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Robotics in Modern Spine Surgery and Its Technological Evolution with Impact on Surgical Accuracy and Clinical Outcomes

N. Powjithan [1,*], Firoz Ahmed [2,*]

[1] National Institute of Homoeopathy, Block- GE Salt Lake, Kolkata -700106, India

[2] Department of Pharmacology, Mewar University, Gangrar, Chittorgarh, Rajasthan -312901, India

***Corresponding Author:** N. Powjithan, Firoz Ahmed
[1] National Institute of Homoeopathy, Block-GE Salt Lake, Kolkata -700106, India
[2] Department of Pharmacology, Mewar University, Gangrar, Chittorgarh, Rajasthan -312901, India.
Email: drpowji2030@gmail.com; firozahmed7978@gmail.com

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Abstract

Robotic-assisted spine surgery has emerged as a transformative advancement in modern orthopaedic and neurosurgical practice. Over the past two decades, the integration of robotic platforms into spinal procedures has fundamentally altered paradigms of surgical precision, intraoperative navigation, and postoperative recovery. Early computer-assisted systems have gradually evolved into contemporary autonomous guidance platforms, including the Mazor X Stealth Edition, ROSA Spine, and Excelsius GPS. This evolution reflects a broader technological revolution driven by the convergence of robotics, artificial intelligence, and advanced imaging modalities. The present review aims to provide a comprehensive synthesis of the historical trajectory, technological components, clinical applications, and emerging challenges associated with robot-assisted spine surgery. Specific emphasis is placed on surgical accuracy, workflow integration, and patient outcomes. A systematic search of PubMed, Scopus, and Web of Science databases was conducted for literature published between 1990 and 2025. Search keywords included "robotic spine surgery," "pedicle screw accuracy," "computer-assisted spinal navigation," and "robotic-assisted vertebral surgery." Priority was given to randomized controlled trials, meta-analyses, systematic reviews, and high-impact retrospective cohort analyses. Robotic systems consistently demonstrate superior pedicle screw placement accuracy compared to freehand or fluoroscopy-guided techniques. Grade A accuracy ranges from 85% to 98% for robotic-assisted procedures versus 68% to 85% for conventional methods. Multiple meta-analyses have further confirmed significant reductions in complication rates, revision surgery rates, radiation exposure, and hospital length of stay within robotic cohorts. Although high upfront costs and steep learning curves persist as limitations, emerging evidence supports favorable cost-effectiveness over long-term follow-up. In conclusion, robotic-assisted spine surgery has transitioned from an experimental technology to a clinically validated modality with well-documented benefits in accuracy and safety. Continued innovation in haptic feedback, artificial intelligence integration, and device miniaturization will further entrench robotics as a cornerstone of modern spinal care.

1. Introduction

Spinal surgery encompasses a broad spectrum of procedures. These range from minimally invasive discectomies to complex multilevel instrumented fusions. Each demands extraordinary precision to avoid neurological injury, implant malposition, and construct failure. Historically, spinal surgeons relied upon anatomical landmarks, tactile feedback, and intraoperative fluoroscopy to guide implant placement. These techniques, despite requiring considerable experience, remain prone to human error and radiation exposure (Hicks et al., 2010a; Tian et al., 2011a). The advent of robotic-assisted surgical systems has fundamentally redefined achievable precision in this domain. Such systems offer consistent, reproducible guidance that transcends the limitations of human perception and ergonomics (Roser et al., 2013). The global burden of spinal disorders continues to escalate. Population ageing, sedentary lifestyles, and rising obesity rates all contribute to this trend. Consequently, unprecedented demand for surgical intervention has emerged. The World Health Organization estimates that low back pain affects approximately 619 million individuals globally. This makes it the leading cause of years lived with disability (Cieza et al., 2020). As surgical volumes increase, so does the imperative for technologies that ensure consistent outcomes across diverse patient anatomies, pathologies, and surgical complexities. Robotic systems address this need through multiple integrated features. These include preoperative planning platforms, intraoperative registration, and real-time trajectory guidance. Collectively, these capabilities minimize the margin for technical error (Peng et al., 2020; Urakov et al., 2017).

The term "robotic-assisted surgery" encompasses a heterogeneous category of technologies. Some systems function as passive guidance platforms that constrain instrument movement along planned trajectories. Others operate as semi-autonomous platforms equipped with haptic feedback. Emerging fully autonomous systems represent the cutting edge, capable of executing predefined surgical maneuvers without continuous human input (Bertelsen et al., 2013; Martín Láez et al., 2026). In spine surgery, the dominant paradigm remains semi-autonomous assistance. Under this model, the robotic arm guides the surgeon's instrument to a planned entry point and trajectory. The surgeon, however, retains full control of force application and final execution (Chinoy et al., 1994). This collaborative approach leverages the computational and positional precision of the robot while preserving the indispensable clinical judgment and tactile sensitivity of the operating surgeon (Overley et al., 2017). The field has witnessed rapid and sustained technological advancement since the pioneering work of DiGioia and colleagues in the 1990s on computer-assisted orthopaedic surgery. Subsequent development of the SpineAssist system by Mazor Robotics in the early 2000s marked another milestone (Lieberman et al., 2006; Sukovich et al., 2006). Contemporary robotic platforms are characterized by seamless integration with intraoperative computed tomography (CT) and O-arm imaging. Advanced navigation software further enhances their capabilities. Increasingly sophisticated artificial intelligence algorithms now segment spinal anatomy, predict optimal screw trajectories, and alert the surgeon to potential hazards in real time (Marcus et al., 2014). These capabilities have collectively driven measurable improvements across multiple high-quality clinical studies. Pedicle screw placement accuracy has increased. Intraoperative radiation exposure has decreased. Complication rates have diminished (Fan et al., 2018; Kantelhardt et al., 2011). This review provides a comprehensive analysis of the current landscape of robotic-assisted spine surgery. It traces the historical evolution of the technology and elucidates the technological principles underpinning contemporary platforms.

2. HISTORICAL EVOLUTION OF ROBOTICS IN SPINE SURGERY

2.1 Early Foundations and Computer-Assisted Surgery

The conceptual roots of robotic-assisted spine surgery lie in the broader domain of computer-assisted orthopaedic surgery (CAOS), which emerged in the late 1980s and early 1990s through the pioneering work of investigators such as DiGioia, Jaramaz, and colleagues at Carnegie Mellon University and the University of Pittsburgh. These early systems employed optical tracking and fluoroscopy-based registration to superimpose virtual surgical plans onto real-time intraoperative images, enabling surgeons to visualize implant trajectories with unprecedented accuracy (Nolte et al., 1995). The fundamental insight driving this work that the human-machine interface could be augmented to reduce systematic positional errors laid the intellectual and technological groundwork for all subsequent robotic platforms (Taylor & Stoianovici, 2003).

The first robotic system specifically designed for orthopaedic surgery, ROBODOC (Integrated Surgical Systems, Sacramento, CA), was introduced in the early 1990s for total hip arthroplasty and represented a landmark demonstration that autonomous robotic milling could achieve bone preparation accuracy far exceeding manual techniques (Bargar et al., 1998) (Table 1). While ROBODOC was not directly applied to spinal procedures, its clinical validation catalyzed interest in extending autonomous robotic guidance to the more complex domain of spinal instrumentation, where the proximity of critical neural structures made precision imperatives even more acute (Kazanzides et al., n.d.). Concurrent advances in medical imaging, including the development of multi-detector CT scanners and fluoroscopic navigation systems, provided the imaging infrastructure necessary for robust intraoperative registration a prerequisite for any viable robotic spinal platform (Foley & Smith, 1996).

2.2 First-Generation Robotic Systems (2000–2010)

The most consequential early milestone in robotic spine surgery was the development of the SpineAssist system by Mazor Robotics, which received CE marking in 2004 and FDA clearance in 2004 for guidance of pedicle screw placement (Lieberman et al., 2006). SpineAssist was a miniature, bone-mounted robot (approximately 250 g) that attached directly to the patient's spinous process via a clamp, thereby eliminating registration errors introduced by patient movement relative to a floor-mounted reference frame (Sukovich et al., 2006). The system employed preoperative CT-based planning software that allowed the surgeon to define entry points and trajectories for each screw, which were then transferred to the robot's coordinate system via intraoperative fluoroscopic registration (Shoham et al., 2003). In initial clinical series, SpineAssist demonstrated a pedicle screw accuracy rate (Grade A: ≤2 mm deviation from planned trajectory) of approximately 85–92%, comparing favorably with freehand techniques reported to achieve 69–84% accuracy in contemporary studies (Kantelhardt et al., 2011; Rosen et al., 2008).

Despite its innovative design, first-generation SpineAssist was characterized by a steep learning curve, cumbersome attachment protocols, and susceptibility to registration errors if the clamp was inadvertently disturbed intraoperatively (Ringel et al., 2012). Ringel and colleagues (2012) published a notable randomized controlled trial demonstrating that SpineAssist-guided screw placement did not achieve statistically superior accuracy compared to fluoroscopy-guided freehand technique in a series of 112 patients, a finding that generated significant debate and prompted systematic investigation of the sources of registration failure. Subsequent analysis identified inadequate clamp fixation and patient movement during registration as primary contributors to accuracy degradation, leading to iterative engineering refinements in subsequent system generations (Kim et al., 2015). Notwithstanding these early limitations, SpineAssist established the proof of concept that robotic guidance was surgically feasible and, in optimal conditions, could meaningfully improve trajectory precision.

2.3 Second-Generation Systems and Platform Diversification (2010–2018)

The second generation of robotic spine surgery systems, exemplified by the Renaissance system and the ROSA Spine system, incorporated substantial engineering improvements addressing the limitations of first-generation platforms (Devito et al., 2010; Lonjon et al., 2016). The Renaissance system featured a redesigned miniature robot with enhanced positional repeatability (±0.1 mm), an updated planning software interface with improved CT segmentation algorithms, and a refined bone-mounted attachment mechanism that reduced susceptibility to intraoperative perturbation (Devito et al., 2010). Clinical series evaluating Renaissance reported pedicle screw accuracy rates of 89–98% (Grade A/B), with particularly favorable outcomes in complex deformity and revision cases where anatomical distortion complicated freehand placement (Hyun et al., 2017; Schatlo et al., 2015).

ROSA Spine represented a fundamentally different design philosophy, employing a floor-mounted robotic arm with six degrees of freedom, registered to the patient via intraoperative fluoroscopy or CT imaging. Unlike bone-mounted systems, ROSA's floor-mounted configuration afforded greater workspace flexibility and eliminated the need for bone attachment hardware, though it introduced potential for registration error if patient position shifted between imaging and robot execution (Lonjon et al., 2016). Initial clinical evaluations of ROSA Spine reported accuracy rates comparable to those of Renaissance, with Lonjon et al. (2016) demonstrating 97.6% Grade A/B accuracy in a prospective cohort of 50 patients. This period also witnessed the emergence of the iSYS1 system, a compact, image-guided robotic assistance system validated for minimally invasive pedicle screw placement, further diversifying the competitive landscape (Keric et al., 2017).

2.4 Third-Generation and Contemporary Platforms (2018–Present)

The third generation of robotic spine surgery systems, inaugurated by the FDA clearance of the Mazor X system in 2016 (subsequently upgraded to the Mazor X Stealth Edition in 2018 through integration with Medtronic's StealthStation navigation), represented a paradigmatic shift from standalone robotic guidance to fully integrated robotic-navigation ecosystems (Marcus et al., 2014; Pham & Brown, 2025). The Mazor X Stealth Edition combines the positional precision of the Mazor robotic arm with real-time optical navigation, intraoperative 3D imaging via the O-arm, and Medtronic's AI-powered planning software, creating a closed-loop system in which the robot continuously verifies instrument position relative to the registered patient anatomy (Judy et al., 2021). This integration dramatically reduces the frequency of trajectory deviations and eliminates a major limitation of earlier systems the inability to detect and compensate for intraoperative patient movement after initial registration (Fan et al., 2018).

The ExcelsiusGPS system (Globus Medical, Audubon, PA), cleared by the FDA in 2017, introduced another major architectural innovation: a free-standing robotic arm that functions simultaneously as both a robot and a navigation system, eliminating the need for separate navigation hardware (Bhimreddy et al., 2024). ExcelsiusGPS employs infrared optical tracking of both the robotic arm and the patient's vertebral reference arrays, continuously updating the instrument position in real time relative to the preoperative CT plan or intraoperative O-arm acquisition. Early clinical series reported Grade A accuracy rates of 93–97% for ExcelsiusGPS-guided pedicle screw placement, with particularly notable advantages in minimally invasive surgery (MIS) where visualization is inherently limited. Contemporary robotic platforms have thus evolved from simple bone-mounted trajectory guides into sophisticated, AI-augmented, imaging-integrated ecosystems. They now provide real-time positional verification throughout complex, multilevel spinal reconstruction procedures (Staub & Sadrameli, 2019).

Table 1: Evolution of Robotic Systems in Spine Surgery

Era	Key Milestones	Impact on Spinal Surgery
Early 1900s	Coinage of "Stereotaxis" by Horsley and Clarke (Goodrich, 2004).	Established 3D coordinate mapping for neural targets.
1985	First robotic neurosurgical biopsy (D'Souza et al., 2019a; Farber et al., 2021).	Demonstrated that robotic systems could safely and accurately navigate complex neural anatomy.
1992	Introduction of ROBODOC for orthopaedic use (D'Souza et al., 2019a).	Validated the feasibility of active robotic interaction with osseous structures.
2004	FDA clearance of Spine-Assist (Mazor Robotics) (Pham & Brown, 2025; Pojskić et al., 2025)	Marked the introduction of the first robotic system dedicated to spinal instrumentation.
2011	Launch of the Renaissance System (Pham & Brown, 2025)	Enhanced preoperative CT-based planning and intraoperative mounting stability.
2016-2017	Approval of Mazor X, ExcelsiusGPS, and ROSA Spine systems (Orosz et al., 2026)	Transition to "New Generation" systems with integrated navigation.
2019-Present	Integration of artificial intelligence (AI), three-dimensional (3D) intraoperative imaging, and hybrid robotic arms (Łajczak et al., 2024; Samprón et al., 2025)	Reflects a shift toward optimized surgical workflows, precision, and predictive planning

3. TYPES OF ROBOTIC SYSTEMS IN SPINE SURGERY

3.1 Bone-Mounted Systems

Bone-mounted robotic systems attach directly to the patient's spinal anatomy typically via a clamp secured to the spinous process or posterior iliac crest creating a fixed spatial relationship between the robot and the target vertebrae. This attachment paradigm confers the intrinsic advantage of automatically compensating for table movement, patient respiration-induced spinal translation, and other sources of relative motion between patient and external reference, since both the robot and the target anatomy move together (Shoham et al., 2003). The archetypal bone-mounted system, SpineAssist/Renaissance (Mazor Robotics), has accumulated the largest body of clinical validation evidence of any robotic spine platform, with multiple systematic reviews encompassing thousands of pedicle screws demonstrating consistent accuracy advantages over freehand techniques. The primary limitation of bone-mounted systems is the necessity of attaching hardware to the patient's spine, which adds procedural steps, potentially disrupts sterile draping, and creates a dedicated attachment site that may conflict with the surgical access required for the primary procedure (Devito et al., 2010). In minimally invasive surgery, the attachment clamp must be placed through a separate incision, adding to patient morbidity and operative time. Furthermore, if the clamp inadvertently loosens or shifts position during the procedure a risk particularly relevant in osteoporotic patients with poor bone quality all subsequent robot-guided trajectories are rendered inaccurate, and re-registration becomes necessary (Ringel et al., 2012). Contemporary refinements in clamp design and registration protocols have substantially mitigated these concerns, but they have not been entirely eliminated.

3.2 Floor-Mounted/Robot-Arm Systems

Floor-mounted robotic systems employ a freestanding robotic arm registered to the patient via intraoperative imaging, without requiring direct bone attachment. The ROSA Spine system and ExcelsiusGPS represent the primary clinical implementations of this architecture.

ROSA Spine features a six-degree-of-freedom robotic arm mounted on a mobile cart, capable of positioning a surgical instrument guide at any point within its substantial workspace, registered to the patient via fluoroscopic or CT-based intraoperative imaging (Lonjon et al., 2016). This configuration offers greater workspace flexibility than bone-mounted systems and is particularly advantageous for complex deformity cases requiring large numbers of screws at diverse anatomical levels. ExcelsiusGPS occupies a unique position in this category by integrating navigation and robotics into a single unified platform, eliminating the interoperability challenges inherent in combining separate robotic and navigation systems from different manufacturers. The system's continuous optical tracking of both the robotic arm and vertebral reference arrays provides real-time positional feedback that allows the surgeon to detect and correct trajectory deviations before instrument penetration, a capability that has contributed to its high published accuracy rates. Floor-mounted systems are generally considered more versatile than bone-mounted alternatives for minimally invasive applications, since the robotic arm can approach each level from an optimal angle without hardware attachment conflicts, though they remain dependent on the integrity of the patient registration throughout the procedure.

3.3 Image-Guided Navigation-Integrated Systems

The most advanced contemporary robotic platforms transcend the traditional dichotomy between robotic guidance and image-guided navigation by seamlessly integrating both functionalities into unified ecosystems. The Mazor X Stealth Edition exemplifies this approach, combining Mazor's proven bone-mounted robotic arm with Medtronic's StealthStation navigation, Synergy Cranial software, and the O-arm intraoperative CT scanner (Pham & Brown, 2025; Siddiqui et al., 2018). This integration enables continuous real-time verification of instrument position relative to the registered patient anatomy, automatic detection of registration errors secondary to patient movement, and direct intraoperative feedback to the surgeon via the navigation display a closed-loop quality assurance mechanism absent from earlier standalone robotic systems (Table 2).

Artificial intelligence-powered planning modules, such as Medtronic's Spine Guidance AI (SGAI) integrated within the Mazor X ecosystem, further enhance the capabilities of navigation-integrated systems by automating CT segmentation, proposing optimized screw trajectories based on bone density and morphology analysis, and flagging anatomical risk factors such as narrow pedicles or aberrant vascular anatomy. The Brainlab Spine & Trauma navigation system, integrated with the Cirq robotic positioning system, represents another navigation-integrated platform cleared for clinical use in Europe and gaining traction internationally (Dea et al., 2016). These fully integrated ecosystems represent the current technological frontier, and their continued evolution incorporating augmented reality visualization, enhanced haptic feedback, and machine learning-driven outcome prediction will define the next generation of robotic spinal surgery (Bertelsen et al., 2013).

3.4 Emerging and Experimental Platforms

Beyond established commercial platforms, a diverse landscape of experimental and early-commercial robotic systems continues to emerge from academic engineering programs and medtech startups. Spine robotic systems under investigation include cable-driven parallel robots offering enhanced force transparency, continuum robots designed for delivery through natural orifices or cannulas, and cooperative control systems that physically couple the surgeon's hand to a robotic assistant, enabling tremor filtering and force scaling(Bertelsen et al., 2013). The Vicarious Surgical platform, though primarily developed for general surgery, exemplifies the broader miniaturization trend toward millimeter-scale robotic manipulators that may ultimately enable endoscopic or percutaneous spinal procedures with degrees of dexterity currently unachievable with rigid instrumentation. Soft-robotic approaches, in which compliant, pneumatically actuated structures conform to anatomical constraints without imposing rigid forces on delicate neural and vascular structures, are also under active investigation for applications in spinal canal decompression and intradural surgery. Machine learning algorithms trained on large imaging datasets are being developed to enable robotic systems to autonomously identify safe corridors between critical structures, predict optimal bone purchase trajectories, and adapt intraoperatively to unexpected anatomical variations capabilities that would meaningfully reduce dependence on preoperative planning accuracy. While the majority of these technologies remain in preclinical or early-phase clinical investigation, their development trajectory points to a future in which the robotic spine surgery landscape of 2030 will differ substantially from today's environment.

Table 2. Comparative Characteristics of Contemporary Robotic Systems in Spine Surgery

Robotic system	Mounting Type	Tracking method	Arm kinematics	Unique features
Mazor X Stealth Edition	Bed-mounted.	Optical (StealthStation navigation).	Serial arm.	Enables 3D volumetric mapping for collision avoidance (Pham & Brown, 2025)
ExcelsiusGPS	Floor-mounted.	Optical (integrated GPS navigation).	Serial arm.	Incorporates active skive detection and facilitates direct screw insertion without K-wires (Ong et al., 2022).
ROSA ONE Spine	Floor-mounted.	Stereoscopic optical tracking.	Serial arm.	Demonstrates high adaptability across both neurosurgical and orthopaedic applications (Łajczak et al., 2024)
Cirq (Brainlab)	Table-mounted.	Optical tracking.	Compact serial arm.	Modular architecture compatible with Brainlab navigation (Terry et al., 2024)

4. TECHNOLOGICAL COMPONENTS AND WORKING PRINCIPLES

4.1 Robotic Arm Architecture and Kinematics

The mechanical architecture of robotic arms used in spine surgery must satisfy demanding and often contradictory design constraints: sufficient stiffness to maintain submillimeter positional accuracy under the loads imposed by surgical instruments; adequate compliance to prevent tissue injury if the arm encounters unexpected resistance; and a compact form factor compatible with the limited access imposed by sterile draping, surgical lighting, and the operating team's spatial requirements (Shoham et al., 2003). Contemporary spine robotic arms employ serial or parallel kinematic chains with five or six degrees of freedom, configured to provide sufficient workspace coverage for the thoracolumbar spine while maintaining the high structural stiffness necessary for accurate trajectory maintenance (Bertelsen et al., 2013).

The Mazor X system employs a parallel robotic architecture specifically a Stewart platform variant that provides inherently high stiffness and load-bearing capacity relative to its compact dimensions, enabling the arm to resist deflection under the forces generated by drilling and tapping without requiring a bulky, heavy structure (Pham & Brown, 2025). In contrast, ROSA Spine and ExcelsiusGPS employ serial six-degree-of-freedom arms resembling industrial robots, which offer greater workspace flexibility and ease of programming but require more sophisticated stiffness compensation algorithms to maintain equivalent positional accuracy (Lonjon et al., 2016). Actuator technologies in current systems include brushless DC motors with harmonic drive gear reducers chosen for their low backlash, high gear ratio, and compact form in combination with position encoders providing angular resolution better than 0.001 degrees (Shoham et al., 2003).

4.2 Imaging Modalities and Registration

Accurate registration the mathematical transformation that relates the robot's coordinate system to the patient's anatomical coordinate system is the fundamental prerequisite for all robot-guided surgical interventions and represents the greatest technical vulnerability of current systems (Foley & Smith, 1996; Nolte et al., 1995). Registration accuracy directly determines the clinical accuracy of the guided procedure; a registration error of 1 mm translates to an equivalent displacement of the robot-guided instrument relative to planned position. Contemporary robotic spine systems achieve registration via one of three primary modalities: paired-point fluoroscopy, in which the robot's planned trajectories are matched to intraoperative AP and lateral fluoroscopic images through automated or user-guided landmark identification; volumetric CT matching, in which preoperative CT data is registered to intraoperative CT or cone-beam CT (CBCT) via automated image-based registration algorithms; and surface-based registration, in which a tracked pointer or scanner maps the exposed anatomical surface to the corresponding preoperative CT surface mesh (Devito et al., 2010).

Intraoperative CT, most commonly acquired via the Medtronic O-arm or Ziehm Vision FD Vario 3D systems, has become the gold standard imaging modality for robotic spine surgery registration due to its superior soft-tissue contrast, 3D volumetric data acquisition, and capability for automatic image-based registration without manual landmark identification (Siddiqui et al., 2019; Fan et al., 2021). The O-arm system acquires a 360-degree acquisition in approximately 13 seconds with a radiation dose approximately equivalent to 3–5 conventional fluoroscopic images, generating volumetric data that is automatically transferred to the robotic navigation software for registration. Post-registration accuracy verification using tracked reference probes has demonstrated mean registration errors of 0.5–0.8 mm for CT-based registration, well within the ≤1.0 mm threshold generally considered adequate for accurate pedicle screw guidance (Siddiqui et al., 2018).

4.3 Navigation and Tracking Systems

Optical infrared tracking, employing passive retroreflective spheres or active infrared-emitting diodes mounted on rigid reference arrays, is the dominant tracking modality in contemporary robotic spine surgery (Foley & Smith, 1996). Infrared cameras typically arranged in a stereo configuration with baselines of 40–60 cm triangulate the three-dimensional position of tracked markers with submillimeter accuracy over a working volume of approximately 1 m^3, sufficient to encompass the robotic arm, surgical instruments, and patient reference arrays simultaneously (Taylor & Stoianovici, 2003). The Medtronic StealthStation S8 system, integrated with the Mazor X Stealth Edition, provides optical tracking with a mean tool tip error of less than 0.7 mm, which when combined with the robotic arm's positional repeatability of ±0.1 mm, yields a system accuracy budget adequate for safe pedicle screw guidance in pedicles as narrow as 5 mm (Siddiqui et al., 2018).

Electromagnetic (EM) tracking represents an alternative to optical systems, offering the ability to track instruments inside tubular structures such as cannulas without requiring direct line of sight to the camera. EM tracking systems employ a localizer generating a precisely characterized magnetic field, within which miniature sensor coils embedded in tracked instruments report their position and orientation. While EM tracking is extensively used in bronchoscopy, endoscopy, and vascular interventions, its clinical adoption in spine robotics has been limited by susceptibility to ferromagnetic interference from surgical instruments, implants, and operating room equipment, as well as by lower positional accuracy compared to optical systems in the open working environment of spinal surgery (Hummel et al., 2006). Hybrid optical-EM systems that leverage the complementary strengths of each modality are an active area of research but have not yet achieved widespread clinical adoption.

4.4 Preoperative Planning Software

Sophisticated preoperative planning software is an essential and increasingly sophisticated component of contemporary robotic spine surgery platforms, transforming segmented CT data into actionable surgical plans that define implant type, size, position, and trajectory for each vertebral level to be instrumented. Planning platforms such as the Mazor X's Brain software, ExcelsiusGPS's Accuimage planning system, and ROSA's integrated planning module present the surgeon with multiplanar CT reconstructions, 3D vertebral renderings, and automated candidate trajectory suggestions based on pedicle morphology analysis. The surgeon reviews and modifies these proposals based on clinical judgment, adjusting entry points and angles to optimize bone purchase, minimize risk of cortical breach, and accommodate individual anatomical variations (Devito et al., 2010).

Artificial intelligence is progressively augmenting the planning workflow, with deep learning algorithms trained on large annotated CT datasets capable of automating vertebral segmentation, pedicle identification, and trajectory optimization with accuracy approaching that of experienced surgeons. Medtronic's Spine Guidance AI module, integrated within the Mazor X Stealth ecosystem, employs convolutional neural network architectures to automatically segment each vertebra, identify the pedicle isthmus, and propose trajectories optimized for maximal pedicle fill ratio while maintaining safe margins from cortical walls. Studies comparing AI-proposed versus surgeon-planned trajectories in simulation environments have demonstrated equivalent or superior accuracy for the AI system across the majority of vertebral levels, with particular advantages in severely deformed or previously operated spines where anatomical distortion challenges manual planning (Siccoli et al., 2019).

4.5 Intraoperative Control and Safety Systems

Robotic spine systems incorporate multiple layers of hardware and software safety mechanisms designed to prevent unintended motion that could injure adjacent neural or vascular structures. Hardware safety measures include torque sensors at each joint that detect unexpected resistance indicative of contact with unintended tissue, triggering automatic arm retraction; electromagnetic brakes that rigidly lock the arm in its current position within milliseconds of any loss of system integrity; and position and velocity limits enforced by dedicated safety monitoring microcontrollers that operate independently of the main control computer (Shoham et al., 2003; Taylor & Stoianovici, 2003). Software safety mechanisms include virtual fixtures or forbidden zone constraints that prevent the robot from moving into user-defined exclusion volumes surrounding critical anatomy, trajectory monitoring algorithms that continuously compare planned versus actual arm position and halt motion if deviations exceed predefined thresholds, and patient motion detection routines that compare real-time tracking data from the vertebral reference array to expected position and trigger re-registration prompts if movement is detected.

Force feedback and haptic rendering represent an important but currently underdeveloped dimension of robotic spine surgery safety. Current clinical systems provide limited haptic feedback beyond the mechanical resistance of the robotic arm itself; the surgeon cannot 'feel' through the robot the tactile cues of cortical breakthrough, nerve root contact, or vessel encounter that experienced surgeons rely upon during freehand instrumentation. Active research in haptic rendering algorithms and compact force-torque sensor integration aims to restore this sensory channel in robotic surgery, translating instrument-tissue interaction forces into scaled haptic feedback delivered to the surgeon's hand through a master controller or instrumented handle.

Clinical implementations of meaningful haptic feedback in commercial spine robotic systems are anticipated within the next decade. This expectation is driven by continued improvements in sensor miniaturization and control bandwidth.

5. INDICATIONS AND APPLICATIONS IN SPINE SURGERY

5.1 Pedicle Screw Placement

Pedicle screw fixation remains the most common and best-studied use of robotic guidance in spine surgery. This procedure involves placing screws through the pedicle and into the vertebral body to create a rigid spinal construct (Tian et al., 2011b). The pedicle itself is a narrow bony channel. Its diameter typically ranges from 5 to 15 mm depending on spinal level and patient anatomy. The pedicle is bounded on its superior and inferior sides by nerve roots. The medial border lies next to the spinal cord or cauda equina. The anterior border faces the aorta or vena cava. A cortical breach during screw placement can cause neural injury, cerebrospinal fluid leak, vascular damage, or construct failure. Accurate trajectory guidance is therefore critically important. Robotic assistance is ideally suited for this role (Hicks et al., 2010b). Multiple systematic reviews and meta-analyses have shown that robotic-guided screw placement achieves significantly higher accuracy than freehand or fluoroscopy-guided methods.

5.2 Degenerative Spine Disease

Degenerative lumbar spine disease represents the largest volume indication for robotic-assisted spine surgery. This category includes disc herniation, spinal stenosis, spondylolisthesis, and adjacent segment disease. The high prevalence of these conditions explains much of this volume. In addition, instrumented fusion plays a well-established role in their definitive surgical management (D'Souza et al., 2019b; Peng et al., 2020b). Robotic-assisted transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF) have been evaluated in multiple comparative studies. These studies have demonstrated several benefits. After the learning curve, operative time is reduced. Pedicle screw accuracy is equivalent or superior. Radiation exposure to both the patient and surgical team is significantly lower. Functional outcomes are comparable or improved relative to conventional techniques (Urakov et al., 2017). The minimally invasive approach to lumbar fusion is particularly well suited to robotic guidance. Reduced visualization in MIS TLIF amplifies the value of robotic trajectory confirmation. Multiple series have documented accuracy rates exceeding 95% for robotic MIS TLIF pedicle screws. This compares favorably to 83–91% for freehand MIS techniques (Peng et al., 2020a; Urakov et al., 2017).

6. CHALLENGES AND LIMITATIONS

Robotic spine surgery faces substantial economic and technical barriers despite its clinical advantages. Capital costs range from 500,000 to 2,000,000 per system, with an additional 500 - 1,500 in disposable expenses per case. Cost-effectiveness analyses demonstrate that robotic guidance is economically justifiable only at high-volume centers exceeding 250 cases annually, below which fixed capital costs cannot be adequately amortized. Registration errors represent the most critical technical limitation, arising from patient movement, inadequate bone clamp fixation in osteoporotic patients, line-of-sight interruption to tracking cameras, or imaging artifacts from metallic hardware. Such errors can produce trajectory deviations of several millimeters, potentially breaching pedicle walls or approaching neurovascular structures. Contemporary safeguards including continuous position monitoring and mandatory verification steps are not infallible, particularly at small thoracic pedicles where even 1 mm of registration error may prove hazardous. Intraoperative CT acquisition delivers 2–4 mSv per scan, with cumulative doses reaching 8–16 mSv across planning, registration, and confirmatory imaging. Paradoxically, robotic guidance often reduces total fluoroscopy time compared to conventional techniques, as a single CT acquisition substitutes for repeated fluoroscopic checks.

The learning curve extends operative time by 30–60 minutes per case during program implementation, increasing anesthesia exposure and operating room costs. Structured training programs and dedicated robotic nursing staff are necessary to minimize this effect. Physical footprint constraints create spatial conflicts in smaller operating suites where robotic carts, navigation towers, CT systems, and standard equipment compete for limited space. Soft-tissue navigation remains limited, as current systems excel at bone-targeted guidance but provide no real-time visualization of thecal sac, nerve roots, or paraspinal vessels, since preoperative CT does not reflect intraoperative tissue displacement from retraction or cerebrospinal fluid egress. AI integration introduces additional concerns, including performance degradation from distribution shift, model opacity that complicates surgeon oversight, data governance issues surrounding patient imaging datasets, and evolving regulatory frameworks for adaptive algorithms. Addressing these challenges requires institutional commitment to training programs, achievement of volume thresholds for economic viability, and continued technological innovation in system design, deformable registration, and AI transparency.

7. CONCLUSION

Robotic-assisted spine surgery has evolved from an experimental technology to a clinically validated modality with documented advantages in pedicle screw accuracy, radiation reduction, and revision rates. However, significant barriers including high costs, steep learning curves, spatial constraints, and limited soft-tissue navigation must be addressed before universal adoption can be achieved. Future innovations in augmented reality, haptic feedback, and autonomous execution promise to further expand the scope and safety of robotic guidance. Ultimately, the surgical community bears the responsibility to critically evaluate and judiciously implement these technologies, ensuring that robotic precision translates into tangible, lasting benefit for the hundreds of millions of patients worldwide suffering from debilitating spinal disorders.

Declaration

Author Contributions

N.P & F.A written and revised the whole manuscript.

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Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

Ethical Approval

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Data Availability Statement

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