Robotic-Assisted Surgery: State-of-the-Art Development, Clinical Challenges, and Future Directions

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Abstract: Surgical robots, as an advanced integration of artificial intelligence, precision engineering, and biomedical technology, have gained widespread adoption in modern clinical practice. This paper provides a comprehensive review of the current advancements, challenges, and future trends in surgical robotics across multiple specialties, including laparoscopic, orthopedic, neurosurgical, cardiovascular interventional, and puncture robots. While robotic systems have demonstrated superior precision, minimal invasiveness, and improved clinical outcomes compared to traditional methods, significant challenges remain, such as high costs, limited haptic feedback, and technical complexities in certain procedures. For instance, the Da Vinci system has revolutionized minimally invasive surgery but faces economic sustainability issues. Future directions emphasize AI-enhanced preoperative planning, multi-modal imaging fusion, miniaturization, and 5G-enabled remote surgery, which promise to further refine robotic precision, expand accessibility, and optimize surgical workflows. By analyzing these developments, this paper aims to offer valuable insights for researchers and industry stakeholders, facilitating the evolution of surgical robotics toward greater intelligence, affordability, and clinical efficacy.

1 INTRODUCTION

With the continuous advancement of clinical medicine, surgical robots have become increasingly mature in multidisciplinary clinical applications. They are now widely utilized in procedures such as hysterectomy, prostatectomy, lobectomy, and spinal pedicle screw implantation, demonstrating clinical outcomes comparable to or even superior to traditional surgery, particularly in complex operations where they exhibit higher precision and safety (Neis et al., 2024, Ping et al., 2024, Xue et al., 2024). Undoubtedly, as a product of the deep integration of artificial intelligence, precision engineering, and biomedical technology, surgical robots are driving modern surgical practices into a new era of intelligence and precision. Recent breakthroughs in 5G remote control, augmented reality (AR) navigation, and autonomous decision-making algorithms have further expanded their application scope, covering specialized fields such as general surgery, orthopedics, neurosurgery, and even vascular interventions. However, these surgical robots also faces numerous challenges, including high costs leading to poor economic accessibility, low cost-effectiveness, and unsustainable economic models. Investigating the current status and trends in this field, as well as analyzing key bottlenecks in clinical translation, will contribute to enhancing the efficacy of surgical robots and better serving public healthcare.

This paper aims to provide a comprehensive analysis and overview of the current developments, challenges, and future trends in laparoscopic surgical robots, orthopedic surgical robots, neurosurgical robots, cardiovascular interventional robots, and puncture robots, with the goal of offering multidimensional insights for scientific research and industrial advancement in the field of medical robotics.

2 LAPAROSCOPIC SURGICAL ROBOTS

Laparoscopic surgical robots represent an advanced medical device that integrates traditional laparoscopic

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techniques with robotic technology, aiming to enhance surgical precision, flexibility, and safety. The fundamental principle involves performing minimally invasive surgery through remotely operated robotic arms, reducing surgeon hand fatigue and surgical trauma while providing clearer three-dimensional visualization and more stable instrument control. Typically, a laparoscopic surgical robot system consists of a master console, slave devices, and surgical instruments. The master console allows surgeons to remotely control the robotic arms via joysticks or foot pedals, while the slave devices include multi-degree-of-freedom robotic arms and an endoscope for precise instrument manipulation and real-time imaging.

2.1 Thoracic Laparoscopic Robot

In thoracic surgery, robot-assisted thoracoscopic surgery (RATS) is increasingly becoming mainstream in lung cancer treatment. The PORTaL study (n=6,646 cases) demonstrated that robotic lobectomy outperformed conventional thoracoscopic surgery in terms of intraoperative blood loss, number of lymph nodes dissected, and postoperative complication rates, highlighting its feasibility and safety (Lee et al., 2024). Single-port robotic lobectomy (SP-RATS) has shown low postoperative complication rates (e.g., median hospital stay of 3 days and a conversion-to-thoracotomy rate of only 0.8%) in treating large tumors (such as NSCLC with diameters >5 cm), making it a viable alternative in select cases and for experienced surgeons (Lee et al., 2024). The RAVAL trial further confirmed that the robot-assisted group exhibited lower postoperative pain scores and shorter hospital stays (average reduction of 1.5 days) in early-stage lung cancer treatment (Lee et al., 2024).

In mediastinal tumor resection, particularly for complex anterior and posterior mediastinal lesions, robotic systems demonstrate significant advantages. Single-port robotic technology reduces postoperative trauma through high-precision maneuvers, leading to shorter recovery times and decreased analgesic requirements. This approach enables bilateral visualization, particularly in identifying the left phrenic nerve, while the flexibility of robotic wristed instruments and adjustable cameras enhances surgical safety and efficiency (Manolache et al., 2023). The robotic 3D visualization and articulating instruments facilitate systematic lymph node dissection (e.g., mediastinal lymph nodes), significantly increasing the average number of lymph nodes retrieved (≥10 stations) and reducing the risk of missed lesions (Cerfolio et al., 2017).

Regarding improvements in robotic arm precision and flexibility, the da Vinci Xi system exemplifies advancements. Compared to the Si system, all Xi instruments feature extended arm lengths, while the inter-arm distance can be reduced from 6 cm (Si) to 8 cm (Xi). An additional joint (patient clearance joint) allows the arms to rotate away from the patient's body or other arms, minimizing collisions and enhancing maneuverability. Furthermore, as shown in Fig. 1, the Xi platform incorporates a laser alignment system and an integrated stapler, further improving surgical accuracy and safety (Ricciardi et al., 2017).

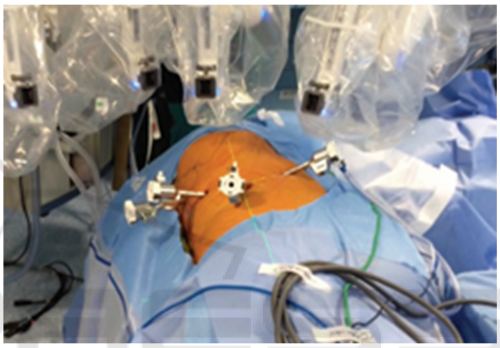


Figure 1: Xi surgical cart positioning: laser crossair (Ricciardi et al., 2017).

2.2 Gynecological Laparoscopic Robot

Compared to traditional gynecological surgery, robot-assisted surgery demonstrates superior precision and safety in gynecologic oncology. The latest Xi Da Vinci surgical system incorporates a four-arm architecture, Firefly™ fluorescence imaging (for real-time tissue perfusion assessment), and an optimized port placement strategy, significantly improving accessibility in deep pelvic dissection (Matsuura et al., 2024). Its enhanced targeting system minimizes arm collision risks, facilitating complex procedures such as lymphadenectomy in ovarian cancer with greater efficiency (Settnes & Topsoee, 2015).

In benign gynecological surgeries, including ovarian cystectomy, the Senhance® robotic system has gained widespread adoption. By integrating haptic feedback and eye-tracking technology, it achieves comparable efficacy to conventional laparoscopy while reducing surgeon fatigue. Unlike the Da Vinci® system, Senhance® employs reusable instruments, allowing surgeons to leverage their laparoscopic expertise more effectively and addressing some limitations of the Da Vinci® platform (Šiaulys, 2019).

China's domestically developed "MicroHand S" robotic system has also seen preliminary applications in gynecology. Featuring 7-degree-of-freedom instruments and 3D visualization, it has been successfully used in single-port laparoscopic ovarian cystectomy, with costs over 30% lower than imported systems (Šiaulys, 2019).

Additionally, Medtronic's HUGO™ RAS system, a newly launched robotic-assisted surgery platform, has demonstrated its capability in cadaveric gynecological studies. The system efficiently performed various surgical tasks—including retraction, cutting, coagulation, and dissection—across different anatomical regions without technical complications. Its customizable docking configuration allows adaptation to complex pelvic surgeries, such as radical ovarian cancer resection (Alletti et al., 2022).

3 UROLOGICAL LAPAROSCOPIC ROBOT

Robot-assisted surgery has been widely adopted in various urological procedures, including pyeloureterectomy, adrenal tumor resection, lymph node dissection, and radical laparoscopic lymphadenectomy for nonseminomatous testicular cancer. These robotic techniques enhance surgical precision and safety while minimizing trauma and shortening recovery time (Autorino & Porpiglia, 2020).

Recent advancements in intraoperative imaging have achieved significant breakthroughs. Indocyanine green (ICG) labeling of vascular and lymphatic systems substantially improves intraoperative visualization of anatomical structures. In robot-assisted partial nephrectomy (RPN), near-infrared fluorescence (NIRF) imaging enables precise identification of renal artery branches, reducing intraoperative bleeding risks. The combination of ICG and NIRF enhances landmark recognition, facilitates complex reconstruction, and improves oncological outcomes (Cacciamani et al., 2020).

Further integration of intraoperative ultrasound and 3D modeling enables real-time surgical navigation. For instance, the NeuroSAFE technique (nerve-sparing frozen section analysis during robotic prostatectomy) combines frozen-section pathology and augmented reality (AR) guidance to optimize nerve-sparing surgery (NSS) in radical prostatectomy (RP). Studies demonstrate that NeuroSAFE increases the number of patients eligible for NSS without compromising surgical margin status or biochemical recurrence (BCR) rates (van der Slot et al., 2022).

Artificial intelligence (AI) integration in robotic surgery demonstrates significant advancements across the surgical workflow. For preoperative planning, deep learning techniques enable automated analysis of CT and MRI images to identify and segment critical anatomical structures including tumors, blood vessels, and organs. During intraoperative navigation, the combination of robotic systems with deep learning algorithms facilitates real-time tracking of surgical instruments and internal organs, ensuring surgical precision. Machine learning models further analyze intraoperative data to provide real-time decision support regarding optimal resection paths and avoidance of critical structures. Postoperatively, deep learning technology automates image analysis to evaluate surgical outcomes, assessing tumor resection completeness and residual lesions (Bellos et al., 2024).

4 ORTHOPEDIC SURGICAL ROBOTS

Orthopedic surgical robots represent a technological platform that integrates robotic arms, navigation systems, and artificial intelligence assistance to achieve precise bone positioning, implant placement, and minimally invasive procedures. The core value lies in surpassing the limitations of manual operations while enhancing surgical standardization and reproducibility. Through advancements in navigation accuracy, AI integration, and robotic arm flexibility, these systems have significantly improved clinical outcomes in hip/knee arthroplasty and spinal surgeries.

The Stryker Mako system utilizes CT scans to generate patient-specific 3D bone models, combined with haptic feedback-enabled robotic arms, reducing acetabular cup positioning errors to within 1°. By integrating 3D preoperative planning with intraoperative robotic assistance, surgeons benefit from real-time feedback to ensure accurate acetabular cup placement and leg length restoration. The system merges preoperative planning with robotic execution, allowing surgeons to prepare the acetabulum and precisely position the cup using a handheld robotic arm, minimizing complications (Ram et al., 2023).

A flexible drilling system developed by the University of Hamburg enables curved femoral milling in total hip arthroplasty (THA). The experimental team tested the integrated system—comprising mechanical assembly, embedded position sensing, optical tracking, and navigation—on sawbone models. Results demonstrated milling boundary accuracy of 75.232% within ±1SD and 93.924% within ±2SD, confirming its capability to perform curved-path milling in femurs, addressing challenges posed by complex anatomy inaccessible to rigid tools (Fujad et al., 2018).

Figure 2: “Tuoshou” Robotic base station (A), optical tracking system (B), and toolset (C) (Chang, J., et al., 2022).

Nanjing Tuoshou Medical’s high-precision surgical robot, "Tuoshou," employs deep learning algorithms to intraoperatively identify bone landmarks in real time, reducing registration duration. As shown in Fig.2, The robot consists of a robotic base station, an optical tracking system (OTS), and a toolset for navigation and positioning, together with surgical navigation and positioning software. In a multicenter randomized controlled trial comparing thoracolumbar pedicle screw fixation with the TiRobot system, safety assessments revealed no significant differences in operative time, instrument success rate, technical success rate, or procedural success rate. However, the Tuoshou group exhibited smaller K-wire placement deviations and higher pedicle screw accuracy than the TiRobot group, demonstrating superior precision and reduced invasiveness for spinal applications (Chang et al. 2022, Gandhi, 2023).

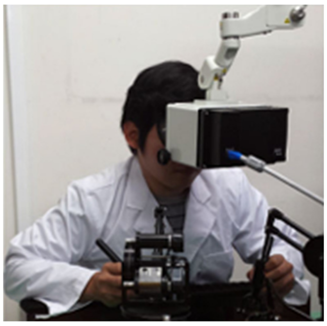
5 NEUROSURGICAL ROBOTS

Neurosurgical robotic systems represent an advanced integration of robotic arms, image-guided navigation, and artificial intelligence, designed to enhance procedural safety through precise positioning and stabilized operation. Recent breakthroughs in this field focus on three key areas: frameless high-precision localization, flexible miniaturized designs, and multimodal image fusion.

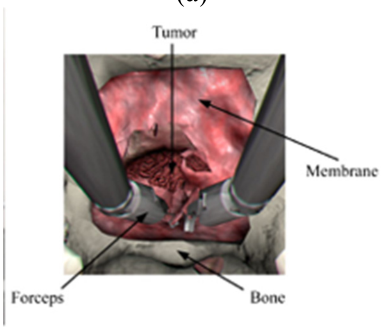
Kim et al. developed an MRI-compatible continuum robot capable of navigating narrow anatomical pathways to access deep brain regions while minimizing collateral tissue damage. Utilizing smart materials (e.g., McKibben pneumatic artificial muscles), these robots achieve high-precision bending and extension, adapting to intricate intracranial environments (Gandhi, 2023). Advances in soft robotics have further expanded neurosurgical applications, with researchers implementing sliding mode control for stretchable soft robotic modules to improve motion accuracy and response speed, thereby enhancing stability in dynamic brain tissue (Gandhi, 2023).

For multimodal image fusion, the ROSA One system employs 3D structured light technology to achieve submillimeter registration accuracy. By integrating real-time imaging updates to compensate for brain shift caused by cerebrospinal fluid loss, it addresses localization inaccuracies inherent in conventional navigation (Zhou et al., 2023). Modern deep learning models can predict tumor margins and vascular distribution, enabling robotic systems to optimize surgical trajectories. The CyberKnife system, leveraging AI-driven respiratory synchronization, maintains 0.5 mm targeting precision in spinal radiosurgery (Eljamel, 2008).

Additionally, neurosurgical robots are being integrated with virtual reality (VR) simulation platforms. As shown in Fig.3, the Lindbergh surgical rehearsal system allows surgeons to train for complex procedures in a virtual environment, shortening the learning curve. A collaborative effort between Mexico’s National Autonomous University and the University of Tokyo introduced an interactive VR simulator for transsphenoidal tumor resection. Its dynamic motion scaling (DMS) feature refines fine motor control near target areas, reducing healthy tissue damage. Although this approach increases operative time, it significantly improves safety (Heredia-Pérez et al., 2019).



(a)



(b)

Figure 3: Interactive VR simulator for transsphenoidal tumor resection (Heredia-Pérez et al., 2019). (a) User interacting with the simulator through two haptic interfaces and a stereo-monitor; (b) screenshot of the simulation indicating virtual components

6 CARDIOVASCULAR INTERVENTIONAL ROBOTS

Cardiovascular surgical robotics is a technology that utilizes robotic systems to assist surgeons in performing minimally invasive procedures on the heart and blood vessels. Its core lies in integrating three-dimensional high-definition imaging, multi-degree-of-freedom robotic arms, and remote control technologies to overcome the physical limitations of traditional surgery. In recent years, key technological innovations have been achieved in structural design and material advancements, AI-assisted instrument tracking, as well as force feedback and operational precision.

The third-generation robotic system, co-developed by Beijing Institute of Technology and Kagawa University, employs dual linear sliding mechanisms to enable simultaneous delivery of catheters and guidewires. Equipped with advanced force-sensing capabilities, the system supports coordinated manipulation of catheters and guidewires, surpassing human surgeons in performance and enabling more intricate and complex surgical procedures (Zhao et al., 2022).

A convolutional neural network (CNN)-based cross-frame real-time recognition model has demonstrated high accuracy and stability in tracking and localizing surgical instruments. Specifically, the model exhibits a low RMSE value, indicating minimal positioning error, while its high AUC value confirms superior accuracy in distinguishing different instrument states, thereby replacing traditional manual assessment (Zhang et al., 2024).

Meta's Segment Anything Model (SAM), trained on over 110 million medical images, achieves zero-shot transfer learning for segmentation tasks, adapting to novel image distributions while matching the performance of fully supervised models. Users can guide the model via various prompts—such as clicks, bounding boxes, or text descriptions—to facilitate target segmentation. The optimized SAM operates efficiently in real-time environments, making it suitable for time-sensitive applications (Zhang et al., 2024).

Researchers from the Medical Robotics and Micro-Nano Devices Research Center at the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, have designed and developed a compact 2-degree-of-freedom (2-DOF) robotic catheter system. By employing long short-term memory (LSTM) and gated recurrent unit (GRU) networks, the system predicts the slave robot's position and computes appropriate compensation values. Simulation studies in CoppeliaSim and physical experiments validate the effectiveness of the neural network controller. Results demonstrate that the controller significantly enhances master-slave position tracking while minimizing positional errors, contributing to autonomous navigation and improved patient safety (Ricciardi et al., 2017).

7 PUNCTURE ROBOTS

Puncture robots are automated medical devices typically composed of robotic arms, sensors, control systems, and image-guidance modules. They are designed to perform precise and navigated puncture procedures on targeted tissues or organs within the patient's body. The robotic arm executes the puncture operation, while integrated sensors provide real-time monitoring of needle position and orientation to ensure procedural accuracy. The control system utilizes image-processing algorithms to determine optimal puncture trajectories and guides the robot in performing highly precise maneuvers. Due to their ability to enhance surgical precision, reduce physician radiation exposure, minimize patient discomfort, and alleviate clinician workload, these robotic systems are widely adopted in interventional radiology, oncology, and ultrasonography.

7.1 Interventional Radiology Puncture Robot

Interventional radiology puncture robots integrate robotic arms and control systems with advanced imaging modalities such as CT, MRI, and ultrasound to perform a variety of clinical functions, including biopsy, ablation therapy, injection therapy, and neurointerventions. These robotic systems have been widely adopted in vascular interventions, particularly in coronary, peripheral, and neurovascular procedures. Commercial platforms such as the CorPath GRX and Magellan Robotic System leverage remote-control technology to achieve precise manipulation of guidewires and catheters, significantly reducing operator fatigue while enhancing procedural stability. Studies have demonstrated that these robotic systems achieve comparable—if not superior—precision compared to manual techniques (Zhang et al., 2024).

In musculoskeletal interventions, puncture robots are extensively utilized for needle biopsies, deep brain stimulation electrode placement, and skull-base biopsies. For instance, as shown in Fig.4, in bone biopsy procedures, augmented reality (AR)-guided navigation systems enable real-time overlay of digital content onto the surgical field, substantially reducing the number of required CT scans and radiation exposure. This advancement not only minimizes patient radiation dose but also shortens procedural duration while maintaining safety and efficacy (Albano et al., 2023).

Figure 4: CT-Guided Lumbar Biopsy with AR Navigation system (Albano et al., 2023).

7.2 Oncology Puncture Robot

Oncology puncture robots represent an advanced integration of medical imaging navigation (including CT, MRI, and ultrasound) with robotic manipulator systems, designed to assist physicians in performing percutaneous biopsies, ablations, and other minimally invasive procedures with high-precision targeting and trajectory planning. By leveraging CT or MRI-based image guidance, these robotic systems achieve accurate tumor localization. Equipped with multi-degree-of-freedom robotic arms, they enable flexible needle insertion at various angles while maintaining operational stability.

During the puncture procedure, the system provides real-time visualization of needle tip position and insertion trajectory to ensure targeting accuracy. Furthermore, the robotic platform can autonomously optimize puncture paths based on patient-specific anatomical considerations, thereby avoiding critical tissues and organs. These technological advancements not only improve procedural success rates and reduce complications but also significantly decrease physicians' radiation exposure, enhancing overall operational safety (Kissler & Settmacher, 2016).

7.3 Ultrasound-Guided Puncture Robot

Ultrasound-guided puncture robots represent an advanced medical technology that integrates real-time ultrasonic imaging with robotic control systems to achieve highly accurate percutaneous procedures. These systems employ three core technological components: (1) multi-degree-of-freedom robotic positioning, (2) dynamic ultrasound image feedback, and (3) intelligent control algorithms.

In prostate cancer diagnostics, Stoianovici et al. developed an MRI-compatible robotic system for transrectal ultrasound (TRUS)-guided prostate biopsies. The system's modular design achieved submillimeter needle positioning accuracy (<1 mm), with clinical validation leading to FDA clearance. For breast interventions, Navarro-Alarcon et al. created a compact robotic system featuring ultrasonic motor actuation and Bowden cable transmission, enabling MRI-compatible remote operation with 1.29 mm targeting precision. This system's open-control architecture significantly enhanced trajectory planning flexibility for complex breast biopsy procedures (Palep, 2009).

8 DISCUSSION

Despite remarkable advancements and demonstrated innovation potential across multiple medical specialties, the widespread adoption of surgical robotic systems continues to confront significant challenges. The most prominent barrier remains the prohibitively high total cost of ownership. Taking the da Vinci Surgical System as a representative example, the initial capital expenditure encompasses not only the robotic console and associated peripherals (including specialized instruments and stereoscopic camera systems) but also installation and comprehensive training programs, with complete system configurations frequently exceeding several million dollars (Longmore et al., 2020). Furthermore, recurring operational expenses - comprising single-use disposable instruments, periodic maintenance contracts, and mandatory recalibration of reusable robotic arms - substantially increase the lifetime cost of ownership.

Within the domain of laparoscopic robotic systems, current technological limitations manifest primarily as prolonged operative durations (particularly evident in complex procedures such as pancreaticoduodenectomies) and the absence of sophisticated haptic feedback mechanisms (Kissler & Settmacher, 2016). This tactile deficiency forces surgeons to rely exclusively on visual compensation for precision control, potentially elevating the risk of iatrogenic tissue trauma (Sebastian, 2017). Emerging solutions focus on the integration of multimodal imaging fusion technologies, combining indocyanine green fluorescence imaging (e.g., Firefly technology), real-time intraoperative ultrasonography, and preoperative CT/MRI datasets to enhance surgical navigation capabilities (Li et al., 2024).

Gynecological robotic platforms face distinct technical obstacles including restricted visual fields during large myomectomy procedures and insufficient end-effector articulation degrees-of-freedom (Park et al., 2023). Next-generation systems are evolving toward precision personalized medicine through artificial intelligence-enhanced preoperative planning algorithms. Recent investigations demonstrate that AI-generated three-dimensional navigation models can automatically delineate tumor margins and vascular architecture with 92% accuracy in endometrial cancer surgeries, establishing reliable "no-fly zones" that significantly reduce ureteral injury rates (Knigin et al., 2024).

Orthopedic robotic assistance is currently constrained by substantial physical footprints (with systems like the da Vinci occupying approximately 100 cubic feet of operating room space), creating logistical challenges including cable management issues and increased infection control concerns (Qi & Liang, 2018). While device miniaturization and enhanced precision represent clear developmental trajectories, these engineering advancements may perpetuate elevated system costs. Promising research directions include the development of advanced multimodal image registration software integrating CT, MRI, and real-time ultrasound data to expand soft tissue interaction capabilities, alongside the implementation of U-Net convolutional neural networks for optimized bone metastasis identification and osteotomy path planning (Yuan et al., 2024).

Neurosurgical robotic applications confront unique material compatibility challenges, where MRI/PET hybrid imaging systems exhibit characteristic noise artifacts and spatial registration inaccuracies (Zhou et al., 2023). The impending deployment of 5G network infrastructure promises to enable real-time teleoperated procedures, allowing expert surgeons to remotely control robotic systems in underserved medical facilities while maintaining sub-millisecond latency thresholds (Zhou et al., 2023).

Cardiovascular robotic platforms, despite demonstrating measurable advantages in reduced postoperative recovery periods and decreased complication rates, continue to face fundamental technical limitations when managing extracorporeal circulation-dependent procedures such as multi-vessel coronary artery bypass grafting (Badhwar et al., 2023). Maintaining instrument stability during beating-heart operations remains particularly challenging. Anticipated technological solutions include the development of advanced force feedback systems, miniaturized instrument designs, and AI-powered decision support modules to enhance complex case adaptability (Onan, 2018).

Percutaneous robotic systems continue to face fundamental challenges in targeting accuracy. While current technologies integrating CT-based volumetric reconstruction and six-degree-of-freedom robotic positioning have achieved submillimeter precision, persistent issues including image distortion artifacts, signal noise interference, and needle tip localization uncertainty still compromise procedural reliability. To address these challenges, the field is advancing through several innovative approaches: optimizing trajectory planning algorithms via deep learning, implementing augmented reality-based real-time navigation systems, establishing robust telesurgery network infrastructure, and promoting international regulatory harmonization. The convergence of artificial intelligence and augmented reality technologies represents the most promising developmental pathway for enhancing procedural accuracy and reliability.

These synergistic technological advancements will systematically address current limitations while facilitating broader clinical adoption across surgical specialties, ultimately advancing the paradigm of precision medicine. As technological breakthroughs continue to emerge and cost-reduction strategies mature, surgical robotic systems are positioned to become indispensable components of future healthcare delivery systems, offering patients unprecedented levels of procedural safety and therapeutic accuracy.

9 CONCLUSION

Through a comprehensive evaluation of five key domains—laparoscopic, orthopedic, neurosurgical, cardiovascular interventional, and puncture robotics—surgical robotic technology has evolved from a standalone assistive tool into a sophisticated multi-disciplinary integration platform. The enhanced lymph node dissection accuracy of the da Vinci Xi system in thoracic surgery, the superior pedicle screw placement precision of the Tuoshou orthopedic robot, and the deep brain maneuverability of MRI-compatible neurosurgical robots collectively validate the substantial advantages of robotic systems in improving surgical safety and minimally invasive outcomes. Particularly in complex anatomical regions, robotic platforms incorporating fluorescence navigation and AI-based preoperative planning achieve levels of precision unattainable with conventional techniques.

Nevertheless, critical challenges persist in both technological and clinical implementation. Economically, the prohibitively high acquisition costs and substantial annual maintenance expenses limit widespread adoption. Technically, the absence of haptic feedback introduces a 29% risk of potential tissue damage in laparoscopic procedures, while the bulky footprint of orthopedic robotic systems complicates operating room logistics. Additionally, the lack of standardized training protocols necessitates an average of 80–120 procedures for surgeons to achieve proficiency, further hindering scalability. To realize the democratization of this technology, a tripartite support framework must be established: (1) Policy-level interventions to optimize reimbursement structures and pricing mechanisms; (2) Industrial advancements to accelerate domestic production of core components; (3) Clinical standardization to develop evidence-based surgical pathways. Only through such coordinated "technology-industry-clinical" synergy can the goal of accessible precision medicine be achieved, extending robotic-assisted care to grassroots medical institutions. Looking ahead, sustained technological iteration and innovative care models are poised to usher in a new era of intelligent, personalized, and equitable surgical practice.

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