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Recent Trends and Future Prospects of Robotic Surgery in Health Care

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Abstract

Robotic surgery has transformed modern medical procedures by integrating surgical precision with advanced technological innovation. This review traces its evolution from early robotic systems of the 1980s and 1990s to present-day platforms incorporating laparoscopy, telerobotics, artificial intelligence (AI), haptic feedback, and real-time imaging. Between 2013 and 2023, the field witnessed rapid innovation, including the development of modular, portable, single-port, and multi-arm robotic configurations tailored to diverse surgical needs. Ergonomic improvements and enhanced user interfaces have contributed to surgeon comfort, while semi-autonomous and autonomous systems, enabled by advanced path-planning algorithms, point toward a future of greater surgical autonomy. The potential of nanorobotics further expands the frontier of minimally invasive interventions. However, the rapid pace of development also raises ethical, legal, and safety concerns that must be addressed. This review highlights recent progress, current capabilities, and the future potential of robotic surgery, emphasizing its transformative impact and the interdisciplinary efforts required to ensure its responsible implementation.

Keywords: Robotic Surgery, Technological Advancements, Artificial Intelligence, Telerobotics, Haptic Feedback.

Introduction

Definition and scope of robotic surgery

In order to perform procedures with greater accuracy, control, and flexibility, surgeons employ robotic devices in robotic surgery, a minimally invasive surgical approach. Usually, these systems include a camera for vision, robotic arms, and a console where the surgeon controls the tools. Surgeons may now carry out intricate operations with more precision thanks to technology, which makes it easier to carry out delicate activities in confined areas. The capabilities and use of robotic surgery have grown over time because to developments in robotic systems, imaging technologies, and AI integration, making it a crucial component of contemporary healthcare. Urology, gynaecology, cardiothoracic surgery, neurology, spinal surgery, general surgery, and even pediatric surgery are among the many areas that are currently included in robotic surgery. Because robotic surgery offers previously unheard-of precision, less invasiveness, and better patient outcomes, it has greatly enhanced medical procedures across a range of professions. Systems like da Vinci have helped robotic prostatectomy, nephrectomy, and bladder cancer resections in urology by enabling accurate tumour removal, less blood loss, and quicker recuperation. High dexterity in limited places is essential for treating pelvic organ prolapse and urine incontinence, two conditions that these devices excel at treating. Similar to this, robotic technologies have revolutionized gynaecological surgeries, such as hysterectomy, myomectomy, endometriosis resection, and pelvic floor repairs, by facilitating smaller incisions, quicker recovery times, and better fertility-preserving techniques (1). Robotic systems like da Vinci Xi have also led to advancements in cardiothoracic surgeries, including lung resections, valve repairs, and coronary artery

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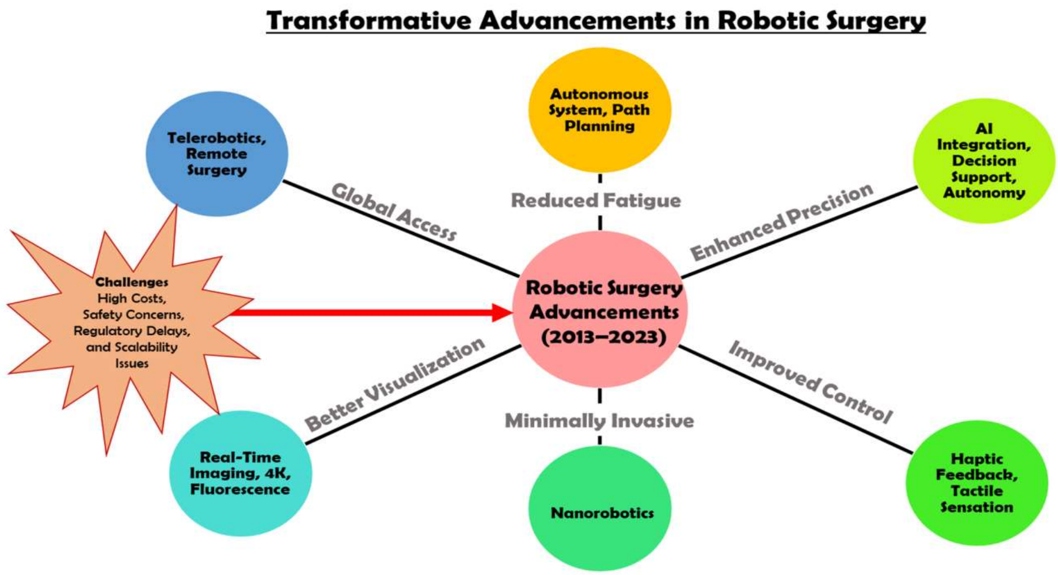

Graphical Abstract

bypass grafting. These procedures allow for less intrusive methods, which lessen trauma and improve recuperation. Real-time imaging capabilities improve the results of surgeries like lung resections for cancer treatment by enabling precise navigation across intricate circulatory and pulmonary structures (2). Platforms like ROSA have helped neurosurgery by facilitating precise procedures in deep brain stimulation, spinal surgery, and brain tumour removal (3). These systems guarantee submillimetre precision, which is essential for negotiating complex neurological networks and managing ailments like epilepsy and Parkinson's disease. With precise imaging and planning, technologies such as the Mazor Robotics Renaissance System and T-Solution One have transformed spinal fusion and deformity corrections in spinal surgery, lowering risks and enhancing recovery (4,5). Robotic platforms that provide dexterity and visualisation have improved general surgery applications, such as colorectal surgeries, gallbladder removal, hernia repair, and bariatric procedures, guaranteeing accurate resections and less invasiveness. According to Rivero-Moreno et al. (2023), these devices enhance surgeon ergonomics and lessen fatigue, particularly during extended procedures, leading to higher-quality care. Innovations in pediatric surgery have also been made possible by robotic devices, which allow for increased accuracy in confined spaces, which is essential for thoracic and paediatric urological treatments (6). The adaptability of these technologies is demonstrated by the emerging uses of robotic surgery in orthopaedic, plastic, and transplant procedures. Robotic devices increase safety and efficacy in liver transplants by improving tissue handling and suturing precision. Platforms like Mako are utilized in orthopaedics for joint replacements because they offer better implant placement precision, lower problems, and speed up patient rehabilitation (7).

Historical Advancements in Robotic Surgery (Pre-2013)

The foundations of robotic surgery were laid during the mid-20th century, driven by advancements in teleoperation systems originally developed for non-medical applications. Early military-funded research focused on creating remote manipulation technologies to safely handle hazardous

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materials, such as radioactive substances, in environments that posed significant risks to human operators. These explorations established the principles of telepresence, where operators could perform tasks remotely with precision and control—concepts that later shaped the trajectory of surgical robotics (8). A pivotal milestone occurred in 1985 with the introduction of the PUMA 560 robot, which marked the first documented instance of robotic assistance in a surgical procedure. This system, a product of industrial robotics, was employed to perform a stereotactic brain biopsy, a delicate operation requiring sub-millimetre accuracy (9). Although rudimentary by modern standards, this groundbreaking application underscored the potential of robotics to transform surgical practice and set the stage for further innovations in the field (Figure 1).

First-Generation Surgical Robots (1980s–1990s)

During the 1980s and 1990s, the development of first-generation surgical robots marked significant progress in the integration of robotics into clinical practice. One of the earliest examples, the Arthrobot, emerged in 1983 in Canada and was primarily designed for orthopaedic procedures. This system aided surgeons in the precise positioning of limbs during joint replacement surgeries, demonstrating the potential of robotic systems to enhance accuracy in complex tasks (10). Another pioneering advancement came in 1988 with the development of Probot at Imperial College London, which was specifically created for prostate surgery. Probot distinguished itself as the first fully autonomous robotic system tailored to perform a single surgical task with high precision, paving the way for task-specific robotic applications in medicine (11). In 1992, the introduction of ROBODOC represented a milestone in orthopaedic surgery. Approved for use in the United States, ROBODOC was the first robotic system designed for precise bone preparation in hip replacement surgeries. Its ability to

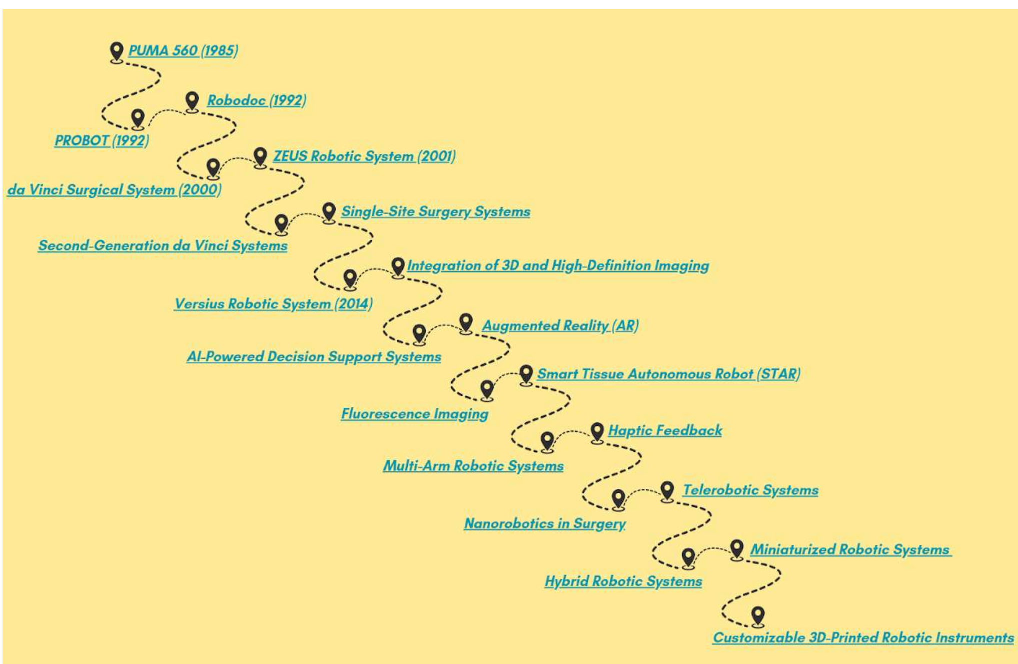

Fig. 1: Historical advancements made in the field of robotic surgery.

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perform accurate and repeatable procedures significantly minimized errors in implant placement (12,13).

Second-Generation Robots and Early Laparoscopic Integration (1990s)

Eventually, the 1990s witnessed remarkable advancements in robotic surgery, particularly with the introduction of second-generation systems and their integration into laparoscopic procedures. A notable milestone was achieved in 1994 with the development of AESOP (Automated Endoscopic System for Optimal Positioning) by Computer Motion. AESOP was the first robotic system designed to assist in minimally invasive surgeries by holding and stabilizing laparoscopic cameras under voice control (14,15). Then in 1998, Computer Motion introduced the ZEUS Robotic System, which allowed surgeons to manipulate robotic arms for laparoscopic surgeries. ZEUS featured multi-arm control and haptic feedback, providing greater precision in delicate tasks. Its capabilities were demonstrated in the ground breaking Lindbergh operation in 2001, the world's first teleoperated robotic surgery, where a surgeon in New York performed a laparoscopic cholecystectomy on a patient in Strasbourg, France, via a high-speed fibre-optic connection (16). The advent of the da Vinci Surgical System in 1999 by Intuitive Surgical marked a pivotal moment in robotic surgery. The da Vinci system introduced cutting-edge 3D high-definition imaging and articulated instruments capable of mimicking human wrist movements, offering unmatched dexterity and precision. In 2000, it became the first robotic system to receive FDA approval for general laparoscopic surgery, revolutionizing minimally invasive techniques across multiple specialities, including urology and gynecology(9). These second-generation systems laid the groundwork for modern robotic surgery by enhancing visualization, precision, and the ability to perform complex procedures remotely.

Early Clinical Applications and Innovations (2000–2010)- third generation

The period between 2000 and 2010 was marked by significant advancements and clinical applications of robotic surgery, with the da Vinci Surgical System leading the way. The da Vinci platform received FDA approvals for urology in 2001, cardiothoracic surgeries in 2004, and gynecological procedures in 2005, revolutionizing minimally invasive approaches in these fields (17). In parallel, the development of the SOCRATES System by Computer Motion in 2001 enabled telesurgery integration with the ZEUS system. This technology facilitated remote surgical procedures, allowing surgeons to operate over significant distances, thus expanding access to specialized care (18). In 2006, the Smart Tissue Autonomous Robot (STAR) emerged as a research focus, aiming to develop semi-autonomous systems capable of performing high-precision suturing on soft tissues. Although still in experimental phases at the time, STAR laid the groundwork for integrating autonomy into surgical robots (19). In 2008, the introduction of NeuroArm, the world's first MRI-compatible robotic surgical system, represented a breakthrough in neurosurgery. NeuroArm allowed surgeons to perform intricate procedures with real-time imaging, ensuring enhanced precision while operating near critical brain structures (20).

One of the key areas of focus was the integration of haptic feedback, which aimed to provide tactile sensation to surgeons operating through robotic systems. Early prototypes demonstrated the potential of haptic technology to improve control and reduce the risk of inadvertent tissue damage, addressing a major limitation of robotic surgery systems that relied heavily on visual cues (21). Another major advancement was the introduction of EndoWrist technology by the da Vinci Surgical System. This innovation mimicked the movements of the human wrist, providing instruments capable of better dexterity and

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precision in constrained surgical environments (22). Additionally, the development of multi-arm robotic systems allowed multiple surgical tasks to be performed simultaneously, significantly reducing operation times and improving efficiency in complex procedures (23). Progress in miniaturization also expanded the applicability of robotic systems, particularly in pediatric and microsurgical fields. Miniaturized tools enabled surgeons to perform delicate procedures in smaller anatomical spaces, thereby opening new avenues for robotic surgery in specialities such as neurosurgery and ophthalmology (24).

Advancements in Robotic Surgery (2013–2023)

Since 2013, significant advancements in enhanced robotic systems have revolutionized surgical procedures, improving precision, flexibility, and accessibility. These developments have focused on several core areas, including hardware upgrades, system miniaturisation, and integration with cutting-edge imaging and AI technologies.

Technological Advancements

AI Integration

Since 2013, significant advances have been made in the integration of Artificial Intelligence (AI) into robotic surgery, transforming surgical practices. The evolution of AI in this field can be categorized into several key areas: decision-support tools, predictive analytics, enhanced imaging and computer vision, and autonomous capabilities. AI-based decision-support systems have become essential tools for guiding surgeons during operations. These systems use deep learning algorithms to analyze data in real time, providing insights and suggestions that assist with complex decision-making. For example, AI can detect potential errors or complications, such as improper instrument positioning or tissue damage, and alert the surgeon, thus reducing human error. Notable systems like IBM Watson for Oncology and Intuitive Surgical's da Vinci platform have incorporated AI to enhance intraoperative accuracy and decision-making (25,26). Additionally, machine learning models have been increasingly used to analyze preoperative data, including patient demographics, medical history, imaging data, and laboratory results, to predict surgical risks and outcomes. For instance, AI can predict complications like infections or bleeding, allowing for better preoperative preparation and post-surgical management (27).

AI-driven image recognition has transformed surgical visualization by enhancing preoperative imaging (CT, MRI) and intraoperative video feeds. Advanced computer vision enables precise 3D reconstructions and identification of subtle anatomical structures, improving accuracy in minimally invasive procedures (28). One of the more futuristic developments in AI integration has been the exploration of autonomous or semi-autonomous robotic surgery. While human oversight remains essential, AI-driven robots are gradually being trained to perform certain repetitive tasks without direct human intervention. For example, AI-assisted robots have been used for suturing or tissue manipulation with increasing independence, aiming to minimize surgeon fatigue during long procedures (29). AI systems provide real-time feedback by analyzing surgical data, tracking performance metrics, and identifying areas for improvement.

Haptic Feedback and Tactile Sensation

Apart from sight, other feedback has also been extensively explored in the field of robotic surgery, for example, advancements in the field of haptic feedback and tactile sensation have dramatically enhanced the surgeon's ability to interact with tissues and perform more precise procedures. One of the most important innovations in robotic surgery since 2013 has been the integration of force feedback systems, which provide surgeons with the sense of touch, allowing them to "feel" tissue properties such as stiffness,

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texture, and resistance in real-time. Traditionally, robotic surgery systems, such as the da Vinci Surgical System, offered minimal tactile feedback, making it difficult for surgeons to assess the physical properties of tissues, such as their elasticity, resistance, or the presence of underlying structures (30). The introduction of advanced force feedback systems has begun to close this gap, enabling more natural interaction between the surgeon and the surgical site. Modern robotic platforms, such as Intuitive Surgical's da Vinci Xi and Versius, have made significant strides in incorporating force feedback into their systems. For example, da Vinci Xi has improved the sensitivity of its force feedback, allowing surgeons to detect subtle variations in tissue properties, such as changes in resistance when dissecting through different tissue layers (31). Additionally, some robotic systems now provide multi-directional force feedback, allowing surgeons to feel forces in multiple axes, which is critical for performing delicate tasks like suturing or dissecting tissue (32). Tactile feedback plays a critical role in distinguishing between different tissue types, such as muscle, fat, or tumour.

New developments in virtual force feedback technology have also made it possible for surgeons to manipulate and control robotic instruments with greater precision by providing real-time tactile cues. These systems simulate the sense of pressure when interacting with different tissue types, helping surgeons make more informed decisions during procedures. For example, when suturing or handling delicate tissues, robotic systems with tactile feedback allow the surgeon to feel variations in resistance, enabling them to adjust force accordingly to avoid tissue damage (31). Soft-tissue simulation has become an important research area, aiming to improve the representation of tissue elasticity and force in real-time. Another key development in haptic feedback has been its application in surgical training. Virtual reality (VR) and augmented reality (AR) systems, when combined with force feedback, provide simulated surgical environments where novice surgeons can practice procedures without risk to patients (33).

Telerobotics and Remote Surgery

Telepresence systems now incorporate high-definition cameras, real-time video streaming, and stereoscopic displays, allowing surgeons to visualize the surgical field as if they were physically present. For instance, the integration of 4K and 8K resolution imaging in robotic systems has dramatically improved the clarity of surgical sites, ensuring safer and more effective procedures (34).Reliable communication networks are a cornerstone of remote surgery. The deployment of 5G networks has significantly reduced latency, ensuring seamless interaction between the surgeon and the robotic system (35). Low-latency communication allows for real-time feedback and precise control of robotic instruments, even over long distances. This has enabled complex surgeries, such as laparoscopic and cardiovascular procedures, to be performed remotely without compromising safety or effectiveness.Telerobotics has made it possible for skilled surgeons to operate across international borders. This capability has been particularly beneficial in providing care to patients in remote or conflict-affected areas. Several successful trials have demonstrated the feasibility of performing cross-border surgeries using telerobotic systems, paving the way for global surgical collaboration. Virtual reality (VR) and augmented reality (AR) tools have become integral to training surgeons in remote robotic procedures. These technologies simulate real-world scenarios, allowing surgeons to refine their skills in a controlled environment before performing live operations. Training systems now include haptic feedback, enhancing the realism of simulated surgeries and preparing surgeons for remote procedures with high precision. Space agencies, including NASA, have explored the use of telerobotics for performing surgeries

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on astronauts during long-term space missions (36). Advances in autonomous robotic systems and real-time teleoperation have enabled the development of surgical robots that can be controlled remotely from Earth, addressing medical emergencies in microgravity environments (37,38).

Real-Time Imaging and Visualization

As previously mentioned, advancements in real-time imaging and visualization have been pivotal in transforming robotic surgery. These developments span high-definition imaging, augmented and virtual reality integration, and advanced intraoperative imaging techniques, improving outcomes for patients while enhancing the surgeon’s ability to perform complex procedures. For instance, the development of 3D and 4K imaging has significantly enhanced the visual capabilities of robotic surgery systems, providing high-definition, lifelike images. Surgeons now have a more detailed and immersive view of the surgical field, improving their ability to distinguish fine anatomical structures whereas 3D imaging enables depth perception and higher precision. The introduction of 4K imaging, which offers four times the resolution of standard HD, has further refined visual clarity. This high-definition imaging has not only improved the precision of surgical manoeuvres but also reduced the risk of complications such as accidental injury to critical structures (34). The integration of augmented reality (AR) and virtual reality (VR) into robotic surgery has transformed both preoperative planning and intraoperative navigation. This allows for more accurate navigation during surgery, as the surgeon can "see" the patient’s internal structures in a way that was previously impossible with traditional imaging alone (39).

Imaging and Fluorescence-Guided Surgery

Intraoperative imaging has seen significant advancements, particularly with the introduction of fluorescence-guided surgery, which has revolutionized tumour localization and resection. Fluorescence imaging, combined with robotic surgery systems, allows surgeons to visualize and distinguish cancerous tissue from healthy tissue during the operation. Using contrast agents that fluoresce under specific lighting, tumours can be illuminated, making them easier to identify and remove completely. This has been particularly useful in oncological surgeries, such as those for brain, liver, and colorectal cancers, where accurate tumour resection is critical to reducing recurrence rates (40). For example, indocyanine green (ICG) dye is commonly used to highlight tumours, blood vessels, and lymphatic pathways, enhancing the surgeon’s ability to make precise cuts and decisions in real-time. Additionally, intraoperative imaging technologies like robotic ultrasound, infrared cameras, and high-definition optical coherence tomography (OCT) have been integrated into surgical systems (41).

Robotic Systems Design

The development of single-port systems, such as the da Vinci SP (Single Port), introduced a new dimension in minimally invasive surgery. This platform allows surgeons to perform complex operations through a single incision, resulting in reduced scarring, shorter recovery times, and improved cosmetic outcomes for patients. The system uses a flexible robotic arm and an advanced 3D camera to enable precise operations through a single entry point (42,43). This has especially benefitted surgeries in areas requiring precision, such as prostatectomies and cholecystectomies. The demand for more cost-effective and adaptable solutions has led to the development of portable robotic systems. One notable example is the Versius robotic system, designed by the company Medtronic. Unlike traditional bulky systems, the Versius is compact, modular, and designed to be used in smaller operating rooms (44). The modular design of robotic systems like Versius enhances flexibility by allowing arm reconfiguration to optimize workspace and adapt to various operating room layouts (45).

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Multi-Arm Systems

In an attempt to mimic a surgical team, multi-arm robotic systems have made significant strides in enhancing the efficiency, precision, and versatility of robotic surgery. These systems, which incorporate multiple robotic arms into the surgical setup, allow for the simultaneous execution of multiple tasks, improving the overall workflow of the surgical team and reducing the time required for complex procedures. For example, one arm might be used to hold and manipulate the camera for visualization, while the other arms can be used to operate on the tissue, suture, or cauterize. One of the most prominent advancements in multi-arm robotic surgery systems is the introduction of platforms like the da Vinci Xi and da Vinci X, which feature up to four robotic arms that can work simultaneously (31,46). Additionally, the system's single console interface allows the surgeon to control all arms from a centralized point, improving efficiency and reducing the need for multiple assistants. Finally, multi-arm systems provide better visualization by using multiple arms to hold the camera and instruments, ensuring clearer views of the surgical site and improving decision-making during complex procedures.

Ergonomics and User Interfaces

The field of robotic surgery has undergone significant advancements in ergonomics and user interfaces over the past decade, enhancing surgeon comfort, reducing fatigue, and improving surgical precision. These innovations have been instrumental in making robotic systems more accessible, efficient, and effective.Modern robotic systems have prioritized ergonomics to mitigate the physical strain associated with long surgical procedures. Older systems often lead to discomfort and fatigue due to fixed working positions. Recent designs feature adjustable consoles, optimized seat configurations, and customizable controls that allow surgeons to maintain natural postures during surgery. Adjustable console heights and arm supports have become standard, reducing repetitive strain injuries and enabling sustained performance during complex surgeries. Studies have shown that these improvements contribute to reduced musculoskeletal complaints among surgeons, leading to better focus and efficiency in the operating room (9). Physical and cognitive fatigue are significant concerns for surgeons performing long operations. Innovations such as pressure-reducing chair designs, customizable armrests, and foot-pedal adjustments have significantly improved comfort. Additionally, redesigned control systems with minimized physical exertion requirements ensure that surgeons maintain peak performance throughout procedures (47,48). As previously discussed, haptic feedback has been a transformative advancement in robotic surgery. Examples include systems with force-feedback mechanisms that help prevent excessive force application, reducing the risk of tissue damage. Robotic systems now offer greater precision with advanced micro-movements and tremor-filtering technologies. These controls allow surgeons to make minute adjustments, critical for surgeries involving small or delicate anatomical structures. Real-time feedback on instrument positioning and force application enhances the learning experience and ensures the optimal use of robotic systems in clinical practice (49).

Advancements in user interfaces have made robotic systems more intuitive, reducing the learning curve for new users. Modern systems now integrate touchscreens, simplified modular consoles, and streamlined navigation tools. These enhancements allow surgeons to focus on surgical precision without being hindered by complex machine operations. For instance, systems such as the da Vinci Xi feature a more refined interface that simplifies instrument docking and provides real-time system guidance, improving procedural workflow (31). Voice activation enables the hands-free operation of robotic systems, allowing surgeons to adjust

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settings, reposition instruments, or switch modes without interrupting their focus. Systems with gesture recognition interpret hand movements for dynamic instrument control, making the interface more responsive and reducing reliance on manual adjustments. For example, platforms like the Senhance Surgical System use eye-tracking and gesture-based commands to enhance precision and maintain sterility (50). These advancements in ergonomics and user interfaces in robotic surgery over the past decade have revolutionised surgical practice. From enhanced physical comfort and intuitive controls to haptic feedback and AR integration, these innovations have made robotic surgery safer, more precise, and less physically demanding for surgeons.

Nanobots

Nanobots, often referred to as "tiny surgeons," represent a groundbreaking advancement in medical technology, utilizing nanotechnology to perform precise tasks at the molecular and cellular levels. Over the past decade, several key advancements have significantly expanded their capabilities, including external magnetic-driven nanobots, ultrasound-driven nanobots, biological-driven microrobots, and hybrid-driven nanobots. These devices have been applied to various fields such as drug delivery, regenerative medicine, and minimally invasive surgeries. Powered by innovative propulsion systems and guided by external stimuli, these nanobots offer unparalleled precision and efficiency.

External Magnetic-driven nanobots

Various preliminary studies have been conducted to demonstrate the transport and properties of nanorobots using magnetic fields (51,52)]. Research on the use of nanorobots in cancer treatment has also been fruitful. The basis of this drive is that the magnetic spiral nanorobot can use the force generated by the external magnetic field to support the transition from rotation to translation (53,54). Andari et al. developed a magnetic nanorobot using multi-walled carbon nanotubes (CNTs) loaded with doxorubicin (DOX) and an antibiotic. These autonomous magnetized nanodevices can be directed by a magnetic field from outside in complicated biological mediums that produce antibodies into three-dimensional (3D) spheres when prompted by intracellular H2O2 stimulation or local pH alterations in the tumour microenvironmental loading (55). The nanorobot made of magnetic Fe3O4 nanoparticles opens the gate of Fe3O4 nanoparticles, preferentially releasing DOX in the intracellular lysosomal compartment of human cancer cells (HCT116). Gao et al. reported a nickel-silver nanoswimmer that can be guided by an alternating magnetic field and transport small particles at velocities greater than 10 μm/s (56).

External ultrasound-driven nanobots

Creating acoustic conditions is relatively easy. Sound cannot propagate in media such as solids, liquids and air, and can penetrate deep into biological tissues to power nanorobots from the outside without harming the organs. On the other hand, using ultrasound may result in biological oxidative damage, that may impact targeted tumour cells as well as healthy cells. The fundamental idea is that an asymmetrical nanorobot's surface experiences localized acoustic adequate stress from ultrasonic vibrations, which generates a driving force for the nanorobot's motion. Fuel vaporization may be accelerated and tubular nanorobots driven in flexible transitions using vigorous localized acoustic sounds. This microtubule-based robot can move at very high speeds and penetrate tissues with propulsive force (57). García et al. demonstrated that a nanowire-based ultrasound device could rapidly deliver drugs into HeLa cells to achieve near-infrared light-induced drug delivery (58).

Biological-driven nanobots

Bio-powered microrobots or nanorobots are often called biohybrid

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microrobots. They consist of living organisms (cells) and man-made products. Organisms such as sperm and bacteria that move under the power of flagella can serve as motors for biohybrid micro/nanobots. Additionally, sperm has a unique ability to fuse with human cells, which could pose issues with the biocompatibility and safety of micro-nanorobots. According to reports, the biohybrid robot with 3D-printed magnetic tubular microstructures and four arms uses moving sperm as energy and pharmaceutical products. Compared with synthetic microrobots or other nanocarriers, this sperm-hybrid microrobot can lock more drugs into sperm and protect the drug payload from body fluids or enzymatic degradation (59).

Hybrid Driven Nanobots

Several studies have demonstrated the success of nanorobots in achieving drug delivery targets using integrated electronic devices. Studies have shown that nanorobots can bind bacteria and toxins, making them good detoxification ability (52). He et al. developed tubular multilayer microrobots using layer-by-layer self-assembly technology (60). Thanks to the combination of foam and magnetic guidance, the microrobot can deliver doxorubicin to cancer cells at a speed of up to 68 microns/second. Magnetic fields can also be used in combination with other methods to control the movement of nanorobots (59). For example, Professor Garcia's team used electroplating to prepare porous metal rod-like nanorobots (58). The tiny machines can carry twenty times more biomolecules than conventional bots because of their permeable construction. Drug-releasing tiny robots are activated by close to infrared light. Under the guidance of ultrasound and an external magnetic field, tumour cells are effectively killed by drug delivery. developed a hybrid magnetoelectric nanorobot capable of achieving targeted drug delivery, in which drug release is triggered by an external magnetic field (61). Garcia-Gradilla et al. developed an ultrasonically driven, magnetically guided three-section Au-Ni-Au nanowire motor (62). Changing the direction of the applied magnetic field will enable omnidirectional movement of ultrasonic propellant particles. Recent studies have shown that bismuth (Bi) derivatives hold broad promise in biological applications (63). Berardi-Moussaoui et al. reported the development of a self-propelled bipolar tubular microrobot and a proof-of-concept experiment for smart drug delivery. Bi is built on the outer surface of the microrobot and is used as a drug in clinical trials. The surface of two central microrobots is filled with the clinic's first-line cancer drug, DOX, and nickel-plated magnets are used to transport them to cancer cells. Microrobotic cargo is guided by magnets into a tunnel filled with electronics and releases the cargo on demand within seconds (64).

Nanotechnology has significantly advanced healthcare, addressing challenges across diagnostics, treatment, and disease prevention. For cancer therapy, nanorobots are engineered to scan cells, identify malignancies, and deliver targeted treatments, such as doxorubicin-loaded Fe_3O_4 nanoparticles, minimizing damage to healthy tissues (65). In neurodegenerative diseases, nanoparticles crossing the blood-brain barrier enhance diagnostic accuracy and improve treatments like neural stem cell differentiation therapy, offering hope for diseases lacking definitive cures (66). Hormone deficiencies, such as those experienced during menopause, can be mitigated by nano-enabled systems delivering essential hormones to maintain balance (67). Infectious diseases also benefit, with nanorobots surpassing the immune system in neutralizing resistant pathogens like HIV and herpes, breaking down microbial biofilms, and purifying bloodstream infections, ensuring safer and more effective therapies (68,69). These advancements underscore nanotechnology's transformative role in healthcare, driven by innovative solutions and

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the potential for future medical breakthroughs.

Autonomous and Semi-Autonomous Systems

The development of autonomous robotic systems in surgery has been one of the most exciting and transformative areas of robotic technology. Key progress has been made in semi-autonomous robots, which are capable of performing repetitive tasks, and in path planning algorithms that enable robotic systems to navigate and execute procedures with greater accuracy. Semi-autonomous robotic systems are designed to assist with or completely automate certain repetitive tasks that were previously solely under the surgeon's control. One of the most notable advancements in this area is the Smart Tissue Autonomous Robot (STAR), developed by researchers at Johns Hopkins University, was designed to perform soft-tissue surgeries autonomously. STAR utilizes advanced machine learning algorithms to assess the tissue environment and adapt in real-time to variations in the tissue, adjusting its movements accordingly using a combination of force sensors, imaging systems, and robotic arms to perform suturing with remarkable accuracy (19). Other semi-autonomous systems, such as Mazor Robotics for spinal surgery, are also designed to assist in repetitive, high-precision tasks like screw placement or bone drilling (70).

Path Planning Algorithms

One of the major hurdles in robotic surgery is ensuring that the robotic system can navigate the surgical site with extreme precision. The development of path planning algorithms relies heavily on advanced computational methods and artificial intelligence (AI) to create optimal paths for surgical tools. These systems take into account the patient's anatomy, imaging data (e.g., MRI, CT scans), and real-time feedback from the surgical field to plan the most effective route for the surgical instruments. They are particularly useful in minimally invasive procedures and help avoid critical structures like nerves, blood vessels, and organs (71). For example, modern algorithms can adapt in real-time to changes in the surgical environment, such as tissue shifting or unexpected obstacles, ensuring that the robot continuously follows the safest and most precise path (72).

Challenges

Design Challenges

Robotic surgery, while transformative, faces several challenges. Among the most significant is the complexity of designing and implementing systems that are both versatile and precise. This requires intricate engineering, advanced software, and seamless integration with existing medical technologies, making development resource-intensive and technically demanding. Safety concerns also remain critical, as malfunctions such as mechanical failures, software glitches, or control errors can have severe consequences. These issues necessitate rigorous testing, continuous monitoring, and robust fail-safe mechanisms (73). Despite advancements in haptic feedback, the lack of tactile sensation in many systems still poses challenges in delicate procedures, increasing the risk of unintentional damage, particularly in microsurgeries (74). Financial constraints further limit widespread adoption, as robotic systems are prohibitively expensive. The high costs of acquisition, maintenance, and training create disparities in access, especially in resource-constrained regions (75).

Safety issues

Safety concerns in robotic surgery are multifaceted, involving technological, operational, and regulatory challenges that must be addressed to ensure its safe and effective application. Robotic systems rely on intricate machinery and sophisticated software, making them vulnerable to mechanical malfunctions and software glitches. Failures in robotic arms or

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instruments during surgery can lead to delays or errors, posing significant risks to patients (73). Ensuring reliability requires rigorous preoperative testing, predictive maintenance schedules, and real-time diagnostics to detect anomalies during procedures. Another critical issue is the lack of tactile feedback in many robotic systems.

The steep learning curve associated with robotic systems further compounds safety concerns. Platforms like the da Vinci system demand specialized training to ensure proficiency, but surgeon expertise varies widely, and inexperience can lead to suboptimal outcomes. Simulation-based training programs and mentorship by experienced practitioners are critical in overcoming this challenge (76). System calibration issues and delayed responsiveness can also disrupt surgical precision. Even minor delays in translating a surgeon's commands to robotic arms can affect accuracy, particularly in microsurgeries. Accurate calibration and enhanced real-time responsiveness through improved algorithms and hardware are essential to mitigating these risks (77). Quality control (QC) monitoring in robotic surgery is crucial for ensuring safety, precision, and efficacy. One major challenge is system calibration and maintenance. Continuous calibration is necessary to maintain precision during complex procedures. Small errors in calibration can result in significant complications (78). Real-time monitoring of robotic systems is another challenge. Inaccurate feedback or lag in communication between the control console and robotic arms can delay surgical movements, requiring continuous system performance tracking (79).

Regulatory issues

Robotic surgery presents unique regulatory challenges that can impact its development, adoption, and integration into healthcare systems. The approval processes for robotic surgical systems often lag behind their rapid technological advancements, creating delays in bringing new systems to market. Regulatory bodies such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) require extensive preclinical and clinical testing to ensure safety and efficacy, which can be time-intensive and resource-heavy (80). Moreover, the lack of standardized evaluation criteria across regions leads to variability in approval timelines and practices, complicating global implementation. Ensuring compliance with data protection and cybersecurity regulations is another critical aspect. Modern robotic systems often rely on interconnected networks and real-time data transmission, exposing them to potential cybersecurity threats. Breaches could compromise patient safety and violate privacy laws, necessitating strict regulatory oversight (81) (Table 1). Post-market surveillance is another area of concern. Regulatory frameworks need to address how adverse events, software updates, and long-term outcomes are monitored and managed after robotic systems are deployed. Robust systems for reporting and addressing issues can ensure continuous improvement and safety. Without comprehensive and harmonized regulations, the potential benefits of robotic surgery may not be fully realized, and patient safety could be compromised (82).

Scalability

Scalability in robotic surgery remains a significant challenge, as adapting robotic systems to accommodate a broad range of surgical specialities and procedures is complex and resource-intensive. Current robotic systems, such as the da Vinci Surgical System, are primarily optimized for specific surgeries like urology and gynaecology but face limitations in generalizing their application to other domains without significant modifications (83). Designing systems that can handle diverse anatomical and procedural requirements while maintaining precision and safety is a major technical and engineering hurdle. The cost-effectiveness of robotic systems also affects

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Table 1: Timeline of Robotic Surgery Advancement

Year	Advancement	Description
1985	PUMA 560	First robotic assistance in stereotactic brain biopsy, showcasing precision potential.
1992	PROBOT & ROBODOC	PROBOT for autonomous prostate surgery; ROBODOC for precise hip replacement bone preparation.
2000	da Vinci Surgical System	Introduced 3D imaging and articulated instruments, revolutionizing minimally invasive surgery.
2001	ZEUS Robotic System	Enabled the first transatlantic telesurgery (Lindbergh operation), demonstrating remote surgery capabilities.
2006	Smart Tissue Autonomous Robot (STAR)	Advanced semi-autonomous suturing on soft tissues, a step toward robotic autonomy.
2008	Integration of 3D and High-Definition Imaging	Enhanced surgical visualization with 3D and HD imaging, improving precision and safety.
2014	Versius Robotic System	Portable and modular system, designed for flexibility in smaller operating rooms.
2015	Single-Site Surgery Systems	Systems like da Vinci SP enabled complex surgeries through a single incision, reducing scarring.
2016	Augmented Reality (AR)	AR integration enhanced preoperative planning and intraoperative navigation for better accuracy.
2017	Fluorescence Imaging	Improved tumor localization and resection using fluorescence-guided techniques, e.g., ICG dye.
2018	AI-Powered Decision Support Systems	AI provided real-time decision support, reducing errors and enhancing surgical outcomes.
2019	Haptic Feedback	Added tactile sensation, allowing surgeons to "feel" tissue properties, improving control.
2020	Telerobotic Systems & Nanorobotics in Surgery	5G-enabled telerobotics for remote surgery; nanorobotics for targeted drug delivery in cancer therapy.
2021	Multi-Arm Robotic Systems	Systems like da Vinci Xi/X with multiple arms improved efficiency by performing simultaneous tasks.
2022	Miniaturized Robotic Systems	Enabled delicate procedures in smaller anatomical spaces, expanding applications in microsurgery.
2023	Hybrid Robotic Systems & Customizable 3D-Printed Robotic Instruments	Hybrid systems combined propulsion methods; 3D printing allowed for tailored surgical instruments.

scalability. Expanding their use across various healthcare settings requires innovations that reduce manufacturing and operational costs, allowing for broader accessibility. Additionally, the infrastructure of many healthcare facilities, especially in resource-constrained regions, is not equipped to support robotic surgery, limiting its scalability and adoption on a global scale. To overcome these barriers, future efforts must

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focus on creating cost-effective, versatile robotic systems and developing comprehensive training and infrastructure support. Public-private partnerships and government incentives could play a critical role in enabling widespread adoption and scalability of robotic surgical technologies (84).

Production techniques

The development of robotic surgery systems relies heavily on advanced production techniques that combine precision engineering, cutting-edge materials, and innovative design principles. Among the most notable advancements is the use of miniaturization technologies, which enable the production of compact, lightweight robotic components. These advancements allow surgical systems to navigate tight anatomical spaces, improving accessibility and reducing patient trauma during minimally invasive procedures (85). The integration of 3D printing into production has further enhanced customization, enabling the creation of patient-specific surgical tools and implants at a lower cost compared to traditional manufacturing techniques (86). Sensor integration is another critical area of progress, with modern robotic systems incorporating advanced sensors for real-time feedback and improved control. These sensors allow for greater precision and enhanced safety during surgery by detecting subtle movements and changes in tissue resistance (87). Furthermore, the use of high-strength, biocompatible materials has contributed to the durability and safety of robotic instruments, ensuring their effectiveness in complex surgical environments (88). Additionally, supply chain management (SCM) in robotic surgery faces several challenges that impact the availability, cost, and efficiency of surgical procedures. One key issue is the high cost of components and parts used in robotic systems. These components, including precision instruments, robotic arms, and specialized tools, are expensive to produce, and any disruption in the supply of these components can lead to delays in surgeries or increased costs (89). Additionally, global supply chain disruptions, such as those caused by political instability, natural disasters, or pandemics, can hinder the timely procurement of robotic system components. These disruptions are particularly concerning in regions that depend on international suppliers, as delays can lead to cancellations or rescheduling of surgeries, impacting patient outcomes. Finally, logistical challenges related to the transportation, packaging, and storage of robotic systems and their parts can increase costs and time-to-market (90).

Future perspective

The future of robotic surgery holds immense promise, driven by ongoing technological advancements, improving accessibility, and expanding applications across various medical specialities. AI-powered robotic systems can assist in preoperative planning, real-time decision support during surgery, and postoperative analysis, reducing human error and enhancing outcomes. This integration will also aid in personalized medicine, where robotic systems can adapt to a patient's specific anatomical and clinical needs, offering more tailored treatment options. Another major development is the advancement of minimally invasive techniques, where robotic systems enable even smaller incisions, leading to less tissue damage, reduced pain, and quicker recovery times for patients. Technologies like flexible and soft robots are being developed to navigate the body more efficiently, allowing access to areas previously difficult or impossible for traditional robotic systems. This advancement, combined with 3D visualization and augmented reality (AR), will provide surgeons with enhanced spatial awareness, further improving precision and safety during operations. In terms of accessibility, the future of robotic surgery also

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looks towards teleoperation and remote surgeries. With advances in telerobotics, surgeons will be able to perform complex procedures from remote locations, expanding the reach of robotic surgery to underserved regions and improving access to high-quality care (91). This technology will be especially valuable in global healthcare contexts, where trained surgeons may not be available locally. Lastly, robotic surgery education and training are evolving to include virtual reality (VR) and simulation-based learning, helping to train the next generation of surgeons in a risk-free, controlled environment. This shift will allow for better skill acquisition and faster adaptation to robotic systems, ensuring a smooth transition to new technology in clinical settings (92).

Conclusion

Robotic surgery has emerged as a transformative innovation in modern medicine, revolutionizing the way surgical procedures are performed. By combining advanced engineering, artificial intelligence, and minimally invasive techniques, robotic systems have significantly improved surgical precision, reduced patient recovery times, and enhanced outcomes across a wide range of specialities. However, challenges such as high costs, regulatory delays, and safety concerns continue to hinder widespread adoption, especially in resource-constrained settings. The integration of artificial intelligence and machine learning into robotic systems holds promise for advancing automation, improving decision-making, and enabling personalized surgical interventions. Similarly, developments in telerobotics and remote surgery have the potential to extend high-quality surgical care to underserved regions, addressing disparities in global healthcare access. Despite these advancements, there is a pressing need to address ethical, safety, and scalability concerns, alongside fostering multidisciplinary collaboration to refine the technology. Future perspectives also emphasize the importance of robust training programs utilizing simulation and virtual reality to prepare surgeons for the evolving landscape of robotic surgery. In conclusion, while robotic surgery is poised to redefine modern surgical practices, its success will depend on overcoming current limitations and ensuring equitable access. Continued research, innovation, and global collaboration will be crucial to fully realize the potential of robotic surgery as a safe, efficient, and universally accessible tool in healthcare.

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Conflicts of Interest

The authors declare no conflicts of interest.

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