixation for the hover T K-wire and a more lateral entry point with increased medialization to avoid bony overgrowth and extreme slope of the lateral edge of the facet for sturdy docking of the drill sleeve.

In a new application of an existing surgical robot, the ROSA R robot by Medtech (Medtech S.A., Montpellier, France), originally designed for cranial neurosurgical applications, may provide the answer to the technical flaws encountered by Ringel et al [88] The ROSA robot is a freestanding robotic assistant with a floor- fixable base and a rigid robotic arm (Figure 6). This may help mitigate concerns of fixation strength to bony anatomy like those encountered by Ringel et al [88] Additionally, the robotic arm moves in concordance with the patient, based on the tracking camera monitoring, real-time, several percutaneously placed tracking pins to the patient's bony anatomy in reference to tracking spheres affixed to the robot. This technology platform, however, has yet to be validated for use in spinal pedicle instru- mentation but early clinical results are promising. In their prelim- inary study on the novel application of the ROSA robot for spinal surgery, Lonjon et al89 reported an accuracy rate of 97.3% for pedicle screw instrumentation compared to 92% in the FH group. Though seemingly better suited for percutaneous and MIS proce- dures due to improved robotic arm fixation, these are the first published data of the ROSA robot for spinal applications and more data are needed to validate its use.

A discussion of surgical robotics would not be complete without mention of the Da Vinci Surgical System (Intuitive Surgical). The Da Vinci robot was FDA approved in 2000 for general laparoscopic procedures and is most commonly used for prostatectomies and hysterectomies, but spinal applications of the technologically advanced system have been proposed. The Da Vinci robot operates under the telesurgical model by which the surgeon operates the robot as an extension of his or her own arm from a remote telesurgical booth (Fig. 7). The booth is equipped with 3-D vision screens and portals for the surgeon's hands to control robotic instruments. Among the benefits of this robotic assistant that have led to its widespread use in the fields of general surgery, urology, and gynecology are high definition, stereoscopic vision with magnification up to 10×, tremor filtering, limitless wrist range of motion, and improved surgeon ergonomics. Additionally, the telesurgical model allows for close oversight from a separate both affording override, making it an ideal form of trainee education [90-92]

The Da Vinci Surgical System (Intuitive Surgical) has been utilized for laparoscopic anterior lumbar interbody fusion (ALIF) with promising results. The primary obstacles to ALIF remain the ureters and large vessels (aorta, vena cava, and branches thereof) overlying the anterior spine. The first laparoscopic ALIF was reported in 1991, with hopes of shorter hospital stay, quicker recovery, less postoperative pain, and smaller incisions through the MIS approach [93] However, results failed to show any advantage over open ALIF in regards to length of stay, blood loss, or complication rates, and additionally, the technical demands, often foreign to spine surgeons, resulted in a steep learning curve with increased operative time.[94 - 97] For these reasons, the procedure was largely abandoned by spine surgeons. However, with the improved usability of the Da Vinci robot, the procedure and its hypothesized improved efficacy for mobilizing aforemen- tioned approach-related dangers, the Da Vinci-assisted laparoscopic ALIF has again become relevant in the spine realms. Several small case-series

Table 2: Comparision of mazor and ROSA robotics system

Robotics System		
Feature	Mazor*	ROSA
Degree of freedom	6	6
Mount	Bone	Floor
Pre op CT Required	Yes	No
Instrument tracking	No	Yes
FDA Approval	Yes	Yes

studies have evaluated this application of the Da Vinci robot demonstrating successful dissection of overlying large vessels and no ureter- or vessel-related complica- tions.98 - 101 However promising, the use of the Da Vinci is not FDA approved for actual spinal instrumentation and more explo- ration is necessary to validate its use.

Review of literature [Table 1]

Accuracy of screw placement: A total of 22 studies evaluated accuracy of spinal instrumentation implanted using robotics [2,5,6,9,11–15,17,21,22,24,25,27–31, 35–37]. Twenty-one of these studies used variations of the robot developed by Mazor, whereas 1 study evaluated the ROSA robot. Twenty-one studies evaluated pedicle screw accuracy, whereas Dreval et al. evaluated both pedicle screws and guided oblique lumbar interbody fusion (GO- LIF) screws [6], and Bederman et al. evaluated the accuracy of S2–alar–iliac screw placement [2].

Sukovich et al. first reported on the Mazor system in 2006 [35]. They retrospectively evaluated 14 patients in whom 98 pedicle screws were placed. A combination of open and minimally invasive techniques were used. They found that 96% of the screws were within 1–2 mm of the planned trajectory, and they found no instances of breaching of the pedicle, although these authors did not detail their method of grading pedicle screw accuracy. Pechlivanis et al. [25] also retrospectively reviewed accuracy of the Mazor robot during minimally invasive posterior lumbar interbody fusion (PLIF), by using the postoperative CT-based Gertzbein and Robbins system (GRS) to classify pedicle screw accuracy [7,25]. In the GRS, screws completely within the pedicle are Grade A; a breach of < 2 mm is Grade B; a breach of 2 to < 4 mm is Grade C; a breach of 4 to < 6 mm is Grade D; and a breach of > 6 mm is Grade E. In this system, both Grades A and B are deemed acceptable. Pechlivanis et al. found that of a total of 122 screws that were able to be graded in 31 patients, 108 (88.5%) were GRS Grade A, 13 (10.7%) were GRS Grade B, and 1 (0.8%) was GRS Grade D.

Devito et al. have performed the largest retrospective study to date, evaluating 635 patients in whom 3271 pedicle screws were placed.5 Of these screws, 98% were deemed acceptable by fluoroscopy. A subgroup of 646 screws were evaluated with postoperative CT. In this subanalysis, 577 (89.3%) were GRS Grade A; 58 (9.0%) were GRS Grade B; 9 (1.4%) were GRS Grade C; and 2 (0.3%) were GRS Grade D. Hu and colleagues published a series of papers retrospectively assessing pedicle screw accuracy [9–11]. In their first paper,10 accuracy was evaluated using fluoroscopy in 95 patients with 960 screws placed using the Mazor robot (note that accuracy was not graded in all 102 patients; in the other 7 the screw placement was aborted). Of these, 949 (98.9%) were deemed to be accurate. In a follow-up study looking specifically at 9 patients with spinal column tumors, these authors did not mention any misplacements, although accuracy was not graded specifically. Dreval et al. evaluated 14 patients who underwent min- imally invasive pedicle screw placement.6 These authors did not define accuracy, although they stated that all patients had good results. Onen et al. evaluated 27 patients undergoing placement of 136 pedicle screws.24 In their co- hort, 124 (91.2%) were GRS Grade A, 10 (7.4%) were GRS Grade B, and 2 (1.5%) were GRS Grade C. Schatlo et al. published a series of 258 cases with 1265 pedicle screws, and found that 96.2% were acceptably placed (GRS Grade A or B)[29]. Similarly, van Dijk et al. evaluated 112 patients with 494 robotically placed screws [37]. A 97.9% rate of acceptably placed screws (GRS Grade A or B) was noted.

Recently, Macke et al. evaluated the Mazor robot in the treatment of adolescent idiopathic scoliosis specifically [22]. They reported a series of 48 patients with 662 screws in total (2 patients were eliminated from accuracy grading due to inadequate CT scans). They found a 92.7% accept- able placement rate (GRS Grade A or B). Of the 48 mis- placed screws, 30 were GRS Grade C, 10 were GRS Grade D, and 8 were GRS Grade E.

Kuo et al. evaluated the use of secondary registration on pedicle screw accuracy when using the Mazor robot.17 In this protocol, the authors placed a K-wire using the ro- bot, and then reregistered to the guidance system. Any deviation of > 3 mm was repositioned. The authors then graded accuracy when using biplanar fluoroscopy. Three hundred seventeen K-wires were placed using this system. Of these,19 (6.0%) were noted to have a > 3-mm deviation and underwent repositioning. After repositioning, 15 improved to having a < 3-mm deviation, and the remaining 4 required manual adjustment (98.7% final accuracy rate). The authors subsequently validated this accuracy data by using CT-based accuracy grading systems such as the GRS. They concluded that secondary registration increas- es the accuracy rate of robotic pedicle screw placement.

Seven comparative studies evaluating the Mazor robot as opposed to conventional freehand technique with fluoroscopy assistance were identified; this included 3 RCTs. Ringel et al. provided the first RCT in 2012 [27]. They randomly assigned 60 patients evenly into either percutaneous robot pedicle screw placement or the conventional open freehand technique. With the robotic arm, 146 screws were attempted, with an 85% rate of acceptably placed screws (GRS Grade A or B). With the freehand method, a 93% rate of acceptably placed screws was noted. The authors concluded that robotic placement of pedicle screws was inferior to conventional techniques. Hyun et al. performed a similarly designed study, again with 30 patients in each group [12]. They found that all robotically placed screws were acceptably placed. In the freehand group, there was a 98.6% accuracy rate. In addition, the freehand group had 1 violation of the proximal facet, whereas there were none seen in the robotic group. Kim et al. conducted an RCT of minimally invasive

PLIF performed using the
Mazor robot compared with open freehand techniques for PLIF.15 They found a 99.4% accuracy rate when using the robot, and a 99.4% accuracy rate with conventional free-hand techniques. However, there were no proximal joint violations with the robot, and 13 (15.9%) violations with the freehand technique. Kantelhardt et al. compared ro-botic screw placement (both open and percutaneous) with freehand techniques in a nonrandomized, retrospective fashion [13]. They saw significantly better accuracy when using the robot (94.5% vs 91.5% freehand), although there was no difference in accuracy in open robotic or percutaneous robotic fusion.
A prospective case-matched study by Schizas et al. found that robotically placed screws had a 95.3% accuracy rate compared with a 92.2% accuracy rate with con- ventionally placed screws, and concluded that there was no difference between the 2 techniques [31] Schatlo et al. also performed a retrospective case-matched study com- paring robotically placed pedicle screws (both open and percutaneous) with open freehand screws [30]. They found a 91.4% accuracy rate with Mazor, and an 87.1% accu- racy rate with open techniques. Six robotically placed screws required manual revision during the initial operation, and 1 freehand screw required postoperative revision due to misplacement causing radiculopathy. Keric et al. performed a retrospective cohort study in patients with spondylodiscitis between percutaneous robotically placed pedicle screws and open freehand procedures [14]. They found that robotically placed screws were significantly more accurate, and were less likely to require revision for misplacement or loosening.
Roser et al. performed an RCT using 3 arms: freehand instrumentation, standard neuronavigation, and robotic screw placement using the Mazor robot [28]. They found a 99% accuracy rate (GRS A) with robotically placed screws. Standard navigation resulted in 92% accuracy (GRS A), and freehand techniques resulted in 97.5% accuracy. Of note, the authors defined accuracy as only GRS A, which is dissimilar to other studies that also included GRS B as accurate. When including GRS B screws, accuracy rates were 99% with robotics, 97.2% with navigation, and 100% with freehand. Statistical evaluation was not per- formed in this study due to the small sample size of only 18 patients treated with robotics, 9 with navigation, and 10 with the freehand method.
The Mazor robot has also been evaluated for proce- dures other than placement of pedicle screws. Bederman et al. evaluated accuracy of the placement of 31 S2–alar– iliac screws in 14 patients [2]. They found that all screws were accurate, with no breach of the anterior sacrum. Dreval et al. evaluated transpedicular, transdiscal screws in association with GO-LIF [6].Thirty-six patients and 72 screws were evaluated for this procedure. Accuracy was not directly graded, but 1 patient did require revision due to poor purchase.
Lonjon et al. performed the only study evaluating the ROSA robot [21]. They performed a prospective case- matched study comparing robotically placed screws to open freehand techniques. Thirty-six screws were robotically placed, with a 97.2% accuracy rate, and 50 screws were placed freehand with a 92% accuracy rate. An additional 4 screws were attempted robotically, but were un- able to be placed due to technical difficulties.

Radiation exposure
Ten studies evaluated radiation exposure in conjunc- tion with robotic spinal instrumention [12–15,21,24,27,28,31,32]. This included 5 studies comparing robotic procedures with conventional open procedures. Kantelhardt et al. found that robotically placed screws had a mean fluor-oscopy time (FT) of 34 seconds per screw, whereas open freehand screws had a mean FT of 77 seconds.13 There was no difference between percutaneous robotically placed screws and open robotically placed screws. Hyun et al. also found that the mean FT per screw was significantly lower with the robot (3.5 seconds vs 13.3 seconds) [12]. Similarly, the robotically placed screws had decreased radiation output in millisieverts (mSv) when compared with freehand placement (0.13 mSv vs 0.27 mSv). Keric et al. also found that FT was significantly lower with robotically placed screws.14 However, Ringel et al. found that total intraoperative FT was similar be- tween freehand and robotically placed screws [27]. Schizas et al. also found that radiation times were similar (16.7 seconds per screw robotically vs 14.2 seconds per screw freehand) [31]. Onen et al. described an FT of 1.3 seconds per screw, whereas Kim et al. described a total FT of 20.4 seconds.15,24 Roser et al. evaluated both standard naviga- tion and freehand techniques in comparison with robotically placed screws [28]. They reported that FT and radiation dosage were lowest in the standard navigation group, followed by the robotic group. Radiation exposure was highest in the freehand group.
Sensakovic et al. evaluated a new low-dose radiation CT protocol for patients undergoing pediatric idiopathic scoliosis deformity correction performed using the Mazor robot [32]. In this protocol, patients either underwent tradi- tional preoperative CT or low-dose CT. Dose reductions for the preoperative CT were 6.55 mSv in patients with a body mass index < 25, and 9.3 mSv for patients with a body mass index of 25–35. The authors reported that images were adequate for robotic screw placement, although accuracy of screw placement was not graded postopera- tively.
Lonjon et al. evaluated radiation exposure during placement of pedicle screws performed using the ROSA robot as compared with freehand placement [21]. They found that total FT was significantly longer when using the robot (1.23 minutes vs 0.4 minute). The FT per screw was 25 seconds when using ROSA, and 10 seconds when using freehand techniques. In that study, intraoperative fluoros- copy was used for registration and planning purposes.
Radiation exposure (ghaseem)
Thirteen studies evaluated radiation exposure to the surgical team (Table 1). Radiation exposure time (RET) was measured as seconds of fluoroscopy per screw placed for consistency. Kantelhardt et al. compared conventional freehand procedures to robot-assisted open and percutaneous surgeries. The authors discovered a mean RET of 77 seconds/screw for the conventional operations, compared to 43 seconds/screw for robot-guided open surgery and 27 seconds/screw for robot-guided percutaneous surgery.7 Keric et al. observed the outcomes of 90 patients receiving either fluoroscopy-guided freehand surgery or robot-assisted surgery, and also found mean RETs to be longer with freehand – 56.4 seconds/screw and 24 seconds/screw, respectively.8 In Lonjon et al., the opposite effect was observed. The freehand surgeries contained an average RET of 4.8 seconds/screw, compared to 18.5 seconds/screw with robotic assistance with ROSA [9]. The authors attributed this increased radiation time to their practice of using an average of 5.3 radiographic images per patient, whereas normally only two (AP and lateral) are required for accurate image matching with ROSA.
Onen et al. looked at robotic assistance in the

case of 27 surgeries, both open and percutaneous, and found a mean RET of 1.3 seconds/screw with no significant differences between open and percutaneous robotic surgery [10]. Interestingly, the authors of Ringel et al. concluded that the intraoperative radiation time was not different between the freehand and robotics groups, both with a mean RET of 3.8 seconds/screw [11].

Eight studies evaluated Learning curvethe learning curve for spinal in- strumentation placement performed using robotics [5,10,12,15, 22,24,27,29]. Devito et al. found that the ability to place screws robotically was 83.7% in their total cohort, but increased to a 90.8% execution rate when they looked at their most recent procedures [5]. In addition, time per screw placement decreased from 13.5 minutes for single-level cases (4 minutes per screw in multilevel cases) to 10.6 minutes (2 minutes in multilevel cases). Hu et al. evaluated the learn- ing curve specifically, and found that after 30 procedures, the rate of successful placement increased and there was a decreased need for conversion to manual techniques [10]. There were no differences in rates of malpositioning, and the learning effect plateaued after the initial 30 patients. Onen et al. saw a decrease in both FT (from 1.8 seconds per screw to 0.9 seconds per screw) and time for screw placement (from 15.5 minutes to 8.6 minutes) over the course of their experience when comparing their initial 13 patients to their subsequent 14 patients [24]. Hyun et al. similarly found a decrease in time for screw placement (from 5.5 minutes to 4.0 minutes) and FT (from 4.1 seconds to 2.9 seconds) [12]. Kim et al. found a decrease in total FT from 27.5 seconds to 18.5 seconds [15]. Schatlo et al. graded the accuracy of screw placement in 13 surgeons [29]. For each surgeon, accuracy was graded in 5-case increments. The investigators found that misplacement rates peaked between 5 and 25 surgeries, and then steadily declined. Macke et al. also found a decrease in misplacements when comparing the first and last third of their cohort (9.6% vs 7.4%).22 However, Ringel et al. stated that accuracy did not improve over the course of their study, although no spe- cific data were provided [27]

Operative times (Table 1)

18 articles were identified comparing operative time in conventional freehand and robot- assisted surgeries.

Prospective studies evaluating SpineAssist included Roser et al., which used a 3-arm approach and recorded 111.2 minutes per freehand operation, 160.8 minutes per navigation- assisted surgery, and 140.8 minutes per robot-assisted surgery [12]. The same surgeon operated on all patients studied by Lonjon et al. using both open techniques and ROSA-guided robotic assistance; robot-guided procedures took nearly 2 hours longer than freehand ones, at 336 minutes compared to 209 minutes of total operative time [9].

In Keric et al., the surgeons compared percutaneous robot-assisted transpedicular instrumentation to a conventional open approach. It was found that freehand procedures were slightly longer, at 218.9 minutes compared to 202.6 minutes for robotic assistance [8]. Kantelhardt et al. compared operative times for three different techniques: freehand (265.5 minutes), robotic- assisted open surgery (306.4 minutes), and robotic-assisted percutaneous surgery (254.2 minutes) [7]. Solomiichuk et al. concluded that robotic-assisted surgeries could be performed more expeditiously than open freehand ones (226.1 minutes vs. 264.1 minutes), though this was not found to be statistically significant [13].

Length of stay (Table 1)

Kim et al. reported an average time to return to ambulation to be 39.7 hours for freehand procedures and 36.2 hours for Renaissance-assisted surgery, p = 0.363 [18]. Hyun et al. stated the length of stay to be longer for freehand procedures as well (9.4 days vs. 6.8 days), p = 0.020 [14]. For Kantelhardt et al., time to discharge post-operation was 14.6 days following open surgery for the 57 patients who received 286 screws, 11.6 days after robot-guided open surgery for the 20 patients receiving 94 screws, and 10.1 days for robot-guided percutaneous operations for the 35 patients who received 156 screws, p = 0.009 [7]. Less muscle dissection and traumatic injury to soft tissues with minimally invasive approaches may also affect hospital length of stay and result in faster recovery, independent of the effect of the robot [19].

Complication (Table 1)

Kantelhardt et al. reported post-operative infections in 2.7% of robot-guided procedures (only open, not percutaneous) compared to 10.7% of open non-robotic ones, p = 0.04.7 Only in 10 cases (0.6% percutaneous procedures, 12.6% open robotic-guided procedures and 12.2% open procedures) was operative intervention required.7 Data on infections was also disclosed by Keric et al., in which 20.8% of patients had a wound infection following open procedures, while 10.6% of the robot-assisted percutaneous group developed infection, p = 0.104 [8]. Only one of the open procedures was treated by antibiotics as compared to four cases that required surgical intervention, while four robot-assisted surgical patients required additional surgery as compared to three whose complications were resolved by antibiotics [8].

Sixteen articles stated no complications due to the use of the robot in surgery (Table 1). The remaining articles ranged from one to 19 complications [11,20-22]. The majority of the complications were due to technical issues with the robot (hardware or software failure, failed fluoroscopy-to-CT registration) or cannula skidding causing misplacement of screws. Clinical complications with the robot included hemothorax,24 CSF leakage, and pulmonary embolism.17 Devito reported reversible neurological complications in 4 of 593 (0.7%) cases using SpineAssist for pedicle screw instrumentation [25]. Freehand procedures had higher rates of dural tears (four compared to one) when compared to robot groups (p = 0.142) [8]. Both Schatlo and Solomiichuk reported one instance each of radiculopathic nerve root injury in a fluoroscopy-guided procedure (but none in the robot-assisted cohort) [13,21].

Mechanisms of Robotic Failure (joseph)

Twelve studies evaluated reasons for failure of the robot during spine instrumentation [1,5,9,17,21,22,24,25,27,28,30,35]. Reasons for aborting the robotic procedure included failure of registration software and failure to obtain adequate fluoroscopic images. In several studies, soft-tissue pressure on the guiding arm led to inaccurate placement [1,27]. Other rea- sons for failure included the inability to adequately obtain surgically the necessary angles determined

by the registration software. Other studies describe difficulties with keeping the drill guide in position on the slope of the facet, causing a lateral and inferior deviation [17,27,30]. Macke et al. found that patients who had preoperative CTs performed in a prone position had a screw misplacement rate of 2.4%, compared with a misplacement rate of 7.6% in patients whose preoperative CTs were performed in the standard supine position [22].

Discussion

Appropriate instrumentation to supplement bony fusion remains critically important in spine surgery. Recently, surgical robots have been developed and studied for their ability to improve spinal instrumentation techniques. The Mazor robot (SpineAssist or Renaissance) has been the most extensively studied. It is a miniature bone-mounted robot that has 6 degrees of freedom.1,20,35 A preoperative CT is used to plan trajectories, and intraoperative fluoros- copy is used to register the images. The robot then guides the surgeon to the appropriate trajectory. The ROSA ro- bot includes a mobile floor-fixed base attached to a robotic arm with 6 degrees of freedom. A second mobile base has a navigation camera mounted to it. The ROSA is an image-guided device and uses an iliac pin for a reference point. Either intraoperative fluoroscopy or intraoperative CT can be used for planning [4,19,21]. Currently, both robots only have applications in placement of screws for spinal instrumentation; no further applications have been described. Com- parisons between ROSA and Mazor are summarized in Table 2.

Robotics in spine surgery offers the advantage of precision and the removal of human manual error. In this re- view, all studies that evaluated accuracy of screw placement (both pedicle screws and S2–alar–iliac screws) showed that the accuracy rates were high. Most compara- tive studies demonstrated that robotics provides an advantage to traditional freehand placement. However, 1 RCT did show that there was a decrease in accuracy with screw placement using the Mazor robot.27 Overall, the accuracy data suggest that screw placement with the Mazor robot is safe. Although only 1 study evaluated the ROSA robot, it also appeared to show that pedicle screw placement with this device is safe.21 In addition to accuracy through the pedicle, some studies suggested that using robotics for pedicle screw placement allows the surgeon to avoid vio- lating the proximal facet joint, which may provide biomechanical advantages that could preclude the development of adjacent-segment disease.16

There are no large-scale studies to date that have di- rectly compared robotic guidance of pedicle screws with image guidance. Roser et al. did publish a preliminary se- ries evaluating image guidance in comparison with both robotics and freehand placement.28 Because of inadequate power, with only 37 total patients among the 3 treated groups, they were unable to analyze their results. Image guidance provided using intraoperative cone-beam CT has already been shown to be superior to freehand placement [33,38]. As mentioned previously, the ROSA robot does incorporate image guidance into its system, in addition to having the robotic arm.

Radiation exposure to the surgeon and operating room staff is a concern, particularly in minimally invasive procedures [3,8,40]. One potential advantage of robotic spinal instrumentation is to minimize reliance on intraop- erative fluoroscopy. Findings for FT in the Mazor robot were variable, ranging from 1.3 seconds to 34 seconds per screw, probably due to surgeon variability [13,24]. In comparative studies, results suggested that the Mazor robot allowed for FT similar to or lower than FT for open free- hand procedures. However, evaluation of the ROSA robot showed a significant increase in FT when compared with freehand [21]. It should be noted that this study used fluoroscopy for registration and planning. Studies of the ROSA robot performed using intraoperative CT were not avail- able.

Although surgical robotics is promising, it is still clear- ly in its nascent stage. Execution rates for robotic procedures are still not as high as would be ideal. Issues such as soft-tissue pressure on the robotic arm were cited several times in the literature as causing deviations [1,27]. In addition, slipping of the guide down the slope of the facet was com- monly referred to as a major concern.17,27,30

There were several limitations to the present study. An inherent risk of publication bias exists with the literature, as previously mentioned. In addition, there were inconsistencies among the studies in their reporting of pedicle screw accuracy. Although several studies used CT-based methods, some evaluated accuracy using intraoperative fluoroscopy. Similarly, methods of evaluating radiation ex- posure varied among studies. Finally, because most stud- ies used the Mazor robot, the results presented here may not truly represent surgical robotics as a whole, but rather the experience with a particular robot.

Ghasem

Inaccuracy in pedicle screw placement by conventional freehand methods and their resulting clinical complications have served as a basis for technological innovation. With pedicle screw malposition being cited as ranging between 4.9-13%, there is mounting interest in robot- assisted instrumentation in spine surgery and its incorporation into everyday clinical practice [25,27-32]. Currently, Mazor, ROSA, and the recently added Excelsius are the only robotic systems that are FDA approved for pedicle screw trajectory guidance. With a marketed retail base price of $850,000 and annual disposable expenses estimated to be nearing two thousand dollars, concerns for cost-effectiveness are evident [33].

A potential area for offsetting the expenditures associated with the robot are in identifying its effect on patient length of stay. As compared to the freehand cohort, Kantelhardt et al. found a significant reduction in length of stay in the open robotic group and even further reduction in the MIS robot group ($p = .009$).7 Length of stays were recorded as 14.6, 11.6, and 10.1 days respectively [7]. Hyun et al. notably found a 3 day decrease in hospitalization in the MIS robotic arm of their study in contrast to the open freehand group.14 However, this is greatly influenced by the minimally invasive nature of the approach in the robotic group requiring less traumatic tissue dissection as opposed to a substantive effect related to robot usage. The remaining studies evaluating length of stay did not find a statistical difference between the two methodologies of instrumentation. This finding may be impacted by a relatively low number of levels being instrumented at 5 or less, masking a potential difference between groups. In future studies, increased surgeon familiarity with robot assisted screw placement may also play a role in affecting

length of stay, but at this time the data remains inconclusive.

Several studies have focused on evaluating the accuracy of pedicle screw trajectory of robotic systems. Synchronization of a preoperative CT scan and intraoperative fluoroscopy is used for image registration and allows for the implementation of the planned screw trajectory. An exceedingly high proportion of the listed studies showed either comparable or significantly improved accuracy in screw placement in the robotic group. Hu and Lieberman et al. do suggest a learning curve of 30 cases exist with robot use to avoid screw malposition and conversion to manual screw placement [34]. The MIS robot-assisted cohort treated by Bederman et al. displayed 100% accuracy in intrapedicular screw placement [35]. Only one prospective randomized control study performed by Ringel et al. showed inferior accuracy in the robotic group as compared to the freehand group [11]. This finding was largely attributed to motion as a result of using a bed- mounted platform. Kim et al. found no difference in the accuracy between the freehand and robotic group with respect to pedicle trajectory, but did note increased facet violation in the freehand group [18]. In one study comparing screw paths with robot-guidance, navigation, and freehand, accuracies were recorded as 99%, 92%, and 97.5% respectively, although this study was noted to be underpowered [12]. As a result of improved accuracy, clinically significant complication rates were comparable or lower consistently throughout the literature in robot assisted screw placement.

Extended operative time portends negative patient outcomes and has implications on facility cost. Conclusions regarding operating time should be drawn with caution with the available literature as several of the listed studies are composed of surgeons in the early stages of growing their robotic cohorts. Total operative time in Kim et al. is reported as 190 minutes and 220 minutes in the freehand and robotic cohorts, respectively.18 This finding of increased operative time with robotic assisted surgery is echoed in the vast majority of the early literature [11,12,36]. More recent studies conducted by Solomiichuk et al. and Keric et al. in 2017 with larger robotic cohorts show reduced operative time when comparing percutaneous robotic pedicle screw instrumentation to freehand open screw placement in patients with a comparable number of operative levels between groups [8,13]. Follow up studies with advancement in surgeon experience will help to answer the effect of robotic surgery on operative time.

Tapering radiation exposure to the surgical team continues to mount interest and is a potential edge with the usage of robotic assisted instrumentation. Kantelhardt noted a difference of 34 seconds per screw placement with robot assistance as opposed to 77 seconds with freehand technique [7]. Hyun et al similarly displays a significantly decreased fluoroscopy time [14]. However, findings in other studies are not as convincing. Kim et al. and Lonjon et al. show significantly lower fluoroscopy time in their respective freehand groups [9,18]. Of note, Lonjon et al. used the ROSA, which requires additional fluoroscopy time for registration. While no clear conclusion can be drawn regarding the superior method for decreased radiation exposure, fluoroscopy time does appear to trend downward with repetitive use of robotic systems [25]. Most notably, Onen et al. reported a 50% reduction in fluoroscopy time for each screw inserted in their later cases [10].

Conclusion

Robotics in spine surgery is a new technology that holds promise for future applications. Currently, placement of pedicle screws with robotics appears to be safe, and ac- curacy appears to be superior to freehand placement, al- though the data are not conclusive. Radiation exposure is dependent on the type of robot, and from the current literature we were unable to definitively confirm if there is a significant benefit to robotics for this concern. Studies comparing robotics with image guidance are currently lacking. More research is necessary to identify the ideal role for robotics in spinal instrumentation.

Robotics in spine surgery is in its early developmental stages in both an industrial sense as well as surgeon familiarity. Continued innovation to reduce sensitivity to soft tissue pressure, improve work volume, facilitate registration, and enhance surgeon-friendly software will be critical for patient safety and widespread use. At this juncture, robotic screw placement accuracy and complication rates appear to be within an acceptable standard of care. However, juxtaposition of robotics with traditional surgical treatment in metrics of fluoroscopy time, operative time, and length of stay findings remain inconclusive and make it difficult to justify widespread application. Future cost-benefit analyses and studies involving surgeons with extensive robotic experience beyond the suggested learning curve are necessary.

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