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ORIGINAL PAPERS

MODERN SURGERY BETWEEN TRADITION AND INOVATION: FROM THE CLASSIC SCALPEL TO ROBOTICS AND ARTIFICIAL INTELLIGENCE

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Abstract. *Surgery has evolved from rudimentary, high-risk procedures to a sophisticated discipline increasingly augmented by robotics and artificial intelligence (AI). This presentation explores the integration of these technologies into modern surgical practice, highlighting their impact on precision, patient safety, and clinical outcomes. Robotic systems, exemplified by platforms such as the da Vinci and ZEUS Surgical Systems, enhance minimally invasive procedures by improving dexterity, reducing human error, and providing high-resolution three-dimensional visualization. Complementing this, AI leverages vast datasets to support intraoperative decision-making, predict perioperative risks, and standardize procedural assessments. Applications span multiple specialties, including urology, gynecology, cardiothoracic, pediatric, and reconstructive surgery, with telesurgery offering the potential to expand access to expert care globally. Despite these advancements, challenges remain, including technological limitations, steep learning curves, latency in remote operations, and ethical, legal, and data privacy concerns. AI models face issues of generalizability, interpretability, and clinical validation, requiring careful integration into workflows to augment rather than replace human judgment. By examining the history, development, and current applications of robotic and AI-assisted surgery, this presentation underscores their transformative potential to redefine surgical standards, personalize patient care, and guide the education of future medical professionals.*

Key words: Modern Surgery, Robotics, Artificial Intelligence

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Introduction

Surgery is among the oldest and, at the same time, most dynamic branches of medicine, defined by its continuous adaptation to scientific and technological progress. Over the past decades, the rise of robotics and artificial intelligence (AI) has profoundly reshaped surgical practice, opening new perspectives and establishing higher standards of precision and efficency. Anchored in the priciple of *primum non nocere* ("first, do not harm"), medicine, and by extention, surgery, places the patient safety and comfort at its core. The integration of these emerging technologies marks a transition from classical surgery, reliant on the scalpel and the surgeon's manual skills, to a technology augumented discipline supported by algorithms, programmable systems, and high-performance instruments.

Robotic surgery is not intended to replace the surgeon, but rather to serve as a valuable support tool, enhancing the surgical act by reducing human error, improving dexterity, and enabling minimally invasive procedures to be performed with unprecedented accuracy. At the same time, AI complements this process through its ability to analyze vast datasets of clinical and imaging information, provide real-time decision support, and anticipate perioperative risks. In this way, suregry assisted by robotics and AI becomes not merely a technological adjunct, but a trusted partner of the physician, with a direct impact on patient outcomes and quality life.

The objectives of studying this field are multiple: to understand how these technologies integrate into medical practice, to identify their clinical benefits and current limitations, and to anticipatefuture directions of research. The significance of the subject lies in its potential to redefine surgical standards, expand access to advanced procedures, and contribute to the personalization of treatment according to individual patient needs. In an era where medicine is increasingly digitalized, exploring the interplay betwen surgery, robotics and AI is not only an academical pursuit, but a practical necessity for sharping the education of future generations of physicians.

Classical Surgery versus Robotic Surgery

Modern surgery did not truly emerge until the late 19th century; even at that time, infection was common, and surgical outcomes were often poor. Early methods were rudimentary by today's standards, even barbaric, not to mention the fact that anesthesia only began to be used in the mid 1800s. The oldest known surgery is a leg amputation made in Stone Age, performed on a child on the island of Borneo around 31,000 years ago. That person survived the procedure and lived between 6 and 9 years before their remains were intentionally buried in a cave named Liang Tebo, located in East Kalimantan, Indonesian Borneo. [1] Furthermore, the surrounding limestone karst region is notable for containing some of the earliest known examples of dated rock art worldwide. [2]

The concept of using robotics in surgery was first proposed as early as 1967, yet it took nearly three decades - driven by the efforts of the U.S. Department of Defense, alongside pioneering startups and established research institutions - to develop the first fully functional, multipurpose surgical robot. Today, the da Vinci Surgical System, produced by Intuitive Surgical Inc., remains the most widely available FDA-approved multipurpose robotic platform, deployed in operating rooms worldwide. [3]

Conventional surgery performed with a scalpel can be inefficient due to limited access and reduced visibility in hard-to-reach areas, such as the pelvis or thoracic cavity. This can result in larger incisions compared to robotic surgery, as well as significantly greater blood loss and prolonged recovery times. Open surgery is also often associated with a higher risk of infections, hemorrhage, and injury to organs adjacent to the targeted structures. Laparoscopic surgery fits perfectly in this context, as it can be considered a bridge between conventional and robotic surgery. Although it employs minimally invasive techniques and video-guided instruments, control and precision still largely depend on the surgeon’s manual skills. [4]

Robotic Surgery: A Brief Overview

Robotic surgery is an innovative type of minimally invasive surgery where the surgeon uses a robotic system to carry out intricate procedures with a level of precision that surpasses traditional or laparoscopic techniques. This method combines the skills of the surgeon with advanced three-dimensional imaging and versatile robotic tools, allowing for precise and stable movements in anatomically limited spaces. The benefits of robotic surgery include less tissue damage due to smaller incisions, greater accuracy and stability during operations, improved visualization with stereoscopic imaging, and easier handling of instruments in hard-to-reach areas. [5]

Da Vinci Surgical System

The first da Vinci robot in 2000 had three arms with an endoscope attached to one and two instruments. Two years later, a four-arm robotic version was approved, providing improved exposure of anatomical structures and reducing reliance on a surgical assistant. The console had two handles controlled by the surgeon, eliminating hand tremors and scaling down movements for greater precision. The 2006 da Vinci S platform had a 3D HD camera and a touchscreen display. In 2009, the da Vinci Si model was released, allowing dual console surgery and improved training for non-expert surgeons. The Si robot had an upgraded image system and real-time fluorescence imaging. In 2011, platform adjustments allowed for single-port access. The most advanced system from Intuitive Surgical to date is the da Vinci Xi platform, which was released in 2014.

ZEUS Robotic Surgical System

The ZEUS system, developed by Computer Motion in the 1990s, is characterized by three robotic arms - one for camera control and two for surgical instrumentation. It also allows for tele-surgery over long distances and enables precise movements with tremor filtering. ZEUS was mainly utilized in minimally invasive cardiac surgery, urology, and abdominal procedures. Many of its technological advancements were later incorporated into the Da Vinci system, which is now regarded as the standard in robotic surgery.

Clinical Applications

Robotic surgical systems are widely used across various specialties where precision, enhanced visualization, and access to confined anatomical areas are essential. Key applications include:

Urology: Radical prostatectomy, partial or total nephrectomy, ureteral reconstruction. Gynecology: Hysterectomy, myomectomy, treatment of endometriosis, intricate pelvic reconstructive procedures. Cardiothoracic Surgery: Minimally invasive coronary artery bypass, valve repair, mediastinal tumor excision. General and Digestive Surgery: Cholecystectomy, intestinal resections, complex hernia repairs. Reconstructive and Aesthetic Surgery: breast reconstruction following a mastectomy, facial and limb reconstruction. In Pediatric Surgery: correcting congenital anomalies and performing minimally invasive urological and digestive procedures specifically designed for children. Neurosurgery encompasses stereotactic interventions and precision tumor excisions, utilizing high-resolution imaging for enhanced accuracy. [6]

In summary, robotic surgery represents a remarkable fusion of surgical expertise and cutting-edge robotic technology, significantly enhancing the surgeon's capabilities and contributing to improved patient outcomes across a wide range of medical disciplines.

The risks of robotic surgery (RS) primarily stem from challenges related to the technology itself, patient positioning, potential robot malfunctions, and the complexity of the surgical procedure. The lack of tactile feedback combined with the power of robotic arms can lead to technical errors, prolonged operating times, and a steep learning curve for surgeons. Insufficient tactile input may also result in excessive force during tissue manipulation, heightening the risk of inadvertent tissue damage. Additionally, nerve injuries tied to patient positioning have been reported during RS. [6]

Compared to laparoscopic surgeries, robotic procedures tend to involve longer operation durations and have been linked to complications such as ocular strain, cardiac issues, endotracheal tube displacement, and nerve injuries. Furthermore, robotic system malfunctions have been reported in a frequency ranging from 0.4% to 4.6%. According to a study by Rogula et al. on bariatric surgery, robotic gastric bypass did not demonstrate any clinical advantage over conventional laparoscopic methods and was associated with extended operating times. [6]

Telesurgery

Telesurgery, also known as remote surgery, is a medical procedure in which a surgeon performs an operation on a patient from a distant location by controlling robotic instruments through advanced telecommunication technologies. This process relies on high-speed, low-latency networks that transmit real-time three-dimensional images, audio, and haptic feedback, allowing the surgeon to manipulate robotic arms with remarkable precision. By eliminating geographical barriers, telesurgery offers significant benefits such as providing access to specialized care for patiens in remote or underserved areas and facilitating collaboration between experts across the globe.

Latency plays a crucial role in the effectiveness of telesurgery, with an optimal value of less than 200 miliseconds required to ensure both precision and patient safety. Achieving this threshot is vital, as even minor delays can significantly compromise surgical performance. Emerging technologies such as ultra-low latency 6G networks, quantum computing, and artificial intelligence hold considerable potential for enhancing telesurgical outcomes. Nevertheless, etical, legal and cybersecurity concerns must be carefully addressed before large-scale implementation can be realized. The caue of latency in telesurgery are multifaceted, stemming from limitations in network infrastructure, geographyc distances, bybersecurity protocols, and both hardware and software constraints. Promising strategies to mitigate these challebges include the integration of AI-driven algorithms, edge computing, further advancements in 5G connectivity, and the refinement of haptic feedback system. [7]

Artificial Intelligence in Medicine: History, Applications, and Future Directions

Artificial intelligence (AI) is a multidisciplinary field of computer science that aims to develop systems capable of replicating human cognitive functions such as perception, learning, reasoning, and decision-making. In medicine, AI primarily relies on machine learning (ML) and deep learning (DL) techniques that can analyze vast and complex datasets, including imaging, genomics, physiological signals, and electronic health records (EHRs), to produce clinically relevant predictions or support decisions. Contemporary AI models can detect patterns

beyond human perception, offering opportunities for earlier diagnoses, personalized treatments, and improved healthcare efficiency. [8]
The concept of artificial intelligence dates back to 1956, when John McCarthy and colleagues convened the Dartmouth Summer Research Project on Artificial Intelligence, where the term "AI" was first coined. Early work focused on symbolic reasoning and logic-based systems, followed by neural networks and connectionist approaches. Although progress slowed during the so-called "AI winters", the resurgence of computational power, availability of big data, and breakthroughs in DL architectures during the 2010s have propelled AI into mainstream medical research and clinical practice. [9]
AI has found its strongest foothold in radiology and pathology, which together account for roughly 35% of AI-related medical publications. In radiology, AI-based computer-aided diagnosis (CAD) systems can serve as a "second reader" for mammography, CT, or MRI. For example, in a study of 17,884 digital mammograms, an AI-CAD system achieved sensitivity and specificity of 81.7% and 80.2%, respectively, compared to a single radiologist's sensitivity of 77.1%* but higher specificity of 91.7%. Combining AI with human readers raised sensitivity to nearly 88%, though at the cost of lower specificity (75%) compared with human double reading (87%). A meta-analysis covering over one million mammograms similarly reported higher diagnostic accuracy for AI (AUC 0.87) compared to radiologists (AUC 0.81), with AI also reducing reading time by 17–91%. [10] , [11]
In surgery, AI is increasingly applied for risk prediction, intraoperative guidance, and postoperative outcome forecasting. Surgical video analysis is a rapidly developing field: AI models can recognize instruments, anatomy, and phases of procedures. For instance, in laparoscopic cholecystectomy, AI achieved an average accuracy of 89% [95% CI 87.1–90.6], approaching inter-surgeon agreement (90%). Accuracy declined with procedural complexity, from 92% in simpler cases to 81% in the most complex. In laparoscopic gastrectomy for gastric cancer, AI phase recognition reached 90% accuracy, with recall 87% and precision 87%. Similarly, in laparoscopic hernia repair, AI achieved 88.8% accuracy in unilateral and 85.8% in bilateral repairs, while in multi-center laparoscopic cholecystectomy datasets, accuracy was 91%. These findings suggest that AI can assist surgeons by standardizing assessments, monitoring procedural progress, and potentially supporting robotic assistance, although prospective trials proving patient outcome benefits remain scarce. [12], [13]
Computer-aided diagnosis (CAD) exemplifies the translational pathway of AI in medicine. Initially introduced to assist radiologists in detecting suspicious lesions such as breast microcalcifications, CAD has evolved from handcrafted feature engineering to deep learning approaches capable of pixel-level segmentation and probabilistic lesion classification. Modern CAD is now integrated into picture

archiving and communication systems (PACS), enabling quantitative imaging biomarkers. However, while CAD increases sensitivity, it can also raise false-positive rates, sometimes leading to unnecessary recalls or biopsies. For example, when predicting breast cancer response to neoadjuvant chemotherapy, AI-CAD achieved sensitivity 72.6% and specificity 56.8%, compared to MRI's higher AUC (0.776). This underscores the importance of external validation and careful assessment of real-world clinical outcomes beyond accuracy metrics. [14]

The evolution of AI in medicine is moving toward multimodal and foundation models capable of integrating imaging, genomics, clinical notes, and wearable sensor data, thus more closely mirroring complex clinical reasoning. Privacy-preserving techniques such as federated learning are being developed to train models across institutions without centralizing patient data. Meanwhile, regulatory agencies and academic groups are working on guidelines for clinical validation, transparency, and post-deployment monitoring to ensure safe and ethical integration into healthcare workflows. [15]

From the physician's perspective, AI offers advantages such as reducing workload, detecting subtle findings, standardizing diagnoses, and supporting personalized treatment strategies. It can also accelerate research by screening large datasets or automating literature reviews. However, drawbacks include workflow disruption, "black-box" outputs that lack explainability, risks of over-reliance, and uncertainties around medico-legal liability. From the patient's perspective, AI may enable earlier and more accurate diagnoses, tailored therapies, and improved access to expertise, particularly in underserved areas through telemedicine. Yet patients also face potential disadvantages: loss of direct human interaction, privacy risks, unequal access if algorithms are trained on biased datasets, and anxiety about entrusting care to opaque systems. Surveys show clinicians are broadly positive but cautious, while patients increasingly demand transparency about AI in their care. [16, 17]

Despite its successes, AI in medicine has clear limitations. Generalizability remains a challenge: models trained on specific cohorts often perform poorly in new populations. Data bias risks perpetuating healthcare disparities if underrepresented groups are not adequately included. Many high-performing models lack interpretability, which undermines clinician trust and regulatory acceptance. Validation gaps persist, with most studies relying on retrospective single-center data rather than prospective, multi-center trials. Ethical issues surrounding consent, transparency, and patient autonomy remain unresolved, especially in high-stakes areas like surgery. Finally, integrating AI seamlessly into clinical workflows requires robust human-computer collaboration, not substitution, to ensure that technology enhances rather than disrupts patient care.

Conclusions

AI has progressed from its 1956 conceptual origins to become an indispensable tool in medicine, with radiology, pathology, and surgery leading its adoption. Numerical results from mammography, surgical video analysis, and CAD illustrate AI's growing accuracy and efficiency, though challenges in specificity, generalizability, and clinical validation remain. From both physician and patient perspectives, AI promises to augment—but not replace—clinical judgment. Its future depends on rigorous validation, ethical deployment, and transparent integration into healthcare, with the ultimate goal of improving patient outcomes and equity in care delivery. [18]

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