Robotics in Cervical Spine Surgery: The Current Scenario

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Abstract

Cervical spine surgery is technically demanding due to complex anatomy and proximity to vital neurovascular structures. While cervical pedicle screws offer superior biomechanical stability, their placement carries significant risks with traditional freehand techniques. Robotic-assisted spine surgery has emerged as a promising technology to enhance accuracy, safety, and efficiency. This narrative review synthesizes data from recent clinical studies, meta-analyses, and technical reports describing the evolution from freehand techniques through computer-assisted navigation to current robotic systems. Comparative analyses demonstrate that robotic assistance achieves superior accuracy (98%–99%) compared to conventional methods, with an experience-neutralizing effect standardizing outcomes across surgeons of varying expertise. Recent data from Indian populations demonstrate comparable accuracy with anatomically adapted techniques. The review examines current applications, including cervical pedicle screw placement, lateral mass screw fixation, odontoid screw placement, and deformity correction. Critical operational aspects are analyzed, including patient positioning using Mayfield clamp fixation, workflow optimization, and intraoperative accuracy verification protocols. Infrastructure requirements, learning curve considerations, and confirmatory imaging protocols during initial adoption are discussed. Robotic assistance represents a transformative technology with the potential to standardize complex cervical spine procedures across diverse surgical settings while maintaining high accuracy and safety profiles.

Keywords: Cervical spine, minimally invasive spine surgery, pedicle screw, robotic spine surgery

Introduction

Posterior cervical stabilization is a critical procedure for various spinal pathologies, including degenerative diseases, trauma, and deformities. Among the different fixation methods, cervical pedicle screws (CPS) are known to be biomechanically superior, offering up to four times the pullout strength of traditional lateral mass screws. This makes them particularly valuable for complex cases requiring robust, three-column stabilization.

However, the widespread use of CPS has been limited by the technical challenges of their placement. The cervical pedicles are small, and critical structures like the vertebral artery, spinal cord, and nerve roots are in immediate proximity. Traditional freehand techniques have reported malposition rates as high as 31.6%,[1] and while fluoroscopy-guided methods show improvement, significant risks remain.[2]

The evolution of surgical technology led to the introduction of computer-assisted navigation (CAN) and, more recently, robotic guidance systems. The first robotic platform for spine surgery was approved in 2004, and since then, the technology has advanced significantly.[3] Modern third-generation robotic systems, which integrate intraoperative 3D imaging (like an O-arm) with a navigated robotic arm, aim to improve screw placement accuracy, reduce radiation exposure to the surgical team, and potentially shorten the learning curve for complex procedures.[4-6] While robotic assistance is well-established in thoracolumbar surgery,

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its application in the cervical spine is a more recent and evolving frontier.

Materials and Methods

This narrative review was conducted to provide a comprehensive overview of the current state of robotic-assisted cervical spine surgery. The data synthesis is based on a curated collection of literature provided by the authors, including recent prospective and retrospective clinical studies, systematic reviews, meta-analyses, and technical notes.

Data location and selection

The primary sources consisted of peer-reviewed articles from prominent journals in the fields of spine surgery and orthopedics, as well as pre-print manuscripts of recent clinical series. The selection criteria focused on literature published primarily within the last decade that specifically addressed the use of robotic systems in the cervical spine. Key inclusion criteria were studies that reported on the accuracy of instrumentation (using verifiable metrics like the Gertzbein-Robbins classification), safety outcomes (including neurovascular complications), and discussions of surgical workflow, challenges, and technical innovations. Low-quality articles, case reports without clear outcome data, and letters to the editor were excluded to maintain a high level of evidence.

Data extraction and synthesis

Relevant data were extracted from each selected source. This included study design, type of robotic system used, number of patients and screws, screw placement accuracy rates, incidence and type of complications, and qualitative descriptions of surgical techniques, challenges, and solutions. The extracted information was then thematically organized and synthesized to form a cohesive narrative. The synthesis focused on addressing the key themes of this review: the historical background, current applications, accuracy and safety, challenges and lessons learned, and future directions of the technology.

Current Applications in Cervical Spine Surgery

The primary application of robotics in the cervical spine is for the precise placement of posterior instrumentation. This includes the following:

- **Cervical Pedicle Screws:** This is the most studied application. Robotic systems assist in planning and executing the ideal trajectory for screws from C2 to C7, which is especially useful in cases with difficult anatomy, such as in patients with rheumatoid arthritis or severe spondylosis.[7,8] Recent innovations in surgical technique have focused on optimizing entry points for CPS. Dave *et al.* introduced a novel medially shifted cervical pedicle entry point (CPEP) technique in a prospective Indian cohort of 50 patients with 218 sub-axial CPS placed under O-arm navigation. The CPEP was defined as the intersection of a vertical line bisecting the lateral mass and a horizontal line 2 mm inferior to its superior margin. This medially positioned entry point demonstrated 97.24% accuracy with only 2.76% breach rate and no neurovascular complications, effectively reducing soft tissue dissection and mitigating lateral malposition risks associated with conventional lateral entry points.[9] This technique represents an important evolution in addressing the anatomical challenges specific to Asian populations, where cervical pedicle dimensions may be smaller than Western populations. The detailed step-by-step technical workflow for robotic-assisted cervical pedicle screw placement, including specific instrument specifications, drilling parameters, and surgical nuances, has been comprehensively described in our recent publication on custom instrumentation.[7]
- **Lateral Mass Screws:** Although biomechanically less robust than pedicle screws, lateral mass screws are a common alternative. Robotic navigation can also be used to guide their placement, ensuring a safe trajectory away from nerve roots and the vertebral artery.[8,10]
- **Anterior Cervical Surgery:** While less common, the navigation capabilities of robotic systems can be adapted for anterior procedures. For instance, navigation can help ensure the accurate midline placement of cages and plates during an Anterior Cervical Discectomy and Fusion or guide the depth of resection during a corpectomy, which is particularly useful when dealing with ossification of the posterior longitudinal ligament (OPLL).[10]

Evolution from Navigation to Robotics

The evolution of cervical pedicle screw placement has progressed from freehand techniques to CAN and, more recently, to robotic-assisted systems. Understanding the comparative performance of these approaches provides important context.

Navigation Systems: CAN uses intraoperative or preoperative computed tomography (CT) imaging combined with optical or electromagnetic tracking to provide real-time visualization of instrument position. However, evidence regarding navigation's superiority in cervical spine surgery has been inconsistent. A meta-analysis of 4697 CPS found that navigation did not significantly improve accuracy compared to non-navigated placement (94% vs. 96% for screws with breaches ≤2 mm, pooled proportion for complete intra-pedicle placement 76% vs. 82%).[11] Intraoperative reposition and postoperative revision rates showed no significant differences.[11] Despite mixed evidence on accuracy, navigation consistently reduces surgical team radiation exposure and may benefit complex anatomical situations.[12,13]

Robotic Systems: Third-generation robotic systems combine navigation with robotic arm guidance that physically constrains instruments to planned trajectories. This physical restriction limits degrees of freedom, reducing human variability. Comparative studies show promising results. A propensity-matched study comparing robotic to navigation systems found comparable overall accuracy (97.9% vs. 94.3%) but significantly lower lateral breaches with robotics (1.1% vs. 7.7%, $P = 0.037$), relevant given vertebral artery proximity.[14] A prospective comparison of freehand, fluoroscopy, and robotics demonstrated robotic accuracy of 99.34% vs. 98.6% and 97.7% for fluoroscopy and freehand, respectively.[5] Importantly, robotic systems showed an experience-neutralizing effect with no accuracy differences between surgeons of varying experience, whereas freehand and fluoroscopy techniques demonstrated clear learning curves.[5]

Table 1 summarizes comparative accuracy across guidance modalities.[5,11,14-16]

Clinical Implications: While navigation improved visualization, it did not consistently demonstrate superior accuracy in meta-analyses.[11] Robotic systems offer more consistent advantages through physical trajectory constraint and experience-neutralization.[5,14] However, cost and infrastructure requirements necessitate individualized selection based on institutional resources, case complexity, and surgeon experience.[15,16]

Accuracy, Safety, and Feasibility

Multiple studies have demonstrated that robotic assistance leads to a high degree of accuracy in cervical screw placement.

- **Accuracy:** A recent meta-analysis reported a clinically acceptable (minor or no breach) screw placement rate of 98.4% for robot-assisted cervical surgery[17] [Table 2]. This is supported by several clinical series. For example, Soni *et al.*[18] reported a 98.76% clinically acceptable

Table 1: Comparative accuracy of guidance modalities for cervical pedicle screw placement

Technique	Clinically acceptable accuracy (%)	Breach rate (%)	Key advantages	Key limitations
Freehand	68.4–97.7	14.8–31.6	No equipment, lowest cost	High variability, experience-dependent
Fluoroscopy	92–98.6	2–8	Widely available, real-time	Radiation, 2D visualization
Navigation	88–96	2.4–12	3D visualization, reduced team radiation	No physical constraint, registration errors
Robotics	95–99.8	0.6–5	Physical constraint, experience-neutralizing	High cost, setup time

Data from recent meta-analyses and comparative studies[5,11,14-16]

Table 2: Summary of key studies reporting robotic-assisted cervical spine surgery outcomes and accuracy rates

Author (year)	Study design	Technique/System	No. of patients/screws	Key findings (accuracy and complications)	Conclusion
Soni *et al.* (2025)[18]	Retrospective case series	Robot-assisted (MazorX) with Hybrid Dilator Technique	65 patients/565 CPS	**Accuracy:** 98.76% clinically acceptable (G-R Grade A + B). **Complications:** 1.5% major (1 VA injury), 7.7% transient C5 weakness.	The novel hybrid technique is safe and accurate, overcoming instrumentation barriers and facilitating broader adoption of robotic cervical surgery.
Pai *et al.* (2025)[7]	Prospective Study	Robot-assisted (MazorX) with Custom Instruments	22 patients/206 CPS	**Accuracy:** 98.1% clinically acceptable. **Complications:** one deep infection, one non-dominant VA injury.	Robotic-assisted CPS placement with custom instruments is highly accurate and leads to significant clinical improvement.
Vidyadhara *et al.* (2025)[8]	Prospective Study	Robot-assisted (MazorX)	750 patients (49 cervical)/443 CPS	**Accuracy:** 99.8% clinically acceptable overall. **Complications:** Low overall; two deep infections in the full cohort.	Third-generation robotic systems with intraoperative 3D imaging are safe and accurate for posterior anchor placement across the entire spine, including the cervical region.
Kanhangad *et al.* (2024)[5]	Prospective Study	Robot-assisted (MazorX) vs. Freehand vs. Fluoroscopy	180 patients (robotic group)/1225 screws (thoracolumbar)	**Accuracy:** Robotic (99.34%) > Fluoro (98.6%) > Freehand (97.7%). **Experience-neutralizing effect** noted.	Robotic systems demonstrate an "experience-neutralizing effect," allowing surgeons of varied experience to achieve comparable high accuracy.

Table 2: Continued

Author (year)	Study design	Technique/ System	No. of patients/ screws	Key findings (accuracy and complications)	Conclusion
Zhou *et al.* (2023)[17]	Systematic review and meta-analysis	Robot-assisted	7 studies, 160 patients/719 screws	**Accuracy:** 98.4% clinically acceptable.	Robot-assisted techniques for cervical screw placement are accurate, safe, and feasible with promising clinical potential.
Kisinde *et al.* (2022)[19]	Cadaveric Study	Robot-assisted (ExcelsiusGPS)	12 patients/88 CPS	**Accuracy:** 84.1% clinically acceptable. No critical breaches.	Robotic-guided placement of CPS is feasible and safe.
Mao *et al.* (2023)[20]	Cadaveric study	Robot-assisted (MazorX)	4 cadavers/56 CPS	**Accuracy:** 96.4% clinically acceptable. No neurovascular injuries.	Robot-assisted CPS placement is feasible, but anatomical constraints (small pedicles) remain a challenge.
Theologis and Burch (2015)[21]	Retrospective analysis	O-arm navigation	21 patients/121 CPS	**Accuracy:** >99% placed safely. **Complications:** One screw breach (0.8%) caused C5 palsy.	Navigation for CPS is a safe and effective method for complex cervicothoracic deformity and revision surgeries.
Gan *et al.* (2020)[22]	Retrospective cohort	O-arm navigation	297 CPS	**Accuracy:** 77.1% perfect placement (Grade 0), overall breach rate of 22.9%. No neurovascular injuries.	O-arm navigation can improve the accuracy and safety of CPS insertion, though minor breaches are common.
Hojo *et al.* (2014)[1]	Multicenter study	Freehand with fluoroscopy	283 patients/1065 CPS	**Accuracy:** 85.2% acceptable placement. Malposition rate of 14.8%. **Complications:** Two VA injuries.	The malposition rate with the freehand technique is high, especially in patients with rheumatoid arthritis. Guidance tools are recommended.
Yukawa *et al.* (2009)[2]	Retrospective study	Fluoroscopy-guided	144 patients/620 CPS	**Accuracy:** 90.8% acceptable placement. Breach rate of 9.2%. **Complications:** One VA injury, one transient radiculopathy.	Fluoroscopy-assisted technique provides good clinical results, but careful procedure is needed to ensure safety.
Abumi *et al.* (2000)[23]	Retrospective evaluation	Freehand	180 patients/712 CPS	**Accuracy:** Breach rate of 6.7%. **Complications:** One VA injury, two cases of radiculopathy from screws.	Complications can be minimized with sufficient preoperative imaging and strict control of screw insertion.

CPS = cervical pedicle screws, G-R = gertzbein-robbins, VA = vertebral artery

accuracy rate in a series of 565 robot-assisted CPS. Similarly, Vidyadhara *et al.*[8] found an overall clinical acceptability of 99.8% across 443 CPS in a large series of 750 robotic spine surgeries. This level of accuracy is consistently higher than that reported for freehand (97.7%) and fluoroscopy-assisted (98.6%) techniques.[5]

- **Safety:** The primary safety concern with CPS placement is the risk of injury to the vertebral artery or neural elements. The high accuracy of robotic systems directly translates to improved safety. In the series by Soni *et al.*,[18] the rate of vertebral artery foramen breach was only 0.35%, demonstrating exceptional protection of this critical structure. While complications can still occur, such as the single vertebral artery injury (1.5% of patients) reported in that series, they are infrequent and often manageable without long-term consequences. The reduced radiation exposure for the surgical team is another significant safety benefit, as the team can step away during the intraoperative 3D scan.[3]
- **Feasibility:** The use of robotics for cervical spine surgery has been proven to be clinically feasible. Surgeons have successfully performed these procedures for a wide range of pathologies, from degenerative myelopathy to trauma and deformity.[10] The technology is adaptable, and with specific workflows, it can be integrated into both posterior and anterior cervical surgeries.

Challenges, Solutions, and Lessons Learned

Despite its advantages, the adoption of robotics in cervical spine surgery is not without its challenges. A deeper discussion of these hurdles and the innovative solutions developed provides valuable insight for surgeons adopting this technology.

- **Challenge: Infrastructure and Operational Requirements:** Successful implementation of robotic cervical spine surgery requires substantial infrastructure preparation. The operating room must accommodate the robotic system, O-arm imaging equipment, and their respective consoles while maintaining sufficient space for the surgical team's maneuverability.[6] Workflow coordination between multiple systems demands careful choreography to avoid equipment interference and maintain sterile fields.[24]

  - **Solution:** Institutions must invest in specialized training for entire surgical teams to ensure proficient operation of integrated systems.[3] Initial setup time can be longer than conventional approaches, though this decreases significantly with team experience and workflow optimization.[6,25] These infrastructure requirements represent real barriers to adoption, particularly for institutions with limited resources or smaller operative volumes. However, standardized workflows and team familiarity can mitigate these challenges, with experienced centers demonstrating setup times comparable to conventional fluoroscopy-guided procedures.[25]

- **Challenge: Lack of Dedicated Instrumentation and Proprietary Ecosystems:** A major hurdle has been the lack of cervical-specific instruments compatible with robotic systems, which were primarily designed for larger thoracolumbar screws. This limitation is compounded by the "closed ecosystem" model of many robotic platforms, which restricts surgeons to manufacturer-specific implants. This "proprietary lock-in" limits clinical autonomy, preventing surgeons from selecting the most appropriate implant based on clinical evidence, and can lead to significant cost increases.[7,26]
  - **Solution:** Innovative techniques have been developed to overcome this. Pai *et al.*[7] first demonstrated the use of custom-designed screwdrivers and taps to work with standard 3.5 mm and 4.0 mm cervical screws. More recently, Soni *et al.*[18] introduced a novel "hybrid dilator technique," which uses standard lumbar multisystem inflammatory syndrome dilators as an interface between the robotic arm guide and conventional cervical instruments. This workaround eliminates the need for custom tools, preserving robotic accuracy while making the technology more accessible. These innovations not only restore surgical choice but also have significant economic benefits. Soni *et al.*[26] found that using custom drivers with third-party implants led to a 71.6% reduction in implant costs per case compared to proprietary instrumentation, a crucial factor for sustainable health care.
- **Challenge: The Learning Curve:** Like any new technology, there is a learning curve associated with robotic spine surgery. This involves understanding the workflow, from patient setup and registration to surgical planning and execution.
  - **Solution and Lesson Learned:** Studies have shown that robotic systems have an "experience-neutralizing effect." Kanhangad *et al.*[5] conducted a prospective study comparing robotic, fluoroscopy, and freehand techniques among surgeons with varied experience. They found that with robotic assistance, surgeons achieved comparably high accuracy regardless of their individual experience level. This suggests that the technology can help standardize results and potentially flatten the learning curve, allowing less experienced surgeons to achieve outcomes similar to their senior colleagues, a finding supported by Srinivasa *et al.*[6]
  - A critical component of safely managing the learning curve is routine confirmatory intraoperative imaging. During the initial adoption phase (first 30–50 cases), a second O-arm spin after screw placement but before wound closure allows immediate identification and revision of malpositioned screws. Recent Indian series demonstrate that 0.2%–0.66% of robotically placed screws required intraoperative revision when detected on confirmatory scans, with no subsequent revision surgeries needed.[5,8] If navigation accuracy is lost during the procedure, "snapshot" re-registration should be attempted first, followed by repeat O-arm scanning if accuracy cannot be restored. As consistent accuracy (>98% Grade A/B placement) is demonstrated over time, routine confirmatory imaging may transition to selective use for complex cases.

Maintaining accuracy throughout the procedure requires systematic verification. In our consecutive 95 cervical pedicle screw surgeries, only two patients (2.1%) required rescanning due to suspected registration loss. This low rate is attributed to meticulous patient immobilization using chest straps and Mayfield clamp fixation. When navigation images show a discrepancy with actual anatomy, or when the instrument entry point deviates from the planned trajectory, patient movement should be suspected. In such instances, no attempt should be made to proceed with drilling or screw placement. "Snapshot" re-registration is attempted first, and if accuracy cannot be restored, a complete rescan is performed before continuing.

- **Challenge: Patient Positioning and Fixation:** The cervical spine is highly mobile. Unlike the lumbar spine, where a pin can be securely placed in the iliac crest to fix the patient to the robot, there are no simple, safe bony landmarks for rigid fixation in the neck. Reduction maneuvers, distraction, or compression during instrumentation can potentially disrupt robot registration and compromise accuracy.
  - **Solution and Lesson Learned:** The consensus is to use a Mayfield head clamp to rigidly fix the patient's head to the operating table. Our protocol involves performing all reduction and alignment maneuvers either before the initial O-arm scan or only after complete insertion of all planned screws. This prevents any patient movement during the critical phase of screw placement. If reduction is

required mid-procedure, the registration should be verified with a blunt planar probe, and repeat scanning should be performed if accuracy is questionable before proceeding with the remaining screws. The patient is then securely strapped to the table. The robot is mounted to the table, and a "pinless" software registration is used. This relies on the principle that once the patient is secured, there is minimal intraoperative movement, allowing for a stable relationship between the robot and the patient's anatomy.[7] This approach avoids complications such as pin-site infections and the surgical field obstruction caused by bulky spinous process clamps, thereby improving workflow efficiency and enhancing surgical access.[27]

- **Challenge: Feasibility Across Diverse Settings:** The feasibility of robotic cervical spine surgery extends beyond technical capabilities to encompass economic viability, institutional readiness, and adaptability to diverse healthcare environments. While high-volume academic centers may justify the substantial capital investment through case volume, the technology's value proposition becomes more complex for community hospitals or resource-limited settings.[28] The requirement for specialized training, dedicated operating room space, and ongoing maintenance represents recurring costs that must be balanced against clinical benefits.[3,29] However, as technology matures and costs decrease, coupled with innovations in instrumentation compatibility and workflow efficiency, robotic assistance is becoming increasingly feasible across varied institutional contexts.[18,26] The documented improvements in accuracy, safety, and the experience-neutralizing effect suggest that robotic technology may ultimately enhance accessibility to complex cervical spine procedures by standardizing outcomes regardless of surgeon experience level.[5,6]
- **Lesson Learned: Importance of Intraoperative Imaging and Technical Nuances:**
  - **Intraoperative vs. Preoperative Computed Tomography:** Experience has shown that using an intraoperative 3D scan (the "Scan and Plan" workflow) is superior to using a preoperative CT scan. A preoperative CT is taken with the patient in a supine position, which does not reflect the patient's anatomy after being positioned prone on the operating table. Intraoperative imaging provides a real-time, accurate anatomical map for the robot, minimizing errors from positional changes.[8]
  - **Understanding Breach Etiology:** Even with robotic accuracy, breaches can occur. Analysis of these rare events is crucial. Soni *et al.*[18] found that anatomical constraints, rather than technological failure, were the primary cause of the few breaches observed. Specifically, "small pedicle diameters accounted for nearly half of the seven breaches, emphasizing that robotic accuracy cannot overcome fundamental anatomical limitations." This underscores the importance of careful preoperative planning and accepting that some anatomies are not suitable for pedicle screw fixation, even with robotic aid.[18]
  - **Surgical Pearls:** Meticulous surgical technique remains paramount. To prevent the robotic arm from deviating due to soft tissue pressure, surgeons have learned to use separate paramedian skin incisions for screw placement.[18] Another key pearl is to prepare the bony entry point by flattening any sloping surfaces, such as the thoracic transverse processes or hypertrophied facets, to prevent instruments from "skiving" or slipping medially upon contact.[8]
- **Challenge: Complex Revision Surgery in Rigid Deformity:** Revision cervical surgery in ankylosed spines presents unique challenges where conventional surgical approaches become inadequate. Failed instrumentation combined with rigid deformity creates scenarios where standard techniques cannot safely achieve necessary trajectories for successful revision.
- **Solution and Clinical Example:** Robotic guidance transforms these challenging cases from high-risk procedures to manageable surgeries. A compelling example from our series involved a patient with

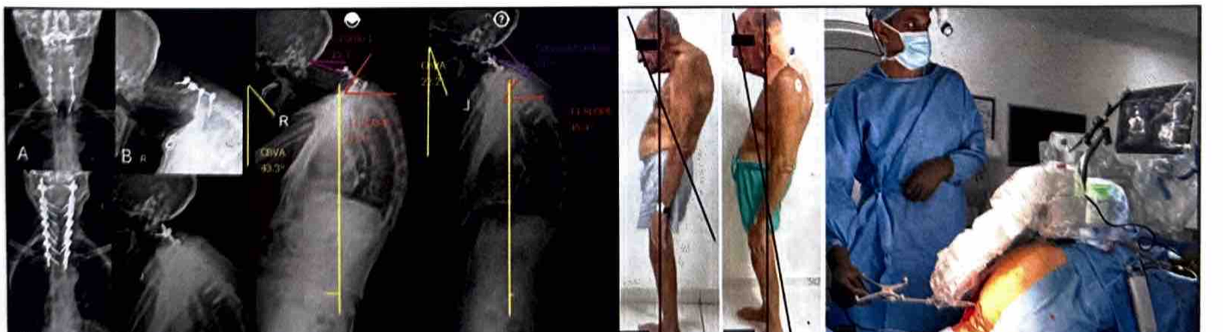

Figure 1: Robotic-assisted revision surgery for ankylosing spondylitis chin-on-chest deformity. (A and B) Preoperative failed instrumentation. (C and D) postoperative correction. (E and F) spinopelvic measurements showing chin brow vertical angle improvement 43.3Â°–22.2Â°. (G and H) clinical transformation, and I: intraoperative robotic drilling in challenging anatomy

ankylosing spondylitis presenting with severe "chin-on-chest" deformity (45° chin-brow-to-vertical angle) following failed conventional C5-T2 instrumentation. The combination of hardware failure and rigid cervical kyphosis created an extreme surgical challenge requiring drilling trajectories dictated by deformity rather than normal anatomy.
- Robotic-assisted revision surgery enabled comprehensive C1-T3 instrumentation through precise high-speed drilling in awkward access angles that would have been dangerous or impossible with freehand techniques. The patient achieved substantial correction of both cervical balance (chin brow vertical angle: 43°–22°) and local kyphosis (38°–4°), with complete restoration of functional head positioning and horizontal gaze. This case exemplifies how robotic precision enables successful outcomes in scenarios where conventional approaches have failed [Figure 1].

Economic Considerations

The cost implications of robotic spine surgery represent a significant barrier to widespread adoption. Third-generation robotic systems require substantial upfront capital investment, with ongoing costs for maintenance, consumables, and training. Different robotic platforms have distinct cost structures, and per-case operational costs can add $8000–$9000 when using proprietary instrumentation.[30,31] However, innovations in custom instrumentation have demonstrated potential for a 71.6% reduction in implant costs while maintaining equivalent accuracy.[26] Recent cost-effectiveness studies show promising results: the incremental cost-effectiveness ratio for robotic-assisted spine surgery has been reported at $22,572, decreasing to $16,980 for one or two levels of instrumentation.[32] Cost-utility analyses demonstrate robotic-assisted procedures achieve superior outcomes ($21,546.80 with 0.68 quality-adjusted life year (QALY) vs. $22,398.98 with 0.67 QALY for non-robotic methods).[33] These benefits derive primarily from indirect cost savings, with documented reductions of $314,661 from avoided revision surgeries and $36,312 from reduced infections annually.[34] Cost-effectiveness is highly dependent on case volume, institutional experience, and the ability to leverage improved outcomes.[28,31]

Healthcare cost structures vary substantially across systems and regions. Most published economic analyses originate from developed healthcare systems with robust insurance coverage. In many regions, including India, health care operates under different financial paradigms with significant out-of-pocket expenditure and varied institutional practices. Direct cost comparisons between institutions or healthcare systems may not be valid, as each center must evaluate robotic technology within its own economic framework.[35] Despite these limitations, the fundamental principle remains consistent: robotic systems can contribute to overall healthcare cost reduction by improving system effectiveness, enhancing safety, and achieving better patient outcomes through reduced complications, revisions, and hospital stays.[28,29] Future research should prioritize region-specific cost-effectiveness studies and long-term outcome evaluations.[29]

Future Directions

The field of robotic cervical spine surgery is advancing rapidly. Future developments are likely to focus on:

- **Dedicated Cervical Systems:** The development of robotic platforms and instruments designed specifically for the delicate anatomy of the cervical spine. This would streamline the workflow and eliminate the need for workarounds.
- **Augmented Reality Integration:** Combining robotic guidance with augmented reality overlays could provide surgeons with "X-ray vision," projecting the planned screw trajectory directly onto the patient's anatomy in the surgeon's field of view.
- **Artificial Intelligence (AI):** AI algorithms could be used to assist in surgical planning by automatically identifying the optimal screw trajectory based on the patient's unique anatomy, potentially improving accuracy even further.
- **Minimally Invasive Procedures:** As instrumentation becomes smaller and more refined, robotics will play a key role in enabling truly minimally invasive posterior cervical fusions, reducing muscle damage and improving recovery times.

Conclusion

Robotic assistance is transforming cervical spine surgery. The technology has demonstrated its ability to significantly improve the accuracy and safety of screw placement, particularly for challenging CPS. While challenges related to instrumentation and workflow exist, surgeons are developing innovative solutions to overcome them, enhancing both clinical autonomy and economic feasibility. The "experience-neutralizing" effect of robotics may help standardize surgical outcomes across surgeons with different levels of experience. As the technology continues to evolve, robotic-assisted procedures are poised to become the new standard of care for complex cervical spine reconstruction.

Author contributions

SV: conceptualization, design, definition of intellectual content, literature search, clinical studies, data acquisition, data analysis, manuscript editing, and manuscript review. AS: conceptualization, design, definition of intellectual content, literature search, data acquisition, data analysis, manuscript preparation, manuscript editing, and manuscript review. TB: definition of intellectual content, literature search, manuscript editing, and manuscript review. HSC: conceptualization, definition of intellectual content, and manuscript review.

Data availability statement

All collected data are available for this study. Data will be provided upon request.

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Conflicts of interest

There are no conflicts of interest.

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