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ORIGINAL ARTICLE

Robotic-assisted anterior and posterior cervical spine surgeries

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Abstract

Introduction Cervical spine surgeries pose unique challenges due to the proximity of critical structures and limited visualization with traditional techniques. Robotic assistance offers potential solutions by providing precise navigation and reducing radiation exposure. We present a series of 30 consecutive patients undergoing various cervical spine procedures utilizing the MazorX Stealth Edition (MXSE) robotic system with intraoperative imaging.

Methods Anterior and posterior surgeries were performed using the MXSE system. Surgical parameters, implant placement accuracy, and patient outcomes were assessed. Data analysis included anthropometric measurements, surgical times, blood loss, radiation exposure, and patient-reported outcomes.

Results Mean age was 52.43 years, with 43.33% females. Procedures included anterior cervical discectomy and fusion, corpectomy, disc replacement, and posterior decompression and fusion. Implant placements were accurate, with no neurological deficits or reoperations. Surgical parameters were comparable to standard techniques.

Discussion Robotic assistance offers accurate implant placement and reduced radiation exposure. Challenges such as vertebra segmentation and surgical approach were addressed. Further research and instrument development are needed for wider adoption.

Conclusion Robotic navigation in cervical spine surgeries enhances precision and safety. Continued advancements in technology and technique are essential for broader implementation.

Keywords Robotic-assisted surgery · Robotic surgical procedures · Cervical vertebrae · Blood loss · Surgical · Radiation exposure

Introduction

Cervical spine surgeries present inherent challenges due to the proximity of critical structures such as major vessels, the spinal cord, and nerve roots [1, 2]. Despite the steep learning curve associated with these procedures, improvements in operative efficiency over time are hindered by the cumulative effects of radiation exposure on surgical teams [3–5]. Traditional two-dimensional fluoroscopy offers limited visualization of the complex cervical spine anatomy, making precise implant placement challenging [6].

Navigation systems utilizing computed tomographic (CT) scans enable visualization of safe bony corridors for implant positioning, but the mobility of the cervical spine limits preoperative CT scan accuracy [7–10]. The third-generation spine robots have in-built navigation capabilities that can be utilized to ensure accurate placement of implants in the cervical spine, without the need for a separate spinal navigation system. When used in conjunction with intraoperative cone-beam CT image acquisition, they provide highly accurate, real-time navigation of instruments with reduced radiation exposure to the surgical team [11, 12]. These robots have been extensively studied for their application in the thoracolumbar spine, while their utility in the cervical spine has been largely limited. Most reports of robot utilization in the

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cervical spine are case reports, cadaveric studies and a series of robot-assisted cervical pedicle screw fixation. All of them acknowledged that the utilization of robots in cervical spine is still in the nascent stage, with majority of the potential untapped. Currently, no studies have utilized the navigation capabilities of the spine robot in anterior cervical surgeries and most studies that have looked at posterior cervical instrumentation have been done on previous generation of spine robots, utilizing intraoperatively acquired cone-beam CT imaging [13–17]. The existing reports highlight the challenges of utilizing robotics in cervical surgery due to its relative mobility and narrow margins for safety [16, 17].

We present a series of 30 consecutive patients undergoing various cervical spine surgeries utilizing the MazorX Stealth Edition (MXSE) robotic system with intraoperative imaging, performed by a single experienced surgeon.

Methods

This prospective study received institutional ethical clearance, with written patient consent obtained. Thirty patients undergoing anterior and posterior cervical spine surgeries with the MXSE were included. The surgeries were performed by a single surgeon experienced in MXSE utilization.

Anterior cervical surgery

During anterior cervical surgery, including anterior cervical discectomy and fusion, anterior cervical corpectomy and fusion, and cervical disc replacement, patients were positioned supine on a radiolucent operating table, with the head secured using Mayfield tongs to minimize movement. Due to the absence of safe bony prominences near the cervical spine in the supine position, direct connection of the robot to the patient was not feasible. The surgeries followed the "Scan & Plan" workflow, with intraoperative robot registration and image acquisition performed to ensure accurate navigation [12].

Stringent measures were implemented to prevent inadvertent patient or robot movement, minimizing the risk of navigation inaccuracies. The cervical spine was accessed anteriorly following robot registration and O-arm image acquisition. The region of interest was delineated, extending to include the symphysis menti to enhance navigation accuracy. Vertebrae of interest were marked with "screws" near the midline to facilitate intraoperative identification when utilizing the blunt passive planar probe, known as the "chicken foot".

Given the absence of a specific "supine" workflow for the MXSE, the navigation screen orientation was horizontally inverted. To mitigate potential confusion, the horizontal inversion transformation tool available on the operation screen was utilized, particularly beneficial during anterior cervical corpectomies using the navigated burr. Verification of the midline location using the "chicken foot" ensured precise anatomical implant placement before final implant placement.

In the event of navigation accuracy loss, restoration of robot registration using a "snapshot" was the initial step. Subsequent verification of accuracy was conducted with the "chicken foot". If inaccuracies persisted, repeat scans were deemed necessary. Postoperative O-arm scans were performed to assess implant position, with no additional fluoroscopy utilized during the procedure (Fig. 1).

Posterior cervical surgery

During posterior cervical surgery, encompassing procedures such as posterior cervical decompression and fusion with lateral mass screws or pedicle screws, and vertebral biopsy, patients were positioned prone on a radiolucent operating

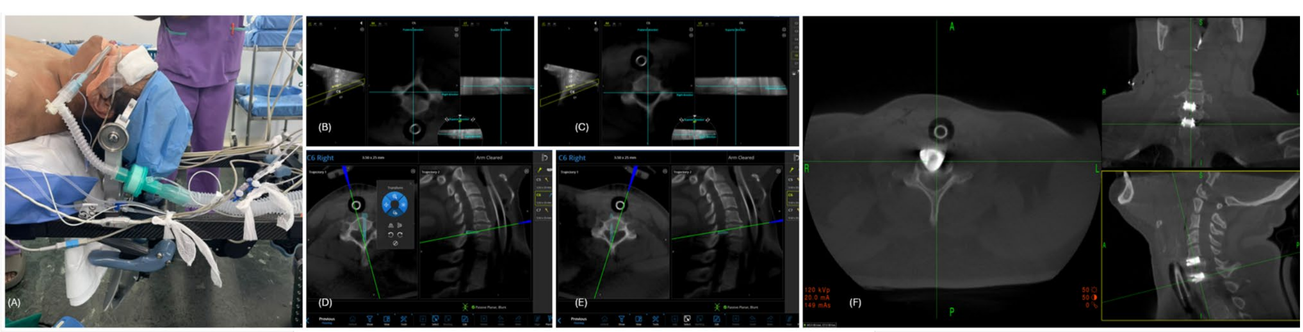

Fig. 1 Clinical photographs depicting the surgical setup and navigation process for anterior cervical surgeries **A** Shows the patient's head secured with Mayfield tongs on the radiolucent operating table. **B** Screenshots from the workstation displaying raw imported data and **C** demonstrate correcting the orientation of the vertebrae, resulting in lateral inversion of the navigation image, which is rectified using the horizontal inversion transformation tool **D**, **E**. These steps ensure proper orientation of the navigation tools during the procedure. Postoperative O-arm scans confirm the anatomical placement of implants

table. Mayfield tongs were utilized to secure the head and minimize movement. Due to the absence of safe bony prominences near the cervical spine in the prone position, direct connection of the robot to the patient was not feasible. All surgeries were conducted following the "Scan & Plan" workflow to ensure accurate navigation [12].

Stringent precautions were taken to prevent inadvertent patient or robot movement, minimizing the risk of navigation inaccuracies. The cervical spine was accessed posteriorly in the standard manner, following robot registration and O-arm image acquisition with self-retaining retractors in place. Initially, in the first five cases, a spinous process-mounted navigation reference frame was utilized, but due to frequent inadvertent movement, a switch was made to a robot arm-mounted reference frame. The obtained O-arm images were transmitted to the MXSE workstation, where trajectories for lateral mass or pedicle screws were planned.

These trajectories served as a guide for the surgeon when using the navigable high-speed burr to create tracks in the bone. Similar to anterior surgeries, a "snapshot" was acquired in case of navigation accuracy loss, with repeat O-arm scans performed when necessary. Postoperative O-arm scans were conducted to assess implant position, with no additional fluoroscopy utilized during the procedure (Fig. 2).

In select cases, the robotic arm was utilized to drill trajectories for lateral mass screws without physical mounting to the patient. This workflow closely resembled the use of the navigable high-speed burr, with the key difference being the removal of spinous processes with a rongeur to allow free movement of the arm guide and drill sleeve to the starting point. "Short tools" were utilized, and the robotic arm was positioned at a height no less than 170 mm to prevent anterior plunging of the "feather touch" drill (Fig. 3).

Demographic, clinical data and surgical parameters were collected for all patients. “Cut-to-close time” is the total time elapsed from the initial skin incision to closure of the surgical site. “Time per screw” was measured as the average time taken to insert each pedicle screw. In surgeries performed using robotic assistance, “Exposure Time” was defined as the time from initial skin incision to complete exposure of the laminae at the decompression levels, “Robot Time” from software mounting the robotic arm to the completion of robot registration prior to the O-arm scan plus the time

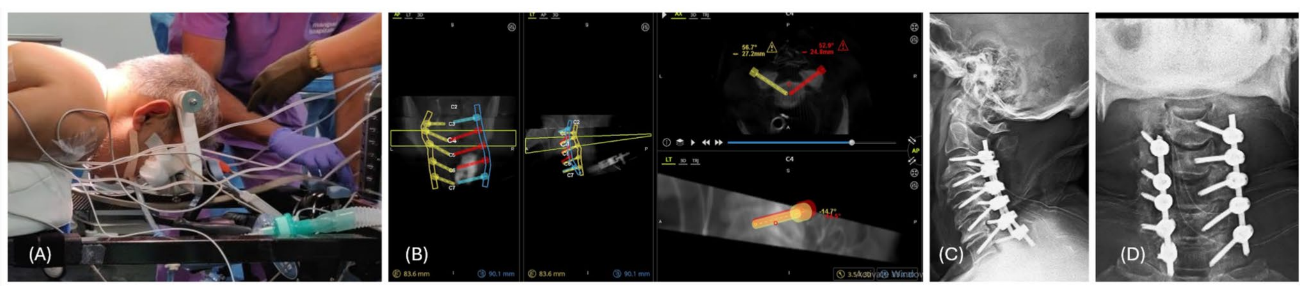

Fig. 2 This figure illustrates the surgical process and outcomes for posterior cervical surgeries. **A** A clinical photograph of captures the patient positioned prone on the operating table with the head secured using Mayfield tongs. **B** A screenshot from the workstation displays the planned trajectory for a cervical pedicle screw. Despite persistent loss of navigation accuracy after placement of the left sided pedicle screws, a bailout strategy was implemented using lateral mass screws on the right side. Post-operative radiographs **C**, **D** confirm the successful placement of implants

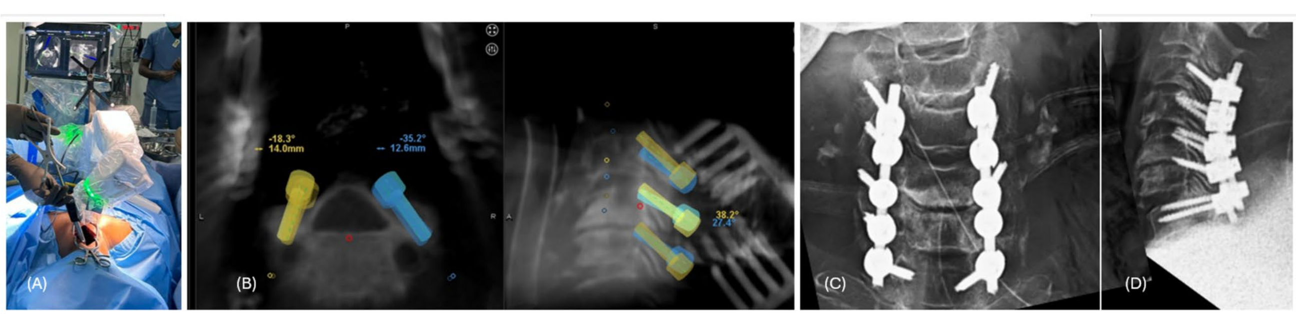

Fig. 3 This figure depicts the process and results of placing lateral mass screws using robotic assistance. **A** A screenshot from the MazorX workstation displays the planning stage for a lateral mass screw. **B** Am intraoperative photograph captures the drilling of the lateral mass guided by the robotic arm. Postoperative radiographs **C**, **D** demonstrate the successful placement of screws, ensuring stability and alignment

taken for planning screws, and "O-arm Time" included time from positioning the O-arm for the anteroposterior fluoroscopy image to finalizing the acquisition of the cone-beam CT image. The amount of blood loss during the surgery was documented in all patients. The mean duration of hospitalization was also noted. Additionally, the planned and executed trajectories of posterior screws were compared and graded using the Gertzbein and Robbins classification, with Grades A and B considered "clinically acceptable". [18] Statistical analysis was performed using SPSS version 20, with qualitative variables expressed as percentages and continuous variables expressed as mean ± standard deviation (SD).

Results

The mean age of the patients was 52.43 years, with females comprising 43.33% of the cohort. The mean body mass index was 26.7. Details of the diagnoses are provided in Table 1, illustrating that 18 patients underwent anterior cervical surgery, with procedures including cervical disc replacement in 8 patients (12 implants), anterior cervical discectomy and fusion in 7 patients, and anterior cervical corpectomy and fusion in 3 patients. Additionally, 12 patients underwent posterior cervical surgery, consisting of lateral mass fixation in 6 patients, pedicle screw fixation in 4 patients, combined lateral mass and pedicle screw fixation in 1 patient, and vertebral biopsy in 1 patient. A total of 65 lateral mass screws and 41 pedicle screws were inserted in 11 patients.

Table 1 Details of diagnosis in anterior and posterior surgeries

Diagnosis	Anterior Surgeries ($n=18$)	Posterior surgeries($n=12$)
Disc prolapse with radiculopathy	15	0
Ossification of posterior longitudinal ligament	1	10
Traumatic unifacetal dislocation	2	0
Revision laminectomy	0	1
Biopsy from vertebra	0	1

Notably, there was an improvement in patient-reported outcome measures following surgery. The operative parameters for anterior and posterior surgeries are summarized in Table 2. Importantly, the frequency of "clinically acceptable" lateral mass and pedicle screw placement was 100%. Furthermore, none of the patients experienced permanent postoperative neurological deficits, and the 90-day reoperation rate was 0. The mean duration of hospitalization was 2.1 days. However, one patient experienced delayed wound healing, necessitating regular dressings until 3 weeks postoperatively.

Discussion

The adoption of robotic assistance in spine surgery has primarily been restricted to the thoracic and lumbar spine, attributed to their relatively limited mobility and larger safe corridors for spinal implant placement. However, the cervical spine's mobility and narrow bony corridors have resulted in limited studies examining the feasibility of utilizing spine robots for cervical implants [13–15]. Current generation of spine robots can utilize both pre- and intraoperatively acquired CT scans for registration [12]. We utilized intraoperatively acquired cone-beam CT scans in all our cervical spine surgeries to accurately reflect intervertebral anatomy of the patient on the operating table, after patient positioning. To our knowledge, this is the first paper to investigate the in vivo utility of the MXSE in placing implants in the cervical spine using the "Scan & Plan" workflow, in conjunction with an intraoperative cone-beam CT scan.

Navigation has been widely employed for implant placement in the cervical spine, with studies indicating higher accuracy with intraoperative image acquisition compared to preoperative acquisition [9]. While some studies have highlighted challenges in vertebra segmentation due to the steep craniocaudal angulation of the pedicle, we did not encounter such issues as the Mazor 5.0 software facilitates visualization of both cranial and caudal segments [16]. Moreover, our study demonstrated comparable accuracy in implant placement, blood loss, and surgical time to those reported by other authors [17].

Table 2 Details of surgical parameters

	Anterior surgeries ($n=18$)	Posterior Surgeries ($n=12$)
Mean "Cut-to-close" time (mins)	64	214
Mean Robot time (mins)	Not applicable	33
Mean O-arm time (mins)	7	7
Mean Time per screw (mins)	Not applicable	3
Blood loss in mL(Mean ± SD)	125 ± 54	625 ± 195

A common problem in robotic cervical spine surgery is the excessive mobility. This is worsened following muscle relaxation under anaesthesia and extensive paraspinal muscle dissection. We preferred to immobilize the head with Mayfield tongs and strapped the patient to the operating table, ensuring minimal movement of the robot-patient unit, in all cervical spine surgeries. While patient-mounted reference frames are available and boast higher accuracy due to proximity to the surgical field, we opted for robot-arm mounted reference frame as it was least likely to be moved inadvertently during surgery [9]. Most robotic spine surgery requires use of bone mounts, for connecting the robot to the patient in a semirigid manner [12, 19, 20]. In the cervical spine, the limited surgical field precluded the use of bone mounts as it was bulky and came in the way of surgical instruments. We used the software mounting feature of the MSXE robot. The MXSE robot utilizes fiducials which are detected on the intraoperative scan and utilizes it to determine the location of the vertebrae in space. Navigation is integrated onto this map for providing visual aid to the surgeons [12]. The ExcelsiusGPS predominantly utilizes continuous real-time visualization of the reflective passive beads and relies on them to determine the location of vertebrae and planned trajectories [17].

While previous feasibility studies have investigated the placement of cervical pedicle screws using the robotic arm guide, we opted against this approach due to the necessity for multiple separate lateral incisions at each level [16]. Instead, we favoured the use of the navigated high-speed burr in these cases. When employing the arm guide for lateral mass screws, we encountered interference from the spinous processes, which were consequently removed with a rongeur as they obstructed the planned drill trajectory. To mitigate the risk of inadvertent damage to critical structures, we ensured that the "feather touch" drill, equipped with a stopper at a depth of 30 mm and a length of 150 mm, was placed at a height of 170 mm. This precautionary measure limited the drill's penetration of the lateral mass to no more than 10 mm and prevented it from inadvertently plunging anteriorly. Additionally, this positioning facilitated visualization of the entry point, ensuring that there was no excess pressure on the arm guide or loss of navigational accuracy. Navigation also allows to identify the thickest part of the occipital bone during occipito-cervical fusion and helps avoid sinuses. Biopsies from critical areas like C2 body and atlanto-axial joint can be safely performed percutaneously utilizing the robot arm for drilling to the appropriate depth and representative tissue can be obtained without extensive dissection.

During anterior cervical surgery, the blunt passive planar probe is useful in determining the adequacy of foraminal decompression, especially near the uncovertebral joint. It guides accurate midline placement of anterior cervical implants in disc replacements, potentially improving longevity of the implant. The navigable burr can be used to direct screw placement parallel to the endplate, avoiding disc space violation while allowing for measurement of screw length. In cases of cervical corpectomy for ossified posterior longitudinal ligament, the navigable burr can be safely used to the appropriate depth, ensuring adequate anteroposterior and mediolateral decompression.

While the role of the spine robot in placing thoracolumbar pedicle screws is well established, the adoption in cervical spine has been slow due to lack of specific instruments [11, 12, 16]. Future research can be directed at development of the cervical specific implants and instruments which can be used through the robot arm guide to allow for wider adoption of the use of spine robot in cervical spine surgeries and cervico-thoracic junctional reconstruction surgeries.

The detailed description of the workflow, which facilitates reproducibility, stands as a notable strength of this study. The limitation of the study includes the lack of a cost-effectiveness analysis. The fact that all surgeries were done by a single experienced surgeon limits generalizability of the results and the lack of a control group does not allow us to evaluate the relative benefit of robotic spine navigation. The absence of long-term outcomes with respect to fusion rates, functional outcomes and hardware-related complications beyond 90 days is another limitation of the study. However, further research focusing on the development of cervical spine-specific instrumentation that can be navigated and utilized through the arm guide will be pivotal for the broader adoption of the MXSE in cervical spine surgery.

Conclusion

Robotic navigation in cervical spine surgeries offers precise implant placement with reduced radiation exposure, enhancing surgical outcomes. The spine robot can be utilized for safely and accurately drilling trajectories for lateral mass and pedicle screws in the cervical spine.

Author contributions MP, VS, BT, AS conceived the research idea, developed research design, and conducted the research. AK, AV were involved in data collection. MP performed the statistical analysis. All authors contributed substantially to the write-up of the article. All authors reviewed and approved the final draft of the manuscript, and all take responsibility of the content of the publication.

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

Declarations

Conflict of 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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