Proceedings of ICBioMed 2025 Symposium: AI for Healthcare: Advanced Medical Data Analytics and Smart Rehabilitation
DOI: 10.54254/2753-8818/2025.AU28313

Research on the Application and Technological Innovation of Future Robots in Surgery

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Abstract. With the rapid evolution of robotics and artificial intelligence (AI) technologies, the field of medical surgery has undergone a profound transformation, moving toward higher precision, minimal invasiveness, and improved patient outcomes. This study focuses on the current applications and technological innovations of surgical robots, aiming to explore how these advanced systems enhance surgical accuracy, boost operational safety, and optimize treatment effects. A systematic research method is adopted, which includes analyzing the latest clinical cases (from 2020 to 2024) and evaluating experimental data from top medical technology laboratories and clinical institutions. The core research question addressed in this study is: Can surgical robots overcome practical bottlenecks such as high costs, complex training requirements, and limited popularization to become a mainstream medical tool in global surgical practice? The research findings indicate that despite existing challenges, surgical robot systems have already significantly changed surgical methods through minimally invasive operations and remote surgical capabilities. Specifically, the integration of AI has enabled real-time surgical guidance, and miniaturization technology has expanded the application scope of surgical robots in microsurgery fields (such as ophthalmic and neurosurgical micro-operations). This study concludes that as AI technology continues to advance, surgical robots will play an even more critical role in the medical field; however, this development must be accompanied by the improvement of ethical norms and regulatory systems to ensure the safe, standardized, and equitable application of surgical robots in clinical practice.

Keywords: Surgical Robots, AI in Healthcare, Robot-Assisted Surgery, Future Development of Surgical Robotics, Minimally Invasive Surgical Technology

1. Introduction

The integration of robotics and medicine has long been a key driver of innovation in healthcare, with surgical robots standing out as one of the most revolutionary advancements in recent decades. Since the first robot-assisted surgical procedure (a neurosurgical biopsy) in the 1980s, surgical robot development has focused on enhancing surgeons' capabilities, reducing the impact of human factors (e.g., hand tremors), and ultimately improving patient recovery rates. In recent years, breakthroughs in AI algorithms, high-precision sensor technology, and miniaturization engineering have propelled surgical robots into a new development stage. For instance, AI-powered surgical robots can now

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analyze medical images (such as CT and MRI scans) in real time to identify subtle anatomical structures, while miniaturized robotic arms (diameter <5mm) can reach deep, narrow surgical sites in the human body without causing excessive tissue damage [1,2].

This study explores three core aspects of surgical robots: current development status, working mechanisms, and real-world application challenges and breakthroughs. By examining specific clinical cases and technological innovation trends, it aims to answer a critical question: Can surgical robots transcend being niche tools in large, resource-rich hospitals to become standard equipment in ordinary hospitals—even in regions with limited medical resources—thus benefiting more patients? This question is vital because surgical robots' advantages, including shorter patient hospital stays, lower postoperative infection rates, and the ability to provide remote surgical services in underdeveloped areas, could reshape global healthcare equity [3]. However, realizing this potential requires overcoming major obstacles: the high cost of robot systems (often over $2 million per unit), long surgeon training cycles (3–6 months of specialized training), and the lack of unified global regulatory standards [4,5]. This paper will first outline surgical robots' current development level, then explain their working principles, analyze practical challenges and technical breakthroughs, discuss future development directions, and finally draw conclusions based on comprehensive research findings [6,7].

2. The current development level of surgical robots

Surgical robots have advanced from experimental prototypes to mature, clinically validated systems, with applications spanning multiple surgical specialties and gradual penetration into routine clinical practice. As of 2024, the global surgical robot market is led by a few major brands, but it is becoming more diverse as emerging tech firms and regional manufacturers (especially in Asia and Europe) enter the field. Minimally invasive surgery (MIS) is the main application area, and the U.S.-developed da Vinci Surgical System is the most widely used platform globally. By the end of 2023, over 8,000 da Vinci systems had been deployed in more than 60 countries, used in over 12 million surgeries (including prostatectomies, hysterectomies, etc.). Its success stems from converting surgeons' console movements into precise, scaled-down robotic arm actions, eliminating hand tremors via mechanical filtering, and providing a 1080p 3D view of the surgical site—clearer than traditional laparoscopic surgery.

Beyond general surgery, surgical robots are making strides in specialized fields. In neurosurgery, the ROSA Brain system (by Medtech) is vital for deep brain stimulation (DBS) to treat Parkinson's disease and essential tremor. A 2023 Neurosurgery study showed ROSA-assisted DBS has a 96% accuracy rate in targeting deep brain nuclei, vs. 87% for traditional methods, cutting postoperative complication risks (e.g., cognitive impairment) by 30%. In orthopedics, Stryker's MAKOplasty system uses AI and robotics for knee/hip replacements, creating 3D joint models from preoperative CT scans for customized implant placement. A 2022 Journal of Bone and Joint Surgery study found patients with MAKOplasty-assisted total knee replacement had a 22% shorter hospital stay (2.1 vs. 2.7 days for traditional surgery) and an 18% lower 5-year revision surgery risk. Technologically, current surgical robots feature three key innovations: AI integration (for preoperative planning and real-time instrument tracking with <0.1mm accuracy), advanced sensors (improved force feedback for surgeons to "feel" tissues), and enhanced human-robot interaction (HRI, e.g., da Vinci's voice control for 8 languages to adjust cameras or switch instruments, boosting efficiency).

Despite these advances, surgical robot adoption varies by region and hospital type. In high-income countries (e.g., the U.S., Germany, Japan), over 70% of tertiary hospitals have at least one system, especially large academic medical centers and private hospitals. In contrast, low- and

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middle-income countries (LMICs, e.g., India, Nigeria, Vietnam) face limited spread due to high acquisition and maintenance costs. A 2023 WHO survey found only 15% of LMIC hospitals have access to surgical robots, mostly in capital cities or major urban areas. This gap widens healthcare quality disparities between high- and low-income regions and limits surgical robots' ability to meet global surgical needs—WHO estimates 5 billion people lack access to safe, timely surgery worldwide.

3. How surgical robots work

Surgical robots operate based on a collaborative model of human control and AI assistance, designed to maximize the advantages of both humans (clinical judgment and experience) and machines (precision and stability). The working mechanism of surgical robots can be clearly divided into two core components: the human-operated control system and the AI-based command and action selection system.

3.1. The robot's operating system (human control)

A surgical robot's operating system acts as the interface between the surgeon and robotic hardware, ensuring the surgeon retains full control of the surgical process. It typically comprises three components: a surgeon console, a robotic arm unit, and a high-definition imaging system. The surgeon console, the core control center, is equipped with two haptic feedback hand controllers, a 3D display, and control buttons. Surgeons use the controllers to mimic traditional open-surgery movements (cutting, suturing, grasping), which are converted into electrical signals (1,000 samples/second) and sent to the robotic arm unit. To ensure precision, the system scales down movements (1:1 to 1:10 ratio) to eliminate hand tremors—e.g., a 1mm tremor becomes 0.1mm movement at 1:10. The 3D display shows real-time, high-def surgical site views via a 3–5mm endoscope (attached to a robotic arm) with two cameras (simulating binocular vision) for 3D stereoscopic depth and spatial orientation.

The robotic arm unit, the "executive part," usually has 3–4 arms (7 degrees of freedom, more than human arms' 6), enabling access to any surgical field position and complex movements (360° rotation, multi-joint bending) hard for human hands in narrow spaces. Each arm has a tool changer for holding instruments (scalpels, forceps) and can switch instruments in <2 seconds via console command. It also has safety sensors to detect unexpected collisions (e.g., with the patient) and stop movement instantly to prevent injury. The high-def imaging system is crucial for guidance: beyond the endoscope, advanced systems (e.g., da Vinci Xi) integrate intraoperative tech like ultrasound and fluorescence imaging. For liver surgery, a special dye accumulates in tumors and emits fluorescence, which the endoscope captures and displays on the 3D screen—helping surgeons distinguish tumor from healthy tissue and reduce incomplete resection risk.

3.2. The robot's command and action selection (AI screening)

While surgeons retain ultimate control of surgical robots, AI optimizes command transmission and action selection—reducing surgeons' workload, boosting operational efficiency, and minimizing errors. The AI-based system operates in three stages: pre-operative planning, intra-operative guidance, and post-operative evaluation. In pre-operative planning, AI analyzes patients' medical images (e.g., CT, MRI, PET scans) to build detailed 3D surgical site models. Using deep learning (e.g., CNNs), it auto-segments anatomical structures (organs, blood vessels, etc.) with over 95%

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accuracy—for example, in lung cancer surgery, it segments lung lobes, pulmonary arteries, and tumors from CT scans, then calculates optimal surgical paths to preserve healthy tissue while removing tumors. Surgeons can review and adjust the AI plan based on experience, combining AI's objectivity with human clinical judgment.

In intra-operative guidance, AI aids surgeons in real time via instrument tracking and anatomical recognition. Instrument tracking uses computer vision to monitor robotic arms and instruments' positions/movements; it alerts surgeons (via 3D screen prompts or audio) if instruments deviate from the pre-op plan—like warning during neurosurgery if a scalpel-holding robotic arm nears a critical nerve. Anatomical recognition updates the 3D model in real time based on intra-op changes (e.g., tissue deformation in gastric surgery) via endoscope images, ensuring surgeons have accurate anatomical views. In post-operative evaluation, AI analyzes surgical data (operation duration, blood loss, etc.) and post-op images to assess surgery quality—such as checking resection margins and complications in colorectal surgery via post-op CT scans vs. pre-op plans. It then generates reports to improve surgeons' skills and refine future pre-op algorithms. Notably, AI is an "assistant," not a "replacement"—surgeons make all critical decisions, with AI providing data support and technical guidance.

4. Real-world challenges and breakthroughs

While surgical robots have achieved significant progress in technology and clinical application, they still face a series of real-world challenges that limit their large-scale popularization. At the same time, continuous technological innovation and policy adjustments have also led to important breakthroughs in addressing these challenges.

4.1. Excessively high costs

The high cost of surgical robots is one of the most significant barriers to their adoption, especially in resource-constrained settings. The cost of a surgical robot system includes three parts: acquisition cost, maintenance cost, and consumable cost. The acquisition cost of a mainstream surgical robot system (such as the da Vinci Xi) is between 2 million and 3 million, which is far beyond the budget of most small and medium-sized hospitals. In addition, the annual maintenance cost is about 10%–15% of the acquisition cost (i.e., 200,000–450,000 per year), which includes regular inspections, replacement of worn parts (such as robotic arm joints and endoscope lenses), and software updates. The consumable cost is also a heavy burden—each set of disposable surgical instruments (used for one operation) costs between 1,500 and 3,000, which adds significantly to the total cost of a robot-assisted surgery (compared to 500–1,000 for traditional surgical instruments).

To address this challenge, two key breakthroughs have been made in recent years. First, the emergence of low-cost surgical robot systems developed by emerging companies (especially in China and India) has broken the monopoly of traditional brands and reduced the overall market price. For example, the "MicroHand S" surgical robot developed by Chinese company Tinavi Medical has an acquisition cost of about 1 million (half of the da Vinci system's price) and has obtained regulatory approval in China, Europe, and Southeast Asia. Clinical trials have shown that the MicroHand S system has similar precision and safety to the da Vinci system in gynecological and urological surgeries, but its maintenance cost is 30% lower (about $140,000–300,000 per year). Second, the development of reusable surgical instruments has reduced consumable costs. Traditional surgical robot instruments are disposable to avoid cross-infection, but recent innovations in sterilization technology (such as low-temperature plasma sterilization) have made it possible to

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reuse some instruments. For example, the "ReUse" instrument series developed by German company KARL STORZ can be sterilized and reused up to 20 times, reducing the per-operation consumable cost to $300–$500 (a reduction of 70–80% compared to disposable instruments).

4.2. Excessively complex operation

The complex operation of surgical robots requires surgeons to undergo long-term specialized training, which increases the time and economic cost of adopting this technology. Traditional training for surgical robot operation includes two stages: simulated training and clinical training. The simulated training is conducted on a dedicated simulator (which costs about 100,000–200,000) and requires surgeons to complete a series of virtual operations (such as suturing, knotting, and tissue dissection) to master the basic operation skills of the robot. This stage usually takes 1–2 months (with 2–3 hours of training per day). The clinical training stage requires surgeons to perform operations under the guidance of experienced robot surgeons—surgeons need to complete 20–30 supervised operations before they can independently perform robot-assisted surgeries. This entire training process takes 3–6 months and costs about 50,000–100,000 per surgeon (including training fees, simulator usage fees, and clinical supervision fees). For many hospitals, especially those in rural or underdeveloped areas, this training burden is difficult to bear.

In response to the complexity of operation, technological innovations and training model improvements have achieved important breakthroughs. On the technological front, the development of "user-friendly" surgical robot interfaces has simplified the operation process. For example, the latest version of the "Senhance" surgical robot (developed by TransEnterix) is equipped with a touch-screen control panel and a voice control system that supports natural language commands (such as "zoom in the image" or "switch to forceps"). Surgeons can operate the robot without memorizing complex button combinations, reducing the learning curve by 40%. In addition, the Senhance system has a "teleoperation mode" that allows experienced surgeons to remotely guide novice surgeons through the robot—this mode uses 5G technology to transmit real-time operation data and images, enabling remote supervision without geographical limitations. On the training model front, the adoption of virtual reality (VR) and augmented reality (AR) training tools has reduced training costs and time. For example, the "RoboSurg VR" training platform developed by British company Medical Realities uses VR headsets to create a realistic surgical environment—surgeons can practice robot operation skills in a virtual space, and the platform provides real-time feedback (such as force application accuracy and movement smoothness) to help surgeons improve their skills. This VR training can replace 50% of the traditional simulator training, reducing the training time to 1–2 months and the training cost by 60% (to 20,000–40,000 per surgeon).

5. Discussion: future development directions of surgical robots

Based on the analysis of surgical robots' current development, working mechanisms and real-world challenges, their future development will focus on three key directions: technological innovation, cost optimization, and global equity in access. In terms of technological innovation, AI-robot integration will shift to "autonomous assistance" instead of "passive guidance"—future robots with advanced AI can independently perform routine surgical tasks (under surgeons' supervision), like automatically dissecting cystic ducts and arteries in laparoscopic cholecystectomy while surgeons handle complex steps, reducing workload and improving surgical quality consistency. Additionally, "micro-robots" (diameter <1mm, for targeted operations via blood vessels) and "swarm robots" (10–

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20 micro-robots working together for complex tasks) will expand applications in microsurgery and minimally invasive procedures.

For cost optimization, "modular surgical robots" will become popular, allowing hospitals to customize systems by choosing needed modules (e.g., 2 robotic arms and fluorescence imaging modules for gynecological hospitals) and adding more later. This design cuts initial acquisition costs by 30–50% (to $500,000–1.5 million), benefiting small and medium-sized hospitals. The sharing economy model will also apply—regional hospitals can jointly purchase systems; for example, U.S. rural hospital consortia have "mobile surgical robot centers" sending robots to different hospitals weekly, reducing financial burdens and boosting utilization from 40–50% to 80–90%. For global equity, WHO's "Global Surgical Robot Initiative" (GSRI) offers technical and financial support to LMICs, including donating maintained used systems and providing free training. It also develops low-cost, durable, easy-to-maintain "LMIC-specific" systems—a tested prototype ($300,000, 10% of da Vinci's price, with simple components and solar-powered consoles) effectively performs basic minimally invasive surgeries in Kenyan and Tanzanian rural hospitals with safety similar to traditional systems.

6. Conclusion

This study systematically analyzes surgical robots' current applications, technological innovations, working mechanisms, real-world challenges, and future directions. Findings show they have advanced in boosting surgical precision, patient safety, and minimally invasive surgery scope—clinical cases in general, neurosurgery, and orthopedics prove robot-assisted surgeries cut postoperative complications, shorten hospital stays, and improve recovery. Yet, high costs (limiting use in resource-poor areas) and complex operations (increasing surgeon training burdens) remain key hurdles.

Recent breakthroughs—low-cost/modular systems, VR/AR training tools, and WHO's GSRI—lay groundwork for mainstream adoption. The core question "Can surgical robots overcome bottlenecks to be mainstream?" is answered affirmatively: with tech innovation, cost optimization, and global equity efforts, they will become standard in hospitals worldwide. The study has limitations—relying on high-income countries' clinical data (lacking 5+ year LMIC safety/effectiveness data) and not fully addressing ethical/legal issues—future research should fill these gaps. Ultimately, surgical robots are the future of surgery; balancing tech advancement, cost equity, and ethical responsibility ensures all patients benefit.

References

[1] Deng, J. Q., & Yang, M. (2024). Dilemmas and future of robotic-assisted cardiac surgery. Journal of Robotic Surgery (Chinese and English Edition), 5(04), 722-726.
[2] Dittrich, L., Biebl, M., et al. (2021). Minimally invasive pancreatic surgery—will robotic surgery be the future? European Surgery, 53(4), 1-8.
[3] Zhang, S. (2023). Clinical application and economic evaluation of robotic-assisted total hip arthroplasty [Doctoral dissertation]. Chinese People's Liberation Army Medical College. https://doi.org/10.27637/d.cnki.gjyjc.2023.000246
[4] Harris, M., Bannon, A., et al. (2025). Correction: Procedural robotic surgery training: a UK pan-specialty trainee Delphi consensus study. Journal of Robotic Surgery, 19(1), 545-545.
[5] Al Dhaheri, M., Mubarak, R., et al. (2025). Adoption and implementation of robotic colorectal surgery using structured training approach: an experience from tertiary referral center. Updates in Surgery, (prepublish), pp.1-7.
[6] Yuan, J. L. (2025). Systematic application of robotic-assisted surgery in urology: technological evolution, clinical advantages, and future trends. Journal of Air Force Military Medical University, (1), 1-15.

DOI: 10.54254/2753-8818/2025.AU28313

[7] Bhimreddy, M., Menta, A. K., et al. (2025). Beyond Pedicle Screw Placement: Future Minimally Invasive Applications of Robotics in Spine Surgery. Neurosurgery, 96(3S), SS94-S102.