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Robotic spine systems: overcoming surgeon experience in pedicle screw accuracy: a prospective study

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Study Design: Prospective single-center study.
Purpose: To compare the accuracy of pedicle screws placed by freehand and under fluoroscopy and robotic assistance with intraoperative image acquisition.
Overview of Literature: Pedicle screws are the most commonly used spinal anchors owing to their ability to stabilize all three spinal columns. Various techniques such as freehand, fluoroscopy-assisted, and navigation-assisted pedicle screw placements have been used with varying degrees of accuracy. Most studies on robotic-assisted pedicle screw placement have utilized preoperatively acquired computed tomography scans. To our knowledge, this is the only study in the literature that compared freehand with fluoroscopy-guided and robotic-assisted pedicle screw insertion with freehand and fluoroscopy.
Methods: In this prospective study, a total of 1,120 pedicle screws were placed in the freehand group (n=175), 1,250 in the fluoroscopy-assisted group (n=172), and 1,225 in the robotic-assisted group (n=180). Surgical parameters and screw accuracy were analyzed between the three groups. The preoperative plan overlapped with the postoperative O-arm scan to determine if the screws were executed as planned.
Results: The frequency of clinically acceptable screw placement (Gertzbein-Robbins grades A and B) in the freehand, fluoroscopy-assisted, and robotic-assisted groups were 97.7%, 98.6%, and 99.34%, respectively. With robotic assistance, an experience-neutralizing effect implied that surgeons with varying levels of experience achieved comparable pedicle screw accuracy, blood loss, O-arm time, robot time, and time per screw. No significant difference in these parameters was found between surgeries commencing before and after 2 PM. No significant differences were noted between the planned and executed screw trajectories in the robotic-assisted group irrespective of surgical experience.
Conclusions: The third-generation robotic-assisted pedicle screw placement system used in conjunction with intraoperative three-dimensional O-arm imaging consistently demonstrates safe and accurate screw placement with an experience-neutralizing effect.

Keywords: Thoracolumbar spine; Robotic surgical procedures; Pedicle screws

Introduction

The quest for minimally invasive and highly accurate techniques for thoracolumbar spine surgery has driven advancements in surgical approaches and instrumentation. Although open surgeries have largely been replaced by minimally invasive techniques, achieving optimal pedicle screw placement remains a crucial but challenging aspect. Accurate screw placement is essential to achieve stability and minimize the risk of neurological and vascular injuries [1-3].

Several factors can hinder accurate pedicle screw placement, including anatomical variations, history of spine surgery, and obesity. Traditionally, surgeons have relied on freehand or fluoroscopy-assisted methods to achieve accurate screw placement. However, these techniques can have accuracy limitations and variability [3-9].

Third-generation robotic spine systems combined with robotic guidance using real-time intraoperative cone-beam computed tomographic (CT) scans offer a potential solution. These scans provide a more precise picture of the intraoperative anatomy in the prone position than preoperative CT scans obtained in the supine position, and the robotic arm ensures that instruments follow a planned trajectory, which minimizes deviations [10].

This prospective study aimed to compare the accuracy and safety of freehand, fluoroscopy-assisted, and robotic-assisted (intraoperative cone-beam CT scan based) techniques for thoracolumbar pedicle screw placement. The accuracy of screw placement with each method was evaluated, and the potential of robotic assistance to consistently achieve high accuracy regardless of surgeon experience was investigated. To our knowledge, this study is the first to assess robotic (intraoperative cone-beam CT scan based) operative time, time per screw placement, and blood loss in thoracolumbar spine pedicle screw instrumentation because most studies have utilized preoperative CT scans in the supine position.

Materials and Methods

After approval from the institutional ethics committee of Manipal Hospital, Bangalore (ECR/34/Inst/KA/2013/RR-19), this single-center prospective study enrolled 527 consecutive patients undergoing thoracolumbar spine surgery, who consented to participate in the study. Patients were randomly allocated by block randomization to one of the three groups: freehand pedicle screw insertion (n=175), fluoroscopy-assisted insertion (n=172), or robotic-assisted insertion using the MazorX Stealth Edition and O-arm (Medtronic Ltd., Dublin, Ireland) scans (n=180). Subsequently, by block randomization, the participants were randomly allocated to one of the four fellowship-trained spine surgeons of varied experience (1, 5, 7, and 20 years). A total of 3,595 pedicle screws were placed, spanning T1 to the ilium, including 60 S2 alar–iliac (S2AI) screws.

Freehand and fluoroscopy-assisted surgical technique

The spine was exposed through a conventional midline incision and subperiosteal dissection of the paraspinal muscles. The thoracic and lumbar pedicle entries were determined by the intersection technique, and in the fluoroscopy-assisted group, the same was confirmed on the anteroposterior and lateral fluoroscopy techniques. The pedicle probe was used to create a track in the pedicle, and a sound would be heard if any breach was detected. A tap of appropriate diameter was used to cut threads in the channel, and the pedicle screw of appropriate diameter and length was placed.

Robotic-assisted surgical technique

A sufficient space with minimal clutter in the operating room is important to accommodate the MazorX and O-arm with their consoles, along with space for their maneuverability. All procedures adhered to the intraoperative “scan and plan” workflow, where robot registration, image acquisition, and screw planning occurred after patient positioning and exposure. All cases involving spinal deformity included multimodal neuromonitoring.

Robotic arm mounting and patient positioning

The robot is mounted to the radiolucent table after the patient is positioned prone under general anesthesia. The surgical field along with the robotic arm was draped aseptically. A midline mini-open exposure was made in lumbar surgeries, and the routine midline approach was used in the thoracic spine and thoracolumbar deformity surgeries. In open cases, thoracic transverse processes were routinely flattened, and lumbar facets were hypertrophied to prevent skiving of the drill, whereas in minimally invasive lumbar cases, this step was skipped. Subperiosteal dissection distal to the L5S1 facet is minimized for the placement of the S2AI screws because we routinely place them with transmuscular or transfascial stab incisions. For lumbar surgeries, the robot was then semirigidly mounted to the patient using a Schanz pin placed in the left posterior superior iliac spine, whereas it was placed in the vertebra below the planned lower instrumented level under fluoroscopy guidance in thoracic instrumentation. However, subsequently, we transitioned to surgeries without Schanz pin mount, as we found minimal movement once patients were rigidly secured to the table. Spinous process clamps were not utilized in any of our cases because they obstruct the surgical field.

Robotic arm registration and image acquisition (O-arm scan) were performed with self-retaining retractors in place in thoracic spine deformities. The robotic arm utilizes infrared and optical cameras to identify obstructed areas, essentially creating virtual "no-fly zones." The robot-navigation registration with a reference tracker ("snapshot") is performed for accurate visualization of navigable instruments. When necessary, this step can be repeated if navigation accuracy is lost intraoperatively due to inadvertent movements of the reference frame. Finally, a blunt passive planar probe is used to mark the middle region of the instrumentation to guide the robot arm. A fiduciary array ("star marker") is placed close to the patient to visualize maximum vertebrae (5–9 depending on the patient's size), and the surgical field is covered with a sterile drape (Fig. 1).

Intraoperative imaging and screw placement

Using the O-arm, orthogonal X-ray images of the surgical area are taken to ensure that all four beads of the "star marker" array are visible. This marker array serves as a reference point for the system to determine the precise location of the vertebrae within the patient's anatomy. The standard O-arm scan has a field of view of 15 cm. However, procedures requiring broader visualization, such as S2AI/iliosacral screw placement, necessitate expanding the field of view to 40 cm.

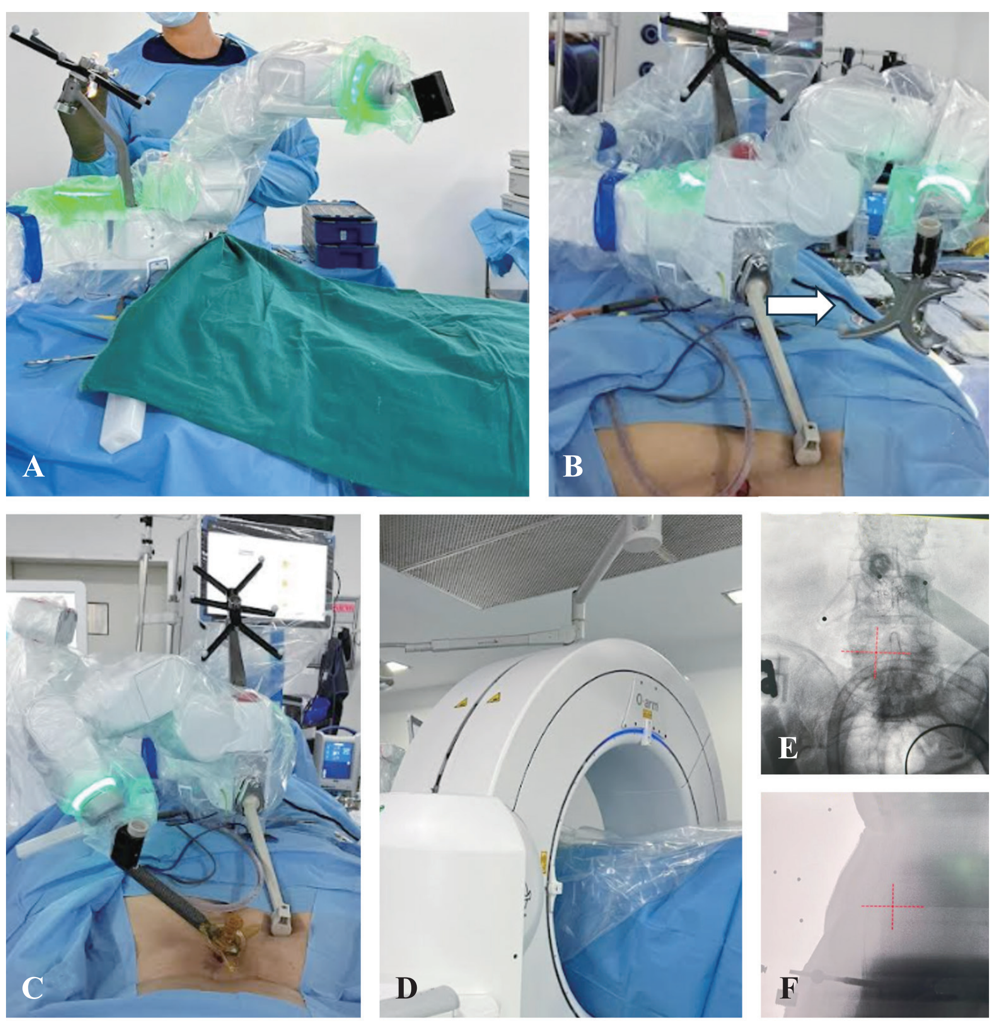

Fig. 1. Clinical photographs showing robot defining "no-fly-zone" **(A)**, robot-navigation registration with "snapshot" (bold arrow) **(B)**, and "star marker" in the region of interest **(C)**. Prior to O-arm scan of surgical area **(D)**, visualization of all four beads of the "star marker" are done on antero-posterior **(E)**, and lateral fluoroscopy **(F)**.

The acquired O-arm images are transferred to the robotic workstation. After marking the vertebrae, the software automatically segments them. Clear visualization of both pedicles in each segment is crucial. Notably, segmentation of the lateral view is prioritized for degenerative lumbar surgeries, whereas the anteroposterior view carries greater importance for thoracolumbar deformity correction. The axes on all three planes must be aligned to achieve a "normal" vertebral appearance before planning screw trajectories. The software facilitates screw planning at each segment, ensuring optimal placement within the bone (intraosseous) across all three planes (axial, coronal, and sagittal). In situations with inadequate pedicle visualization, the software allows us to examine adjacent segments and plan trajectories safely through the remaining bony corridors, even bypassing broken screws or cement in revision surgeries.

A high-speed "feather-touch" drill (3×30 mm and 75,000 revolutions per minute [RPM]) guided by the robotic arm, through a sleeve, creates precise entry points within the pedicles with minimal skiving risk. Subsequently, an appropriately sized tap is selected to cut the necessary threads within the bone. The pedicle screws can be directly placed into the prepared tracks using a torque-limiting power tool guided by the robotic arm. Alternatively, if the screwdriver is incompatible with the robotic arm guide, cannulated screws can be placed over the guide wires.

Surgical approaches for screw placement

For short-segment fixation in the lumbar spine, separate lateral stab incisions are used to create the tracks of the pedicle screws with a single incision allowing up to four screws (Fig. 2). In long-segment instrumentation and deformities, the central levels were instrumented first, and lateral, subfascial, or submuscular incisions were then used separately for the end levels. This minimizes soft tissue pressure on the robotic arm and prevents "skiving." In the thoracic spine, visual confirmation of drill entry is crucial, as soft tissue pressure can sometimes cause medialization of the drill sleeve. To prevent drill maltracking, the sleeve position was adjusted with a finger or by carefully maneuvering the spine. In rare instances of severe kyphosis, the Schanz pin bone mount obstructed the drilling trajectory, necessitating its removal before screw placement.

Robotic S2AI screw placement

The initial track, falling short of the sacroiliac (SI) joint, is created using a high-speed "feather-touch" drill (3×30 mm and 75,000 RPM) guided by the robotic arm and sleeve. Subsequently, a longer 4×60 mm awl-tipped tap is used to traverse across the SI joint. However, given its 6-mm shaft diameter, this 60-mm long tap cannot complete the entire planned screw track of 80–90 mm. Therefore, a final tapping step is performed using a 6.5×60 mm tap to create the full trajectory, allowing for precise S2AI screw placement using the torque-limited power tool without toggle.

Intraoperative imaging and instrumentation

A second O-arm scan may be necessary in procedures involving longer spinal segments (the initial scan might not encompass the entire area of interest), unrectifiable

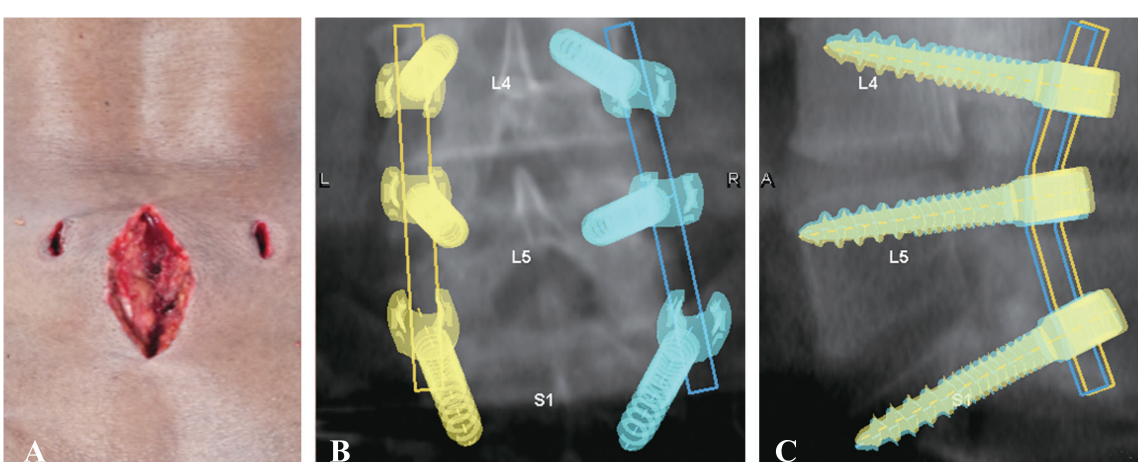

Fig. 2. (A) Clinical photograph showing midline incision for decompression and paramedian incision for screw insertion. **(B, C)** Screenshot of robot workstation showing planned trajectories of the screws.

loss of navigation accuracy, or robotic arm shift (because of excessive pressure). A repeat O-arm scan is performed after the placement of temporary rods for complex procedures such as three-column osteotomies, which allow visualization of critical adjacent structures, ensuring safe bony resection using the navigable high-speed burr.

Data collection

Demographic, clinical, and surgical data were collected for all patients. The "cut-to-close time" is the total time elapsed from the initial skin incision to the closure of the surgical site. The "time per screw" is the average time taken to insert each pedicle screw. In robotic-assisted surgeries, the "exposure time" was defined as the time from the initial skin incision to the complete exposure of the laminae at the decompression levels. The "O-arm time" includes the time from positioning the O-arm for the anteroposterior fluoroscopy image to finalizing the acquisition of the cone-beam CT image, and the "robot time" from software mounting the robotic arm to the completion of inserting the last screw or guidewire. The amount of intraoperative blood loss was documented in all patients.

Postoperative evaluation and analysis

Postoperatively, all patients underwent a final O-arm scan, and screw breaches were graded according to the classification system established by Gertzbein and Robbins [11]. To assess the accuracy of screw placement, Digimizer ver. 6.3 (MedCalc Software Ltd. Ostend, Belgium) was employed, which compared the planned screw trajectories (preoperative workstation image) with the actual screw positions captured in the postoperative O-arm image. The process involved overlaying the images, and a neuroradiologist and a surgeon independently verified the accuracy and angle of insertion. Postoperative pain levels of all patients were assessed using the Visual Analog Scale, and neurological deficits were noted.

To evaluate the effect of the surgical technique (freehand, fluoroscopy assistance, or robotic assistance) and the surgeon's experience on various parameters, data were compared between groups of 45 consecutive patients. The effect of case order on surgical efficiency was also examined by comparing surgeries that commenced before and after 2 PM.

Statistical analysis

Quantitative data, such as the difference in the planned and executed screw angles, are presented as means ± standard deviations. Qualitative data, such as the prevalence of specific outcomes (e.g., infection rates), are expressed as percentages. To compare group means across different surgical techniques, appropriate statistical tests were employed depending on the data distribution. Normally distributed data, the unpaired *t*-test was used. For nonparametric data, the Mann-Whitney *U* test was used when comparing two groups, and one-way analysis of variance test was used for comparisons across three or more groups. Finally, the chi-square test was used to analyze differences in frequencies between categorical variables. A *p*-value of <0.01 was considered significant.

Results

A total of 527 patients underwent thoracolumbar spine surgery. Table 1 summarizes the patient demographics. A total of 1,120 screws were placed in the freehand group (n=175), 1,250 in the fluoroscopy-assisted group (n=172), and 1,225 in the robotic-assisted group (n=180). The frequency of clinically acceptable screw placement (Gertzbein-Robbins grades A and B) in the freehand, fluoroscopy-assisted, and robotic-assisted groups were 97.7%, 98.6%, and 99.34%, respectively. Screw revision due to the intraoperative detection of pedicle breaches was required in 26 (2.3%), 18 (1.4%), and 8 (0.66%) screws in the freehand, fluoroscopy-assisted, and robotic-assisted groups, respectively. Facet joint violations were not observed.

Postoperative complications included superficial infections (n=18; freehand, 8; fluoroscopy-assisted, 6; robotic-assisted, 4), surgical re-exploration (n=3) including deep infections (n=2; freehand, 1; fluoroscopy-assisted, 1), and cauda equina syndrome secondary to epidural hematoma (n=1; fluoroscopy-assisted, 1). No permanent neurological deficits were reported.

Fig. 3 illustrates the distribution of screws placed across different spinal levels with no significant difference across the three groups. Table 2 presents that robotic guidance may have an "experience-neutralizing effect," implying that surgeons with varying levels of experience achieved comparable pedicle screw accuracy, blood loss, O-arm time, robot time, and time per screw with robotic assistance. No significant difference in these parameters was found between surgeries commencing before and after 2 PM. However, Table 3 reveals a significant increase in the overall surgical time for procedures starting later in the afternoon. Most importantly, no significant differences were found be-

Table 1. Table showing demographic and clinical data of the studied sample

Characteristic	Freehand (n=175)	Fluoroscopy-assisted (n=172)	Robotic-assisted (n=180)	*p*-value
Age (yr)	47.2±18.6	49.8±15.4	50.7±19.6	0.166[a]
Frequency of females (%)	48	42	49	0.84[b]
Body mass index (kg/m²)	28.5±4.1	29.1±3.6	28.3±4.2	0.14[a]
Etiology				0.86[b]
Degenerative	98	95	107	
Spondylolisthesis	43	37	41	
Deformity	18	22	20	
Tumor	4	4	3	
Trauma	7	6	7	
Infection	5	8	2	
Total no. of screws	1,120	1,250	1,225	NA
Gertzbein-Robbins grades				<0.01[b]
Clinically acceptable screws (grades A & B)	1,094	1,232	1,217	
Pedicle breaches requiring revision (grades C–E)	26	18	8	
Exposure time (min)	47±14	52±15	35±12	<0.01[a]
Time per screw (min)	3.2±1.4	6.2±1.5	3.5±1.2	<0.01[a]
Cut to close time (min)	143.6±28.4	152.8±42.3	157.9±45.8	<0.01[a]
Blood loss (mL)	642.7±234.6	708.2±283.6	537.2±328	<0.01[a]
Postoperative wound infection	9	7	4	NA
Hematoma	0	1	0	NA

Values are presented as mean±standard deviation, %, or number unless otherwise stated.
NA, not applicable.
[a]By one-way analysis of variance. [b]By chi-square test.

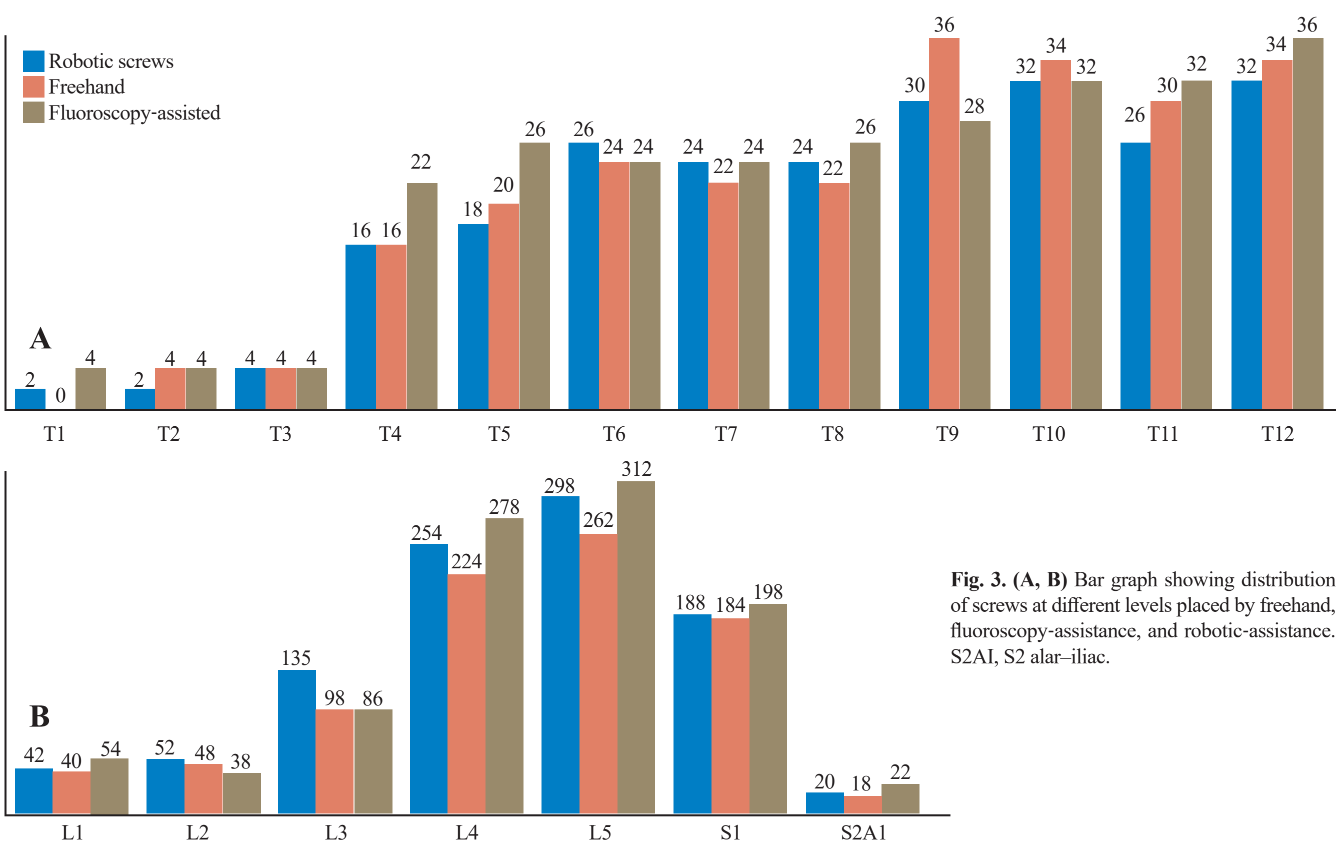

Fig. 3. (A, B) Bar graph showing distribution of screws at different levels placed by freehand, fluoroscopy-assistance, and robotic-assistance. S2AI, S2 alar–iliac.

Table 2. Table showing surgical data in robotic-assisted pedicle screw insertion

	S20 (n=45)	S7 (n=45)	S5 (n=45)	S1 (n=45)	*p*-value[a)]
O-arm time (min)	10.1±2.5	10.5±2.3	10.4±2.6	10.3±2.2	0.87
Radiation dose (mGy)	18.4±4.5	19.2±5.2	19.6±5.7	19.4±6.1	0.73
Blood loss (mL)	538.8±356.9	551.2±301.6	571.2±330.3	487.5±326.1	0.66
Robot time (min)	18.2±3.7	19.3±5.2	19.9±4.5	19.7±3.2	0.22
Time per screw (min)	3.1±1.3	3.4±1.4	3.7±1.1	3.6±0.9	0.08
No. of pedicle breaches	2	3	1	2	

Values are presented as mean±standard deviation or number unless otherwise stated.
[a)]By one-way analysis of variance.

Table 3. Table showing effect of case order on operative efficiency

	Before 2 PM (n=87)	After 2 PM (n=93)	*p*-value
O-arm time (min)	6.9±2.2	8.0±3.9	0.08[a)]
Radiation dose (mGy)	18.5±9.8	15.7±11.3	0.18[a)]
Blood loss (mL)	547.5±469.2	632.3±406.4	0.34[a)]
Robot time (min)	17.0±6.6	18.9±7.6	0.18[a)]
Time per screw (min)	3.3±1.8	3.1±1.0	0.48[b)]
Cut to close time (min)	140.9±34.7	173.8±49.3	<0.01[b)]

Values are presented as mean±standard deviation unless otherwise stated.
[a)]By Mann-Whitney *U* test. [b)]By unpaired *t*-test.

tween the planned and executed screw trajectories in the robotic-assisted group irrespective of surgical experience.

Discussion

Pedicle screws are the most commonly used spinal anchors owing to their ability to stabilize all three columns of the spine, even in the presence of osteoporosis. Various techniques such as freehand, fluoroscopy-assisted, and navigation-assisted pedicle screw placements have been used with varying degrees of accuracy [4-13]. Most studies on robotic-assisted pedicle screw placement utilized preoperatively acquired CT scans in the supine position and reported accuracy rates between 91% and 99%. To our knowledge, this is the only study that compared freehand, with fluoroscopy-guided and robotic-assisted pedicle screw insertion, with freehand and fluoroscopy accuracy being comparable to literature data. Both techniques had significant learning curves and were affected by surgeon experience.

In the examined literature, this study is the first to investigate the application of a third-generation robotic-assisted system for pedicle screw placement in spinal surgery using intraoperative O-arm scans. Our findings support the effectiveness and accuracy of this technology, with a higher success rate (99.34%) than existing data. Not only were the screws accurate, but no significant difference was found in the angle of the planned trajectory and the executed screw. All the eight unacceptable robotic-assisted pedicle screw placements in this study, which were revised, occurred in the first case of thoracic fusion and were a result of medial skiving on the transverse processes. Following this, remedial measures such as flattening of transverse processes and lumbar facets were undertaken to prevent skiving. All subsequent robotic-assisted screw placements in this study were 100% accurate, which had no learning curve, and accuracy was not affected by surgeon experience.

Our experience also yielded valuable insights into maximizing the effectiveness of the robotic system. Standardizing robot mounting and bone mount placement on the right side of the patient streamlined the workflow and ensured optimal arm positioning. Careful positioning of the "star marker" during O-arm scans, particularly in patients who are obese, is crucial for clear image acquisition. Maintaining vigilance throughout the procedure and employing navigation accuracy checks with the blunt passive planar probe are essential to avoid potential navigation errors.

The advantages of newer power tools in robotic-assisted spine surgery have not been explored in previous studies. Compared with previously used instruments, the high-speed "feather-touch" drill, when started before coming in contact with bone, not only reduces the risk of skiving but also prevents any undue force on the robotic arm, which may deviate from the preplanned safe-drilling trajectories. The torque-limiting power tool for tapping and screw placement reduces toggle, thus improving pullout strength, and prevents loosening. These instruments need to hold firmly but also be allowed to take the track directed by the arm guide.

In the thoracic spine, we initially used to place the Schanz pin bone mount in the pedicle of the vertebra below the planned lower instrumented vertebra. However, the bone mount obstructed the trajectory of screws in cases of severe kyphoscoliosis, so we continued the surgery after the removal of the Schanz pin, with minimal movement, retaining accuracy. In subsequent cases, we did not use the bone mount because we preferred visual confirmation of thoracic entries before drilling trajectories and placing screws. These self-retaining retractors were initially left in place during the O-arm scan to minimize disturbance of the construct due to muscle retraction during surgery. However, this too was found unnecessary because they could safely be placed after applying symmetrical retraction forces with minimal patient movement, without compromising the accuracy of the screw. The central screws were inserted first, as their trajectories were reached without excess retraction. The end screws were placed last, as they often required separate lateral, subfascial, or submuscular incisions for the sleeve to reach the required trajectories. When attempted through the midline incision in the early cases, the soft tissue pressure on the robotic arm often resulted in the loss of accuracy and needed repeat registration or scan.

Furthermore, the navigable high-speed burr of third-generation robots offers significant advantages in specific procedures such as posterior transpedicular decompression and complex osteotomies by minimizing blood loss and providing visualization of critical structures.

One of the potential drawbacks of robotic-assisted surgery is the influence of soft tissue pressure on the robotic arm, which can cause slight deviations during screw placement. We employed several strategies to mitigate this effect by making separate incisions for short constructs in the lower lumbar spine, bone rongeuring of the thoracic transverse processes to improve arm guide placement, and utilizing longer incisions for multisegment thoracic fixation. In addition, the zigzag screw placement technique was used to optimize the accuracy of the procedure. With improved instrumentation, the application of robotic-assisted surgery can be extended to minimally invasive thoracic spine surgery.

When planning for S2AI screw insertion, dissection distal to the L5S1 facet joint is not necessary because the entry can be accessed by transfascial or transmuscular stab incisions, thereby reducing blood loss. The use of a 40-cm field of view (instead of the regular 15 cm) to adequately visualize the pelvis and femoral heads has not been described in the literature for robotic-assisted S2AI screw placement. With the current instrumentation, the “feather-touch” drill is unable to cross the SI joint and requires a separate 4×60 mm awl-tipped tap with a 6-mm shaft diameter to accurately extend the trajectory. This too is unable to drill the full length of the trajectory and requires a separate 6.5×60 mm awl-tipped tap to drill the full length of the planned trajectory up to 80–90 mm. Having placed 24 S2AI screws so far, with 100% accuracy, using the abovementioned workflow, the surgical team has extended the routine use of the robot in confidently placing iliosacral screws for unstable vertical sacral fractures. Current limitations are mainly due to the unavailability of sufficiently long instruments for these cases and can be overcome by the development of longer drill bit, taps that have matching shaft diameter, and sequential sleeves with increasing diameters to accommodate the drills and taps.

In the present study, the infection rate was 3.41% and is comparable to that in other studies. A patient developed cauda equina syndrome postoperatively due to epidural hematoma, and it resolved after surgical re-exploration and hematoma evacuation. In the freehand, fluoroscopy-assisted, and robotic-assisted groups, 26 (2.3%), 18 (1.4%), and 8 (0.66%) screw breaches needed revision, respectively. This is comparable to the rates found in the literature, and none of the patients had any permanent postoperative neurological deficits. For S1 screw placement, tapping the far cortex is recommended, and for S2AI screws, increasing the O-arm field of view to 40 cm is necessary for proper visualization.

The learning curve associated with robotic-assisted surgery is well-documented [14,15]. Our data align with these observations, showing no significant difference in the O-arm time, blood loss, robot time, and time per screw compared with other studies after an initial adjustment period [10]. However, the O-arm radiation dose was initially high, highlighting the importance of comprehensive training for the entire surgical team, including radiographers. The learning curve for the O-arm, while not significant, may increase the radiation dose to initial patients while the technician is obtaining two-dimensional (2D) fluoroscopy to localize the “star marker.” Subsequently, with greater experience, localization will be possible with fewer 2D fluoroscopy images, thus minimizing radiation exposure to the patient. In addition, the cut-to-close time mirrored the findings of Khan et al. [10], with longer times in earlier cases likely due to adapting to new workflows.

Levy et al. [16] reported a potential effect of case order on operative efficiency. In the present study, surgeries commencing after 2 PM had a significant increase in the operative time, possibly due to changes in the nursing staff and the complexity of longer-segment fixation.

However, the time per screw remained consistent, indicating that case order did not significantly affect screw placement efficiency.

This study investigated the efficacy and safety of three techniques for thoracolumbar pedicle screw placement (freehand, fluoroscopy-assisted, and robotic-assisted techniques) using intraoperative cone-beam CT scans. The findings demonstrate a high rate of screw placement accuracy with all techniques, with robotic assistance achieving the highest success rate (99.8%) as assessed by the Gertzbein-Robbins grading system. Notably, the study also presents that robotic assistance may mitigate the influence of surgeon experience on accuracy.

This study investigated the application of a third-generation robotic-assisted system for pedicle screw placement in spinal surgery. The findings support the effectiveness and accuracy of this technology, with a high success rate (98.34%) comparable with existing data (91%–99%) [10,17].

Our experience also yielded valuable insights into maximizing the effectiveness of the robotic system. Standardizing robot mounting and bone mount placement on the right side of the patient streamlined the workflow and ensured optimal arm positioning. Careful positioning of the "star marker" during O-arm scans, particularly in patients who are obese, is crucial for clear image acquisition. Maintaining vigilance throughout the procedure and employing navigation accuracy checks with the blunt passive planar probe are essential to avoid potential navigation errors. For S1 screw placement, tapping the far cortex is recommended, and for S2AI screws, increasing the O-arm field of view to 40 cm is necessary for proper visualization. Furthermore, the high-speed burr of third-generation robots offers significant advantages in specific procedures such as posterior transpedicular decompression and complex osteotomies by minimizing blood loss and providing visualization of critical structures.

This study included a relatively large patient population who underwent thoracolumbar spine surgery with diverse etiologies. In addition, the use of a standardized grading system for screw placement accuracy ensured consistency in data collection. However, the long-term outcomes beyond the reported follow-up period were not evaluated.

This study has some limitations. As a preliminary report, it analyzes data from a single-center initial experience with a third-generation robotic system. Long-term outcome studies with larger patient volumes are necessary to comprehensively evaluate the effect of such technology on patient recovery and long-term health. Nevertheless, this work offers valuable insights into the learning curve and technical considerations associated with this evolving technology.

Future prospective, randomized controlled trials directly comparing the three techniques with longer follow-up periods are necessary. Cost-effectiveness analyses may determine the optimal approach based on factors beyond just accuracy and complication rates.

Conclusions

The third-generation robotic-assisted pedicle screw placement system used in conjunction with intraoperative three-dimensional O-arm imaging demonstrates promise for safe and accurate screw placement. Although a learning curve exists, surgeons can leverage their experience and implement efficient workflows to optimize surgical efficiency. The judicious application of robotic guidance, prioritizing anatomical knowledge and tactile feedback during screw placement, is paramount for maximizing patient outcomes. Future studies should focus on long-term clinical outcomes and cost-effectiveness analyses to definitively establish the role of robotic-assisted surgery in spinal procedures.

Key Points

- The third-generation robotic-assisted pedicle screw placement system used in conjunction with intraoperative three-dimensional O-arm imaging demonstrates promise for safe and accurate screw placement.
- Although a learning curve exists, surgeons can leverage their experience and implement efficient workflows to optimize surgical efficiency.
- The judicious application of robotic guidance, prioritizing anatomical knowledge and tactile feedback during screw placement, is paramount for maximizing patient outcomes.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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