Robotic pedicle screw placement

- Robotically assisted and minimally invasive pedicle screw placement at the lumbar spine
- A comparison of key performance metrics of major robotic platforms in spine surgery: a network meta-analysis of 14,462 screws
- Robot-assisted versus navigated spinal fusion surgery: a comparative multicenter study on transpedicular screw placement accuracy and patient outcomes
- Visuohaptic Feedback in Robotic-Assisted Spine Surgery for Pedicle Screw Placement
- 3D-printed guide template for cervical stabilization surgery: A case report
- Robotic-assisted Cervical Pedicle Screw Fixation With Custom Instruments: An Analysis of 206 Screws in 22 Patients
- Clinical efficacy of robot-assisted single-position OLIF with lateral plate combined with posterior unilateral fixation for single-segment lumbar spinal stenosis
- Current Trends and Future Directions in Lumbar Spine Surgery: A Review of Emerging Techniques and Evolving Management Paradigms

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Systematic review and meta-analysis

Robot-assisted spine surgery (RS) has progressively emerged as a promising technology in modern thoracic and lumbar spine surgery, offering the potential to enhance accuracy and improve clinical outcomes. To date, the benefits in thoracolumbar spinal surgery remain controversial. This study aimed to assess RS's efficacy and safety compared to fluoroscopy-assisted surgery (FS) in spinal fusion procedures. Materials and Methods: By the PRISMA guidelines, a systematic review and meta-analysis was conducted, using REVMAN V5.3 software. The review protocol was registered in the Prospective Register of Systematic Reviews (PROSPERO) website with the following registration number: CRD42024567193. Results: Eighteen studies were included in the meta-analysis with a total of 1566 patients examined. The results demonstrated a worse accuracy in FS in cases with major violations of the peduncular cortex (D-E grades, according to Gertzbein's classification) [(odds ratio (OR) 0.47, 95%-CI 0.28 to 0.80, I2 0%]. In addition, a lower complication rate was shown in the RS group compared to the FS group, specifically regarding the need for surgical revision due to screw mispositioning (OR 0.28-CI 0.17 to 0.48, I2 98%). Conclusions: Advantages of robot-assisted techniques were demonstrated in terms of postoperative complications, revision surgery rates, and the accuracy of screw placement. While RS represents a valuable and promising technological advancement in thoracolumbar spinal surgery, future studies are needed to further explore its advantages in thoracolumbar spinal surgery and to identify which spinal surgical approach has greater advantages when using the robot [1)]

Morello et al. provide strong evidence that robot-assisted techniques improve pedicle screw placement accuracy and reduce revision surgery rates compared to fluoroscopy-assisted freehand techniques in thoracolumbar spinal fusion. However, the substantial heterogeneity in complication data, lack of detailed study quality assessment, and omission of cost-effectiveness considerations limit the breadth of their conclusions.

Future well-designed randomized controlled trials (RCTs), stratified by surgeon experience and including cost analyses, are necessary to fully establish the role of RS in spinal surgery.

Systematic reviews

A systematic literature search was executed using PubMed-Medline, Cochrane Central, and Scopus on 30 April 2023. Studies that explored the deviation between final position and preoperative planning of pedicle screws assisted by image-guide navigation or robotic system were included. The data extracted were surgical approach, surgical aid, number of screws evaluated, spinal levels, accuracy and deviation of screws. The quality of the studies was assessed using the revised Cochrane risk-of-bias tool for randomized trials (RoB 2) or the methodological index for non-randomized studies (MINORS) score.

This review included 15 studies, of which 5 used navigation and 10 robotic system. The studies involved 1487 patients, with the evaluation of a total of 7274 pedicle screws, with an assessment of planning and final position. The different methodologies to calculate the deviation include angular deviations in the axial and sagittal planes, 3D angular deviation, and tip and entry point deviation. Regarding screw accuracy, 98.15% of the screws were grade A or B, and 1.85% as category C or D.

Although preoperative planning allows the surgeon to plan the final position of the screw most appropriately, mild deviations from it do not seem to excessively influence the accuracy of the spinal fusion.

A methodologically decent review with clear inclusion criteria and use of proper quality assessment tools. However, it is weakened by a lack of formal heterogeneity analysis, potential biases in study selection, the absence of meta-analytic pooling, and somewhat speculative conclusions regarding the clinical impact of deviations. Future systematic reviews in this field would benefit from stricter methodological transparency, subgroup analyses, and outcome linkage to actual fusion success rather than screw position alone.

Robotic spine surgery systems have significantly impacted spinal procedures by improving pedicle screw placement accuracy and supporting various techniques. These systems facilitate personalized, minimally invasive, and low-radiation interventions, leading to greater precision, reduced patient risk, and decreased radiation exposure. Despite advantages, challenges such as high costs and a steep learning curve remain. Ongoing advancements are expected to further enhance these systems' role in spinal surgery [2)]

Robotic Pedicle Screw Placement is a modern, technology-driven procedure used in spinal surgery to improve the accuracy and safety of placing pedicle screws into the vertebrae. Pedicle screws are critical for stabilizing the spine in various spinal fusion surgeries, which treat conditions like scoliosis, fractures, degenerative disc disease, and spinal deformities. By using robotic assistance, surgeons can achieve highly precise screw placement, minimizing the risk of complications such as nerve damage or improper screw positioning.

Key Elements of Robotic Pedicle Screw Placement: Preoperative Planning:

Before the surgery, the patient undergoes detailed imaging, typically with CT or MRI scans. These scans provide a 3D map of the patient's spine, allowing surgeons to plan the precise trajectory and positioning of each pedicle screw. The robotic system uses this information to generate a surgical plan, which is loaded into the robot's navigation system. Robotic Guidance:

During the procedure, the robot provides real-time guidance based on the preoperative imaging. The robotic arm is positioned over the patient's spine, helping guide the surgical tools to the exact location for pedicle screw insertion. Systems like the Mazor X™ or ExcelsiusGPS™ offer stereotactic guidance, which ensures that the screws are placed along the predetermined paths, minimizing any deviation. Surgical Execution:

The surgeon still maintains control over the procedure, manually operating the tools while being guided by the robot. The robotic platform ensures that the tools follow the precise trajectory needed for each pedicle screw. Some systems also allow for semi-autonomous screw placement, where the robot performs certain steps under the supervision of the surgeon. Intraoperative Imaging:

Robotic systems are often integrated with intraoperative imaging technologies, such as fluoroscopy or O-arm (a mobile CT scanner), to provide real-time feedback. This enables the surgeon to continuously verify the screw placement as the surgery progresses. Benefits of Robotic Pedicle Screw Placement: Increased Accuracy:

Robotic systems offer sub-millimeter accuracy, ensuring that pedicle screws are placed in the correct trajectory and depth, reducing the risk of misplacement, which can lead to nerve injury or vertebral damage. Minimally Invasive:

The precision of robotic systems allows for minimally invasive techniques, which use smaller incisions. This approach leads to less muscle and tissue disruption, reduced blood loss, and faster recovery times compared to traditional open surgeries. Reduced Radiation Exposure:

Robotic guidance reduces the need for continuous fluoroscopy (X-ray) during the procedure, lowering radiation exposure for both the patient and the surgical team. Consistency:

The robotic platform ensures consistency and reproducibility across cases. Even in complex spinal anatomy, the system can guide screws precisely, reducing variability in outcomes. Shorter Operative Time:

While the setup of robotic systems may take additional time, the precision and guidance they offer can reduce the overall time spent in surgery, especially in complex or multi-level spinal fusions. Common Robotic Systems for Pedicle Screw Placement: Mazor X™ Robotic Guidance System:

One of the most widely used robotic systems for spine surgery, Mazor X assists surgeons in planning and executing precise pedicle screw placement. It uses preoperative imaging to create a detailed plan and provides real-time guidance for tool navigation during surgery. ExcelsiusGPS™:

This robotic navigation platform combines preoperative imaging with real-time intraoperative feedback. The robotic arm assists in guiding tools to the exact location for pedicle screw placement. Renaissance™ Robotic System:

An earlier version of Mazor's robotic technology, Renaissance also provides stereotactic guidance for spine surgery. It is widely used for pedicle screw placement in spinal fusion and deformity correction procedures. Step-by-Step Process of Robotic Pedicle Screw Placement: Patient Positioning:

The patient is positioned on the operating table, typically prone (face-down) for spinal surgeries. The spine is stabilized to minimize movement during the procedure. Preoperative Imaging Integration:

A preoperative CT scan or intraoperative 3D imaging is performed. These images are used to create a 3D model of the patient's spine, which the robotic system uses for planning. Surgical Planning:

Using the imaging data, the surgeon plans the optimal entry points, angles, and lengths of the pedicle screws. This information is fed into the robotic system. Robot Positioning and Calibration:

The robotic system is positioned over the patient's spine, aligning with the preoperative plan. Calibration is performed to ensure that the robot is perfectly aligned with the patient's anatomy. Screw Insertion:

The robot guides the surgeon or directly assists in drilling the trajectory and placing the pedicle screws with precise accuracy. The surgeon manually inserts the screws with the robot ensuring the correct path. Intraoperative Verification:

Throughout the procedure, intraoperative imaging (like O-arm or fluoroscopy) can be used to confirm the screw positions and trajectories. Closure:

Once all screws are inserted, the incisions are closed, and the patient is taken to recovery. Challenges and Considerations: Cost: Robotic systems are expensive, and the cost of purchasing and maintaining these platforms can be a barrier to widespread adoption.

Learning Curve: Surgeons need specialized training to effectively use robotic platforms, and there may be a learning curve before they become proficient.

Setup Time: While robotic systems can reduce operative time overall, the initial setup and calibration of the robot can add time to the procedure.

Future of Robotic Pedicle Screw Placement: Integration with Artificial Intelligence: Future systems may incorporate AI to further enhance surgical planning, predict optimal trajectories, and even provide decision-making support during the procedure.

Improved Haptic Feedback: Developing systems that provide real-time haptic feedback will allow surgeons to "feel" the tissue as they work, improving safety and precision.

Autonomous Surgery: While current systems are semi-autonomous, future platforms may offer more fully autonomous capabilities for tasks like screw insertion, allowing surgeons to focus on higher-level decision-making.

Conclusion: Robotic-assisted pedicle screw placement represents a significant advancement in spinal surgery, improving accuracy, safety, and outcomes. As technology continues to evolve, robotic systems will likely become more integrated into routine spinal procedures, offering even more precision and reducing complications.

Results indicated that assisted Robotic pedicle screw placement in TLIF had a lower screw loosening rate and similar patient-reported outcomes compared with the fluoroscopy-guided technique [3)]

Robotic spinal fixation is associated with increased screw placement accuracy and similar operative blood loss, length of stay, and operative duration. These findings support the safety and cost-effectiveness of robotic spinal surgery across the spectrum of robotic systems and screw types [4].

In addition to demonstrating excellent pedicle screw accuracy, early studies have explored the impact of robot-assisted spine surgery on reducing radiation time, length of hospital stay, operative time, and perioperative complications in comparison to conventional freehand technique. The Mazor X Stealth Edition was introduced in 2018. This robotic system integrates Medtronic's Stealth navigation technology into the Mazor X platform, which was introduced in 2016. It is unclear what the impact of these advancements have made on clinical outcomes.

In a multicenter study, both robot systems achieved excellent screw accuracy and low robot time per screw. However, using Stealth led to significantly less fluoroscopic radiation time, lower robot abandonment rates, and reduced blood transfusion rates than Mazor X. Other factors including length of stay, and 90-day complications were similar [5]

Ha Y. Robot-Assisted Spine Surgery: A Solution for Aging Spine Surgeons. Neurospine. 2018 Sep;15(3):187-188. doi: 10.14245/ns.18edi.003. Epub 2018 Sep 11. PubMed PMID: 30196675.

In three cadavers 12 pedicle screws were implanted in thoraco-lumbar segments with the robotic surgery assistant. 3D-fluoroscopy was performed for preoperative referencing, planning and identification of postoperative screw position. The radiation exposure of fluoroscopy and a CT scanner was compared, measuring the Computed Tomography Dose Index (CTDIw).

Pedicle screw positioning was graded according to the Gertzbein-Robbins classification: Eleven of 12 pedicle screws showed optimal transpedicular position (Grade 1), one was positioned less than 2 mm outside (Grade 2). No major deviations were observed. Referencing with 3D-fluoroscopy resulted in a CTDIw reduction of 84% in the cervical- and 33% in the lumbar spine.

Robot-guided PS placement, using 3D-fluoroscopy for referencing, is a reliable tool for minimally invasive PS implantation; radiation exposure can be reduced [6].

Menger et al., investigated the cost effectiveness of adding robotic technology in spine surgery to an active neurosurgical practice.

The time of operative procedures, infection rates, revision rates, length of stay, and possible conversion of open to minimally invasive spine surgery (MIS) secondary to robotic image guidance technology were calculated using a combination of institution-specific and national data points. This cost matrix was subsequently applied to 1 year of elective clinical case volume at an academic practice with regard to payor mix, procedural mix, and procedural revenue.

A total of 1,985 elective cases were analyzed over a 1-year period; of these, 557 thoracolumbar cases (28%) were analyzed. Fifty-eight (10.4%) were MIS fusions. Independent review determined an additional ~10% cases (50) to be candidates for MIS fusion. Furthermore, 41.4% patients had governmental insurance, while 58.6% had commercial insurance. The weighted average diagnosis-related group reimbursement for thoracolumbar procedures for the hospital system was calculated to be $25,057 for Medicare and $42,096 for commercial insurance. Time savings averaged 3.4 minutes per 1-level MIS procedure with robotic technology, resulting in annual savings of $5,713. Improved pedicle screw accuracy secondary to robotic technology would have resulted in 9.47 revisions being avoided, with cost savings of $314,661. Under appropriate payor mix components, robotic technology would have converted 31 Medicare and 18 commercial patients from open to MIS. This would have resulted in 140 fewer total hospital admission days ($251,860) and avoided 2.3 infections ($36,312). Robotic surgery resulted in immediate conservative savings estimate of $608,546 during a 1-year period at an academic center performing 557 elective thoracolumbar instrumentation cases.

Application of robotic spine surgery is cost-effective, resulting in lesser revision surgery, lower infection rates, reduced length of stay, and shorter operative time. Further research is warranted, evaluating the financial impact of robotic spine surgery [7].

Several randomized controlled trials (RCTs) and cohort studies involving robotic-assisted (RA) and free-hand with fluoroscopy-guided (FH) and published before January 2017 were searched for using the Cochrane Library, Ovid, Web of Science, PubMed, and EMBASE databases. A total of 55 papers were selected. After the full-text assessment, 45 clinical trials were excluded. The final meta-analysis included 10 articles.

The accuracy of pedicle screw placement within the RA group was significantly greater than the accuracy within the FH group (odds ratio 95%, “perfect accuracy” confidence interval: 1.38-2.07, P<.01; odds ratio 95% “clinically acceptable” Confidence Interval: 1.17-2.08, P<.01).

There are significant differences in accuracy between RA surgery and FH surgery. It was demonstrated that the RA technique is superior to the conventional method in terms of the accuracy of pedicle screw placement [8].

In 2013 a study evaluated the outcomes of robotic-assisted screw placement in a consecutive series of 102 patients.

Data were recorded from technical notes and operative records created immediately following each surgery case, in which the robotic system was used to guide pedicle screw placement. All cases were performed at the same hospital by a single surgeon. The majority of patients had spinal deformity and/or previous spine surgery. Each planned screw placement was classified as: (1) successful/accurately placed screw using robotic guidance; (2) screw malpositioned using robot; (3) use of robot aborted and screw placed manually; (4) planned screw not placed as screw deemed non essential for construct stability. Data from each case were reviewed by two independent researchers to indentify the diagnosis, number of attempted robotic guided screw placements and the outcome of the attempted placement as well as complications or reasons for non-placement.

Robotic-guided screw placement was successfully used in 95 out of 102 patients. In those 95 patients, 949 screws (87.5 % of 1,085 planned screws) were successfully implanted. Eleven screws (1.0 %) placed using the robotic system were misplaced (all presumably due to “skiving” of the drill bit or trocar off the side of the facet). Robotic guidance was aborted and 110 screws (10.1 %) were manually placed, generally due to poor registration and/or technical trajectory issues. Fifteen screws

(1.4 %) were not placed after intraoperative determination that the screw was not essential for construct stability. The robot was not used as planned in seven patients, one due to severe deformity, one due to very high body mass index, one due to extremely poor bone quality, one due to registration difficulty caused by previously placed loosened hardware, one due to difficulty with platform mounting and two due to device technical issues.

Of the 960 screws that were implanted using the robot, 949 (98.9 %) were successfully and accurately implanted and 11 (1.1 %) were malpositioned, despite the fact that the majority of patients had significant spinal deformities and/or previous spine surgeries. “Tool skiving” was thought to be the inciting issue with the misplaced screws. Intraoperative anteroposterior and oblique fluoroscopic imaging for registration is critical and was the limiting issue in four of the seven aborted cases [9].

Learning curve

Robotic pedicle screw placement learning curve.

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