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Flattening the learning curve – Early experience of robotic-assisted pedicle screw placement in spine surgery

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A B S T R A C T

Aims and objectives: To determine accuracy of pedicle screws placed by freehand, fluoroscopy-assistance and robotic-assistance with intraoperative image acquisition, and determine the presence of learning curve in robotic spine surgery in a prospective single centre study.
Materials and methods: In a prospective study, a total of 1120 pedicle screws were placed in Freehand group (n = 175), 1250 screws were placed in fluoroscopy-assisted group (n = 172), and 1225 screws were inserted in Robotic-assisted group(n = 180). Surgical parameters and screw accuracy were analyzed between the three groups. The preoperative plan was overlapped with post operative O-arm scan to determine if the screws were executed as planned.
Results: The frequency of clinically acceptable screw placement (Gertzbein and Robbins grade A, B) in the Freehand, Fluoroscopy-assisted, and Robotic-assisted groups were 97.7 %, 98.6 %, and 99.34 % respectively. Higher pedicle screw accuracy, and lower blood loss were seen with robotic assistance. There was no significant difference in these parameters between surgeries commencing before and after 2 p.m. We found no statistically significant differences between the planned and executed screw trajectories in robotic assisted group irrespective of surgical experience.
Conclusion: The third-generation robotic-assisted pedicle screw placement system, used in conjunction with intraoperative 3D O-arm imaging, consistently lowered blood loss and increased accuracy of pedicle screw placement in the thoracolumbar spine. It also has easy adaptability into spine practice with minimal learning curve.

1. Introduction

Recent developments in thoracolumbar spine surgery focus on achieving both minimal invasiveness and high precision. Minimally invasive techniques have become the go-to option, but placing pedicle screws accurately during these procedures remains a key hurdle. This accuracy is vital for spinal stability and preventing nerve or blood vessel damage.[1–3]

Precise placement of pedicle screws can be difficult. Things like natural differences in people's spines, past surgeries, and excess weight can all make it harder. Traditionally, surgeons have used either freehand techniques or fluoroscopy to get the screws in the right spot. But research shows these methods aren't always perfect, with studies reporting wide variability.[4–10]

Newer spine surgery robots are like having a steady helping hand in the operating room.[9] They use real-time 3D scans taken during surgery to give surgeons a clearer view of the patient's spine, and guide instruments exactly where they need to go. This improvement over traditional methods could lead to more precise surgeries.[11]

This research examines different methods for placing screws in the thoracic and lumbar spine. The study compares three techniques: freehand, using fluoroscopy-assistance, and using a robot with intraoperatively acquired scans. We looked at the accuracy of each method, with a particular focus on whether the robot could consistently place screws well regardless of the surgeon's experience. In addition, we investigated the learning curve for surgeons of varying experience levels in robotic-assisted pedicle screw placement. Interestingly, this study is one of the first to examine factors like surgery time, screw placement time, and blood loss specifically for the robotic technique with intraoperative scans. Most past studies used CT scans taken before surgery

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while the patient was lying down, which might not perfectly match their actual spinal position during the operation.[9,12–14]

2. Methods

2.1. Study design

This single-center, prospective study received approval from the institutional ethics committee. It enrolled 527 consecutive patients undergoing thoracolumbar spine surgery who consented to participate. Block randomization was used to allocate patients to one of 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 scans (n = 180) from Medtronic Ltd (Dublin, Ireland). Block randomization was again used to assign patients to one of four fellowship-trained spine surgeons with varying levels of experience (1, 5, 7, and 20 years). A total of 3595 pedicle screws were placed, spanning vertebrae T1 to the ilium, including 60 S2 alar iliac (S2AI) screws.

For successful robotic-assisted surgical procedures, the operating room must have sufficient space. This ensures minimal clutter and accommodates the Mazor X, O-arm, and their respective consoles. Additionally, adequate space is crucial for the manoeuvrability of these robotic systems. All procedures followed a standardized intraoperative workflow known as "scan and plan." This workflow involves patient positioning and surgical exposure followed by robot registration, image acquisition, and screw planning. It is important to note that all cases involving spinal deformity incorporated multimodal neuromonitoring.

Patients underwent surgery in the prone position under general anaesthesia on a radiolucent table. Both the surgical field and the robotic arm were then draped in a sterile fashion. We employed a mini-open midline approach for lumbar procedures and a standard midline approach for thoracic and thoracolumbar deformity surgeries. To prevent drill skiving, we routinely flattened the thoracic transverse processes and hypertrophied lumbar facets. S2AI screws were placed with minimal subperiosteal dissection and transmuscular or transfascial stab incisons. Initially, the robot was semi-rigidly mounted to the patient using a Schanz pin placed in the left posterior superior iliac spine, for lumbar surgeries. or placed in the vertebra below the planned instrumentation level with fluoroscopy guidance for thoracic spine surgeries. However, we transitioned away from Schanz pin use due to minimal robot movement after securing patients to the table. Spinous process clamps were never employed to avoid obstructing the surgical field.

Prior to surgery, a robotic arm is prepared for use in conjunction with a preoperative O-arm scan. This involves placing retractors within the thoracic spine and any deformities to provide clear access. The robotic arm itself utilizes infrared and optical cameras to identify potential obstacles, creating virtual "no-fly zones" for enhanced safety during instrument manipulation. To ensure accurate instrument guidance throughout the procedure, the robot undergoes navigation registration with a reference tracker. This registration can be repeated if necessary to maintain precision in case of unexpected movement. Finally, a blunt probe and a "star-marker" array are used to guide the robotic arm and visualize the surgical field, which is then covered with a sterile drape for a safe and controlled operation.

During surgery, intraoperative imaging plays a crucial role in ensuring the precise placement of screws. This is achieved by utilizing an O-arm, which generates orthogonal X-rays of the surgical field. These X-rays are captured to confirm that all four beads of a special "star-marker" array are clearly visible. This marker array acts as a reference point for the O-arm system, allowing it to determine the exact location of the vertebrae within the patient's anatomy.

The standard O-arm scan offers a field of view of 15 cm. However, for procedures requiring a broader visualization, such as S2AI or iliosacral screw placement, the field of view needs to be expanded to 40 cm.

After acquiring O-arm images, they are transferred to a robotic workstation. There, the software automatically segments the vertebrae once they are marked. Clear visualization of both pedicles in each vertebral segment is crucial. Notably, during degenerative lumbar surgeries, segmentation of the lateral view is prioritized. Conversely, the anteroposterior view carries greater importance for thoracolumbar deformity correction surgeries. Before planning screw trajectories, it's important to align the axes on all three planes (axial, coronal, and sagittal) to achieve a "normal" vertebral appearance. The software facilitates screw planning for each segment, ensuring optimal placement within the bone (intraosseous) across all three planes. Even in situations with inadequate pedicle visualization, the software is helpful. It allows us to examine adjacent segments and plan trajectories through safe remaining bony corridors, even bypassing broken screws or cement in revision surgeries.

For short-segment fixation in the lumbar spine, separate small incisions are made on each side to create the screw tracks. This allows for up to four screws to be placed. In longer procedures or when correcting deformities, the central vertebrae are addressed first. Then, separate incisions are made on either side, either just under the surface layer (sub-fascial) or within a muscle layer (sub-muscular), to access the vertebrae at the ends of the segment being stabilized. This approach minimizes pressure on the robotic arm used in surgery and prevents tissue from being scraped or damaged ("skiving"). For the thoracic spine, where visualizing the drill's entry point is critical, special attention is required. Soft tissue pressure can sometimes push the drill sleeve inwards. To prevent the drill from going off-course, surgeons may adjust the sleeve position with a finger or carefully move the spine itself (Fig. 1). In rare cases of extreme spinal curvature ("kyphosis"), a bone mount used for guiding instruments may block the screw placement. If this happens, the mount is temporarily removed before inserting the screw.

Robotic S2AI screw placement utilizes a multi-step process. First, a high-speed "feather-touch" drill (3 × 30mm and 75,000 RPM) guided by the robotic arm and sleeve creates an initial track that stops short of the sacroiliac (SI) joint. This is followed by a longer, awl-tipped tap (4 × 60mm) that traverses across the SI joint. However, due to its 6 mm diameter, this tap cannot complete the entire planned 80–90 mm screw track. To address this, a final tapping step is performed using a slightly wider 6.5 × 60mm tap. This final step creates the full trajectory needed for precise placement of the S2AI screw. The screw itself is then inserted using a torque-limited power tool without toggling.

During procedures involving longer spinal segments, a second O-arm scan might be necessary. This is because the initial scan might not capture the entire area of interest. Additionally, a repeat scan may be

Fig. 1. Clinical photograph showing flattened transverse process with drill sleeve position adjusted by surgeon.

required if navigation accuracy is compromised or the robotic arm needs repositioning due to excessive pressure. Furthermore, for complex procedures like 3-column osteotomies, a repeat O-arm scan is performed after placement of temporary rods. This visualization of critical adjacent structures allows for safe bony resection using the navigable high-speed burr.

2.1.1. Data collection

In this study, data collection encompassed several key areas. Demographic information, along with a comprehensive set of clinical data and surgical parameters, were obtained for all patients. Specific surgical timing measurements were defined: "Cut-to-close time" captured the total duration from the initial incision to closure. "Time per screw" represented the average time spent inserting each pedicle screw. For surgeries utilizing robotic assistance, additional time points were measured. "Exposure Time" documented the period from the initial incision to fully exposing the laminae at the decompression levels. "O-arm Time" included the time from positioning the O-arm for the anteroposterior fluoroscopy image to finalizing the cone beam CT image acquisition. Finally, "Robot Time" encompassed the duration from software mounting the robotic arm to completing the insertion of the last screw or guidewire. In addition, data on screw insertion time and accuracy among the four surgeons were also documented. Also the amount of blood loss during surgery was documented for all patients.

In a post-operative evaluation, all patients received a final O-arm scan. Screw breaches were then graded according to the established classification system by Gertzbein and Robbins.[15] To assess screw placement accuracy, we utilized Digimizer version 6.3 software. This software compared planned screw trajectories from the preoperative workstation image with the actual screw positions captured in the postoperative O-arm image. The process involved overlaying the images, and both a neuroradiologist and a surgeon independently verified the accuracy and angle of screw insertion. Additionally, all patients were assessed for postoperative pain levels using the Visual Analogue Scale (VAS), and any neurological deficits were noted.

In a study to assess the influence of surgical technique (freehand, fluoroscopy-assisted, or robotic-assisted) and surgeon experience on various surgical parameters, we compared data from 45 consecutive patients divided into groups based on technique. Additionally, we investigated the effect of case order on surgical efficiency by comparing surgeries that commenced before and after 2 p.m.

2.1.2. Statistical analysis

Statistical analysis was performed to assess both quantitative and qualitative data. Quantitative data, such as the difference between planned and actual screw angles, was presented as the mean ± standard deviation (SD). Qualitative data, such as the prevalence of specific outcomes (e.g., infection rates), was expressed as percentages. To compare group means across different surgical techniques, we used appropriate statistical tests depending on whether the data followed a normal distribution. For normally distributed data, we used the unpaired *t*-test. For data that was not normally distributed (non-parametric data), the Mann-Whitney *U* test was used for comparisons between two groups, and a one-way ANOVA 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 less than 0.01 was considered statistically significant.

3. Results

3.1. Participants

In this study, 527 patients underwent thoracolumbar spine surgery. Patient demographics are detailed in Table 1. A total of 1120, 1250, and 1225 screws were placed in the Freehand (n = 175), Fluoroscopy-assisted (n = 172), and Robotic-assisted groups (n = 180) respectively. The Robotic-assisted group achieved the highest rate of clinically acceptable screw placement (99.34 %), followed by the Fluoroscopy-assisted (98.6 %) and Freehand groups (97.7 %). Screw revisions due to pedicle breaches were also lowest in the Robotic-assisted group (0.66 %) compared to Fluoroscopy-assisted (1.4 %) and Freehand groups (2.3 %) (see Table 2).

Post-operative complications were uncommon, with superficial infections (n = 16) being the most frequent. Surgical re-exploration due to deep infections occurred in 2 patients, and one patient experienced Cauda equina syndrome from an epidural hematoma, no permanent neurological deficits were reported.

Fig. 2 shows the distribution of screws across different spinal levels, with no significant difference between the groups. Notably, Table 3 suggests that robotic guidance may offer an "experience-neutralizing effect." This means surgeons of varying experience levels achieved comparable results in terms of screw accuracy, blood loss, operative time, and efficiency with robotic assistance. Also screw insertion time is also the same between surgeons with various levels of training. Time parameters also showed no significant difference between surgeries performed before or after 2 p.m. Importantly, the study found no significant discrepancies between planned and executed screw trajectories in the robotic-assisted group, regardless of surgical experience.

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

	Freehand (n = 175)	Fluoroscopy-assisted (n = 172)	Robotic-assisted (n = 180)	*P* value
Age years (mean ± SD)	47.2 ± 18.6	49.8 ± 15.4	50.7 ± 19.6	0.166[a]
Frequency of females	48 %	42 %	49 %	0.84[b]
BMI (mean ± SD)	28.5 ± 4.1	29.1 ± 3.6	28.3 ± 4.2	0.14[a]
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]
Blood loss (mL)	642.7 ± 234.6	708.2 ± 283.6	537.2 ± 328	<0.01[a]
Total Screws	1120	1250	1225	NA
Clinically acceptable screws (GR A & B)	1094	1232	1217	<0.01[b]
Pedicle breaches requiring revision (GR C to E)	26	18	8	
Post operative wound infection	9	7	4	NA
Hematoma	0	1	0	NA

[a] One-way ANOVA.
[b] Chi-squared test.

Table 2
Table showing frequency distribution of etiology across three groups.

	Freehand (n = 175)	Fluoroscopy-assisted (n = 172)	Robotic-assisted (n = 180)	*P* value
Degenerative	98	95	107	0.86[a]
Spondylolisthesis	43	37	41	
Deformity	18	22	20	
Tumor	4	4	3	
Trauma	7	6	7	
Infection	5	8	2	

[a] Chi-squared test.

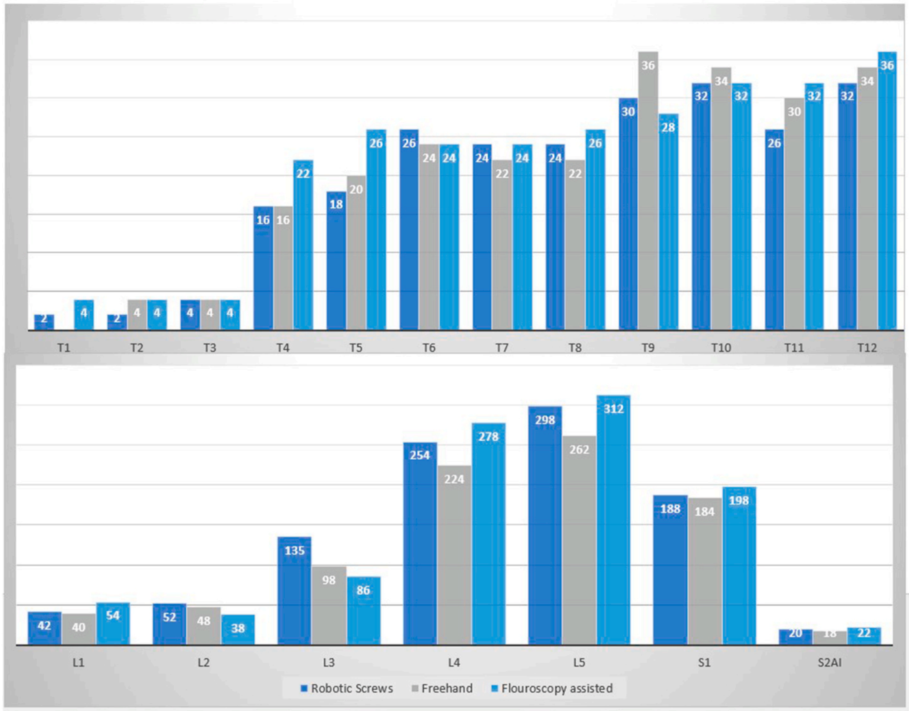

Fig. 2. Graph showing distribution of screws at different levels.

Table 3
Table showing Surgical data in robotic-assisted pedicle screw insertion.

	S20 (n = 45)	S7 (n = 45)	S5 (n = 45)	S1 (n = 45)	*P* value
O-arm time mins (mean ± SD)	10.1 ± 2.5	10.5 ± 2.3	10.4 ± 2.6	10.3 ± 2.2	0.87*
Radiation dose mGy (mean ± SD)	18.4 ± 4.5	19.2 ± 5.2	19.6 ± 5.7	19.4 ± 6.1	0.73*
Blood loss mL (mean ± SD)	538.8 ± 356.9	551.2 ± 301.6	571.2 ± 330.3	487.5 ± 326.1	0.66*
Robot time mins (mean ± SD)	18.2 ± 3.7	19.3 ± 5.2	19.9 ± 4.5	19.7 ± 3.2	0.22*
Time per screw mins (mean ± SD)	3.1 ± 1.3	3.4 ± 1.4	3.7 ± 1.1	3.6 ± 0.9	0.08*
Pedicle breaches	2	3	1	2	

Remarks: * One-way ANOVA.

4. Discussion

Pedicle screws are the most widely used spinal anchors because they can stabilize all three columns of the spine, even in patients with osteoporosis. These screws are inserted using various techniques, such as free-hand, fluoroscopy-assisted, and navigation-assisted methods, each with varying degrees of accuracy.[5–10] Studies on robotic-assisted pedicle screw placement typically involve preoperatively acquired CT scans taken in the supine position and report accuracy rates between 91 and 99 %.[6–10] This study is the only one to compare freehand, fluoroscopy-guided, and robotic-assisted insertion techniques. It found that freehand and fluoroscopy accuracy were comparable to previously reported literature, and that both freehand and fluoroscopic techniques have significant learning curves and are affected by surgeon experience.

This study pioneers the investigation of a third-generation robotic-assisted system for pedicle screw placement in spinal surgery, utilizing intraoperative O-arm scans. Our findings strongly support the effectiveness and accuracy of this technology. The success rate of 99.34 % surpasses those reported in existing literature.

Not only did the robotic system achieve high screw placement accuracy, but there was also no significant difference between the planned trajectory angle and the final screw placement. Notably, all eight unacceptable robotic-assisted pedicle screws encountered in this study, which were subsequently revised, occurred during the first thoracic fusion case. These initial misplacements were attributed to medial skiving on the transverse processes.

To address this issue, remedial measures were implemented, including flattening of the thoracic transverse processes and lumbar facets, which effectively prevented skiving in subsequent procedures. Importantly, all subsequent robotic-assisted screws achieved 100 % accuracy, demonstrating no learning curve and no surgeon experience-related impact on placement accuracy.

In addition to successfully utilizing the robotic system, our experience yielded valuable insights for maximizing its effectiveness. Standardizing robot mounting and bone mount placement on the right side of the patient streamlined the workflow and ensured optimal arm positioning for each procedure. Furthermore, during O-arm scans, careful positioning of the "star marker" was particularly crucial for achieving clear image acquisition, especially in obese patients. Finally, maintaining vigilance throughout the procedure and employing regular navigation accuracy checks with the blunt passive planar probe proved essential to avoid potential navigation errors.

Robotic-assisted spine surgery is undergoing a revolution with the introduction of innovative power tools. These tools not only enhance patient safety but also streamline the surgical process. The high-speed "feather touch" drill, starting its rotation before contacting bone, minimizes the risk of bone fragments compared to traditional instruments. Additionally, it prevents excessive force on the robotic arm, ensuring it adheres to the pre-programmed safe drilling path. The torque-limiting power tool, used for screw placement, reduces bouncing of the screwdriver, leading to stronger screw fixation and preventing loosening over time. While maintaining a firm grip is essential for control, allowing the robotic arm to guide the tool placement optimizes screw positioning. These advancements highlight the potential of newer power tools to improve both safety and efficiency in robotic-assisted spine surgery.

We initially placed the Schanz pin bone mount in the pedicle of the vertebra below the planned lower instrumented vertebra in the thoracic spine. However, this technique caused obstruction during screw placement in severe kyphoscoliosis cases. We found that removing the Schanz pin with minimal movement-maintained accuracy and allowed for continued surgery. Consequently, we opted for visual confirmation of thoracic entry points before drilling and screw placement, eliminating the need for the bone mount altogether.

Similarly, self-retaining retractors were initially left in place during O-arm scans to minimize construct disruption. However, we discovered that symmetrical retraction forces with minimal patient movement achieved the same stability without compromising screw accuracy. This allowed for safe placement of retractors after the scan. Furthermore, central screws were inserted first due to their straightforward trajectories. End screws, requiring separate lateral incisions for sleeve access, were placed last. This approach avoided soft tissue pressure on the robotic arm in the midline incision, which previously caused accuracy issues and repeat scans.

The third-generation robot boasts a navigable high-speed burr, which offers significant advantages in specific procedures. These procedures include posterior transpedicular decompression and complex osteotomies. The burr's capabilities minimize blood loss while providing crucial visualization of critical structures during surgery.

One potential limitation 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, including separate incisions for short constructs in the lower lumbar spine, bone rongeuring of thoracic transverse processes to improve arm guide placement, and utilizing longer incisions for multi-segment thoracic fixation. Additionally, the zigzag screw placement technique was used to optimize accuracy throughout the procedure.

During preoperative planning for S2AI screw placement, dissection distal to the L5S1 facet joint can be avoided. This is because the entry point can be accessed through small incisions that pierce only the fascia or muscle, minimizing blood loss. The use of a wider field of view (40 cm compared to the standard 15 cm) to visualize the entire pelvis and femoral heads during robotic-assisted S2AI screw placement has not been previously described in the literature.

However, the current instrumentation presents some limitations. The "feather touch" drill cannot penetrate the sacroiliac (SI) joint, requiring a separate 4 × 60mm awl-tipped tap with a 6 mm shaft diameter to accurately guide the trajectory. Even this tap is insufficient for the full length, necessitating another 6.5 × 60mm awl-tipped tap to complete the planned 80–90 mm trajectory.

Despite these limitations, the surgical team has successfully placed 24 S2AI screws with 100 % accuracy using the aforementioned workflow. This success has led to the routine use of the robot for confidently placing ilio-sacral screws in patients with unstable vertical sacral fractures. The current limitations could be addressed by developing longer drill bits, taps with matching shaft diameters, and sequential sleeves with increasing diameters to accommodate these instruments.

The current study found a 3.41 % infection rate, comparable to other studies. One patient developed cauda equina syndrome following surgery due to an epidural hematoma. This complication was resolved with surgical re-exploration and hematoma evacuation. The need for screw breach revision occurred in 26 screws (2.3 %), 18 screws (1.4 %), and 8 screws (0.66 %) in the Freehand, Fluoroscopy-assisted, and Robotic-assisted groups, respectively. These rates are comparable to those reported in literature, and importantly, none of the patients experienced permanent postoperative neurological deficits.

During this procedure, specific considerations are made for different screw placements. For S1 screws, it's recommended to tap the far cortex to ensure a secure fit. When placing S2 alar iliac screws, increasing the O-arm field-of-view to 40 cm is necessary to achieve proper visualization of the insertion site.

Surgeons learning robotic surgery go through an adjustment period, which is supported by existing research.[14,16] Our results reflect this, showing similar performance in key areas like imaging time, blood loss, and surgical speed compared to other studies after some initial practice (12). Interestingly, radiation exposure from imaging was high at the beginning. This emphasizes the need for thorough training for the entire surgical team, including radiology technicians. Finally, the total surgery time also mirrored findings from Khan et al., with longer durations in earlier cases, likely due to getting accustomed to the new robotic workflow.[12]

This research offers a promising first look at a new robotic surgical system, but it's important to consider its limitations. Because it's an early report, it only analyzed data from one hospital's initial use. To fully understand the system's long-term effects on patients, bigger studies with more participants followed for a longer period are needed. Despite this, the research provides valuable information about the challenges of learning to use this new technology and the technical aspects to consider for its future development.

This study compared the efficacy and safety of three techniques for placing screws in the spine (thoracic and lumbar vertebrae): freehand, fluoroscopy-assisted, and robotic-assisted. All techniques were evaluated using intraoperative cone-beam CT scans to assess accuracy. Our findings showed a high rate of successful screw placement with all three methods, but robotic assistance achieved the greatest success rate (99.8 %) based on the Gertzbein-Robbins grading system. This suggests that robots might help even less experienced surgeons place screws accurately.

This study examined the effectiveness of a third-generation robotic-assisted system for placing pedicle screws during spinal surgery. Our findings align with existing literature, demonstrating a high success rate (98.34 %) comparable to previously reported ranges of 91–99 %.[12,17–19]

However, robotic-assisted surgery can be impacted by pressure exerted by soft tissues on the robotic arm, potentially causing minor deviations during screw placement. To address this limitation, we implemented several strategies. For short constructs in the lower lumbar spine, we used separate incisions. In the thoracic region, we employed bone rongeuring of the transverse processes to improve placement of the arm guide. Additionally, longer incisions were utilized for multi-segment thoracic fixation. Finally, the zigzag screw placement technique was adopted throughout the procedure to further optimize accuracy.

Our robotic surgery experience wasn't just a success, it provided valuable tips for getting the most out of the system. By mounting the robot and bone mount consistently on the patient's right side, we achieved a smoother workflow and optimal robot arm positioning. Accurate O-arm scans, especially for obese patients, relied on careful placement of the "star marker." Staying focused and using the blunt passive planar probe to check navigation accuracy were key to avoiding errors. For S1 screw placement, tapping the far cortex is best, and visualizing S2 alar iliac screws required a larger O-arm field-of-view (40 cm). The third-generation robot's high-speed burr proved to be a game-changer for certain procedures like posterior transpedicular decompression and complex osteotomies. This new tool minimized blood loss and provided a clearer view of critical structures.

This study analyzed a relatively large and diverse group of patients undergoing thoracolumbar spine surgery. A standardized grading system for screw placement accuracy ensured consistent data collection. However, long-term outcomes beyond the reported follow-up period were not assessed.

While this study provides valuable insights, it has limitations. As a preliminary report, it analyzes data from a single center's initial use of a third-generation robotic system. To comprehensively assess the technology's impact on patient recovery and long-term health, long-term outcome studies with larger patient populations are necessary. Nevertheless, this work sheds light on the learning curve and technical considerations associated with this developing technology.

This research, though offering valuable preliminary findings, has some restrictions. It only analyzes data from one center's first experiences using a new robotic system. To fully understand how this technology affects patients' recovery and long-term health, larger studies with more patients followed for a longer period are needed. Despite this limitation, the study provides important information about the initial learning curve and technical aspects involved in using this evolving technology.

The next step for these techniques is in-depth research. Ideally, future studies would involve comparing all three methods head-to-head through well-designed, long-term experiments. Analyzing the cost-effectiveness of each approach would also be helpful. This would go beyond just accuracy and complication rates, giving us a clearer picture of the best technique for specific situations.

This groundbreaking study sheds light on a previously undocumented area: the detailed, step-by-step process for utilizing a cutting-edge, third-generation robot in conjunction with intraoperative O-arm imaging. Furthermore, the study delves into the challenges that may arise during various procedures and offers practical solutions to overcome them. As spine robotics becomes increasingly popular, this knowledge-sharing effort is crucial for ensuring the success of new adopters of this technology.

5. Conclusion

The latest generation of robotic-assisted pedicle screw placement systems, working alongside powerful 3D imaging during surgery, offer exciting possibilities for safe and precise screw placement. Surgeons need some initial practice, but their existing skills and streamlined processes can help make these procedures faster. The key to success, however, lies in using the robot strategically, with a deep understanding of anatomy and continued reliance on tactile feedback during screw placement. Additionally, robotic spine surgery can help flatten the learning curve, making the procedure more adoptable for surgeons of varying experience levels.

VS, MPK, BT: Conceptualization AS, AK, AV: Data collection SKR: Supervision, ValidationAll authors contributed significantly to the current paper and all authors have approved the final manuscript.

6. Declaration of patient consent FORM

Informed consent was obtained from all participants in the study.

7. Financial support and suponsorship

None.

Consent

Informed Consent was obtained from all study participants.

Ethical statement

Institutional Ethical Committee clearance was obtained prior to commencement of the study.

This study has been conducted in accordance with the ethical principles mentioned in the Declaration of Helsinki (2013)

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Credit authorship statement

VS, MPK, BT: Conceptualization. AS, AK, AV: Data collection. SKR: Supervision, Validation.

All authors contributed significantly to the current paper and all authors have approved the final manuscript.

Declaration of competing interest

The authors did not receive support from any organization for the submitted work. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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