Applications of Artificial Intelligence and Robotics in Surgical Practice

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ABSTRACT: Robotic surgery and artificial intelligence are transforming modern surgery by enhancing precision, minimizing invasiveness, and supporting clinical decision-making. This narrative review, based on 40 studies published between 2020 and 2025, explores their applications, benefits, and challenges. Robotic surgery improves ergonomics and reduces complications and hospital stays, though it often involves longer procedures and higher costs. Artificial intelligence supports all surgical stages through predictive modeling, image guidance, and performance evaluation. Despite ongoing issues with algorithm transparency, data quality, and ethics, both technologies show great potential to advance surgical care toward safer, more efficient, and personalized medicine.

KEYWORDS: Robot; artificial intelligence; surgery; future; technology

SUMMARY: 1. Introduction – 2. Material and Methods – 3. Results – 4. Discussion – 5. Conclusions.

1. Introduction

Robotic surgery is a major medical innovation that improves precision, reduces invasiveness, and enhances recovery, leading to its growing use across specialties. Although the idea dates back to 1967, its practical development accelerated later, with the U.S. Department of Defense pioneering early systems to reduce battlefield casualties.[1] In 1985, it was performed the first robotic-assisted surgery using the Puma 560 for a brain biopsy, [2] but its industrial design limited medical use. Late 1980s innovations included the Robodoc for hip replacements and early robotic urology advances, while NASA and SRI developed telemanipulation and virtual reality systems that laid the founda-

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[1] S. CHATTERJEE, S. DAS, K. GANGULY, *et al.*, *Advancements in robotic surgery: innovations, challenges and future prospects*, in *Journal of Robotic Surgery* 18, 2024, 28.

[2] K. MYLA, N. BOU-AYASH, W.C. KIM, *et al.*, *Is implementation of robotic-assisted procedures in acute care general surgery cost-effective?* in *Journal of Robotic Surgery*, 18, 2024, 223.

tion for modern remote surgery. From 2012 to 2019,[3] robotic-assisted surgery (RAS) represented more than 15% of all general surgical operations. Between 2003 and 2015, the use of RAS increased by 25.5%, driven by the rising preference for minimally invasive techniques. The evolution of robotic platforms, has transformed surgery by improving 3D vision, precision, and dexterity, promoting minimally invasive techniques. Benefits include reduced trauma and faster recovery, but these come with high costs, complex training, and a steep learning curve, requiring integration into surgical education. Also for anesthesia teams, new challenges arise, such as prolonged Trendelenburg positioning, CO_2 insufflation, and limited patient access after robot docking.[4]

Despite high initial costs, robotic surgery may reduce overall expenses by lowering complications, shortening hospital stays, and enabling faster recovery — benefits highlighted during COVID-19. Same-day discharge is feasible with proper patient selection, considering factors like age, lung health, intraoperative events, and surgery timing.

In recent years another big innovation has exploded: the artificial intelligence (AI).

AI has assumed an increasingly central role in the medical field, establishing itself as a strategic resource for the evolution of clinical practice. The COVID-19 pandemic accelerated interest in applying artificial intelligence to manage large volumes of clinical data and care for critically ill patients. Technologies based on machine learning and computer vision have shown significant potential in improving diagnosis, continuous monitoring, and decision support in surgical settings. In particular, the surgical domain is undergoing a deep transformation, wherein the integration of intelligent systems enables a more effective approach to the complexity of clinical decision-making, data management, and the execution of operative procedures.[5]

AI provides advanced tools for the collection, analysis, and interpretation of large volumes of clinical data and diagnostic images, facilitating treatment personalization and more precise surgical planning. During surgery, intelligent technologies assist the surgeon through automatic recognition of anatomical structures, guidance in movements, and real-time monitoring, thereby contributing to error reduction and improved clinical outcomes. AI also proves valuable in the postoperative phase for predictive monitoring, complication management, and optimization of the post-surgical recovery process.[6]

Despite significant progress, the application of AI in surgery remains in its early stages. Substantial challenges persist, including the standardization of methodologies, scientific validation of models, and the need for harmonious integration between technology and clinical practice.

The introduction of AI into the surgical context elicits diverse reactions among professionals: enthusiasts, skeptics, and cautious operators coexist, reflecting the complexity and uncertainties still present in the field.[7] Although the majority acknowledge the benefits, particularly in diagnostics, few foresee a central role for AI in the operating room, and its practical integration remains limited. This gap between

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[3] *Ibidem.*

[4] Y. TAMEZE, Y.H. LOW, *Outpatient Robotic surgery: Considerations for the Anesthesiologist*, in *Advances in Anesthesia*, 40, 2022, 15.

[5] H. LI, Z. HAN, H. WU, *et al.*, *Artificial intelligence in surgery: evolution, trends, and future directions,* in *International Journal of Surgery*, 111, 2025, 2101.

[6] *Ibidem.*

[7] O. CHEVALIER, G. DUBEY, A. BENKABBOU, *et al.*, *Comprehensive overview of artificial intelligence in surgery: a systematic review and perspectives,* in *Pflugers Archiv-European Journal of Physiology*, 477, 2025, 617.

expectations and application underscores the urgency to critically examine the real opportunities and challenges posed by AI adoption.

Only a balanced and multidisciplinary approach can foster a safe, responsible, and sustainable integration of AI in surgical practice, paving the way for a new frontier in medicine.

Aim of this work is analysing all aspects of Robotic surgery and of AI in surgery, its progress, prospects, and their challenges.

2. Material and Methods

A narrative review of the literature was conducted. This review followed a narrative approach and has not been intended as a systematic review. The aim was to synthesize the most recent and relevant literature on artificial intelligence and robotic surgery. Two independent reviewers (V.S and P.C.) evaluated studies through titles and abstract data.

The search was narrowed to articles between 2020 and 2025. The time frame was restricted to 2020–2025 to ensure that the review captured the most recent developments in two rapidly evolving fields (artificial intelligence and robotic surgery). Both domains have undergone major technological, regulatory, and clinical advancements in the past few years, making older literature rapidly outdated. In particular, the period beginning in 2020 corresponds to: the widespread clinical implementation of next-generation robotic platforms; the accelerated integration of AI-driven decision-support systems, fuelled by advances in machine learning and deep learning architectures; and a significant increase in high-quality publications assessing clinical, ethical, and economic implications of these technologies. Limiting the search to the last five years therefore allowed us to focus on state-of-the-art evidence, avoiding dilution from early or obsolete work, and providing a synthesis that is maximally relevant to current clinical practice and policy discussions. We searched on PUBMED; Studies were included if they were full-text articles or review or case reports published in English involved human adult participants (>18 years), and addressed aspects of the diagnosis, management, treatment, economics and ethics. Studies were excluded if they were in other languages, without a visible abstract, not relevant. The research was conducted using the following terms: “robotic surgery for the first topic and “artificial intelligence” and “surgery” for the second one. We selected 40 papers (20 for each macro-area) (Table 1-2).

Title	Authors	Year	Type
Advancements in robotic surgery: innovations, challenges and future prospects.[8]	Chatterjee *et al.*	2024	Review
Is implementation of robotic-assisted procedures in acute care gen-	Myla *et al.*	2024	Review

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[8] S. Chatterjee, S. Das, K. Ganguly, *et al.*, *op cit.*

eral surgery cost-effective?[9]			
Robotic Surgery Techniques to Improve Traditional Laparoscopy.[10]	Williamson *et al.*	2022	Review
Robotic surgery for rectal cancer as a platform to build on: review of current evidence.[11]	Achilli *et al.*	2021	Review
Robotic surgery for colorectal liver metastases resection: A systematic review.[12]	Rocca *et al.*	2021	Review
Robotic surgery for gynecologic cancers: indications,techniques and controversies.[13]	Clair *et al.*	2020	Review
Robotic versus laparoscopic general surgery in the emergency setting: a systematic review.[14]	Anyomih *et al.*	2024	Review
Does robotic surgery have a role in abdominal wall reconstruction? A systematic review and meta-analysis.[15]	Awad *et al.*	2025	Review

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[9] K. MYLA, N. BOU-AYASH, W.C. KIM, *et al.*, *op cit.*

[10] T. WILLIAMSON, S.E. SONG, *Robotic Surgery Techniques to Improve Traditional Laparoscopy*, in *Journal of the Society of Laparoendoscopic,* 26, 2, 2022.

[11] P. ACHILLI, F. GRASS, D.W. LARSON, *Robotic surgery for rectal cancer as a platform to build on: review of current evidence,* in *Surgery Today*, 51, 2021, 44.

[12] A. ROCCA, A. SCACCHI, M. CAPPUCCIO, *et al.*, *Robotic surgery for colorectal liver metastases resection: A systematic review*, in *International Journal of Medical Robot*, 17, 2021, e2330.

[13] K.H. CLAIR, K.S. TEWARI, *Robotic surgery for gynecologic cancers: indications, techniques and controversies*, in *Journal of Obstetrics Gynaecology Research*, 46, 2020, 828.

[14] T.T.K. ANYOMIH, A. MEHTA, D. SACKEY, *et al.*, *Robotic versus laparoscopic general surgery in the emergency setting: a systematic review*, in *Journal of Robotic Surgery,* 18, 2024, 281.

[15] L. AWAD, B. REED, E. BOLLEN, *et al.*, *Does robotic surgery have a role in abdominal wall reconstruction? A systematic review and meta-analysis*, in *Journal of Plastic Reconstructive and Aesthetic Surgeons,* 106, 2025, 353.

Current Status of Robotic Hepatobiliary and Pancreatic Surgery.[16]	Minamimura *et al.*	2024	Review
Advanced Robotic Surgery: Liver, Pancreas, and Esophagus – The State of the Art?[17]	Scognamiglio *et al.*	2021	Review
The safety of urologic robotic surgery depends on the skills of the surgeon.[18]	Palagonia *et al.*	2020	Review
Robotic bariatric surgery for the obesity: a systematic review and meta-analysis.[19]	Zhang *et al.*	2021	Systematic review and meta-analysis
Robotic surgery versus open surgery for thyroid neoplasms: a systematic review and meta-analysis.[20]	Liu *et al.*	2020	Systematic review and meta-analysis
Advancements in Bariatric Surgery: A Comparative Review of Laparoscopic and Robotic Techniques.[21]	Velardi *et al.*	2024	Review
Robotic surgery costs: Revealing the real villains.[22]	Rodrigues Martins *et al.*	2021	Original article
Costs of Robotic-Assisted	Schmidt *et al.*	2021	Original article

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[16] K. MINAMIMURA, Y. AOKI, Y. KANEYA, *et al.*, *Current Status of Robotic Hepatobiliary and Pancreatic Surgery*, in *Journal of Nippon Medical School*, 91, 2024, 10.

[17] P. SCOGNAMIGLIO, B.O. STÜBEN, A. HEUMANN, *et al. Advanced Robotic Surgery: Liver, Pancreas, and Esophagus - The State of the Art?,* in *Visceral Medicine,*37, 2021, 505.

[18] E. PALAGONIA, E. MAZZONE, G. DE NAEYER, *et al., The safety of urologic robotic surgery depends on the skills of the surgeon,* in *World Journal of Urology,* 38*,* 2020, 1373.

[19] Z. ZHANG, L. MIAO, Z. REN, *et al.*, *Robotic bariatric surgery for the obesity: a systematic review and meta-analysis* in *Surgical Endoscopy*, 35, 2021, 2440.

[20] H. LIU, Y. WANG, C. WU, *et al.*, *Robotic surgery versus open surgery for thyroid neoplasms: a systematic review and meta-analysis*, in *Journal of Cancer Research and Clinical Oncology*, 146, 2020, 3297.

[21] A.M. VELARDI, P. ANOLDO, S. NIGRO, *et al.*, *Advancements in Bariatric Surgery: A Comparative Review of Laparoscopic and Robotic Techniques* in *Journal of Personalized Medicine*, 14, 2024.

[22] Y.M. RODRIGUES MARTINS, P. ROMANELLI DE CASTRO, A.P. DRUMMOND LAGE, *et al.*, *Robotic surgery costs: Revealing the real villains*, in *The International Journal of Medical Robotics and Computer Assisted Surgery*, 17, 2021, e2311.

Radical Prostatectomy 1 Year After Surgery Pay Now and Save Later?[23]			
A systematic review of robotic breast surgery versus open surgery.[24]	Maes-Caballo *et al.*	2024	Review
Perioperative considerations for robotic-assisted thoracic surgery.[25]	Bandopadhyay *et al.*	2024	Original article
Robotic versus laparoscopic gastrectomy for gastric cancer: The largest meta-analysis.[26]	Guerrini *et al.*	2020	Meta-analysis
Robotic colorectal surgery and ergonomics. [27]	Wong *et al.*	2022	Review

Table 1

Title	Authors	Year	Type
Artificial intelligence in surgery: evolution, trends, and future directions.[28]	Li *et al.*	2025	Review
Comprehensive overview of artificial intelligence in surgery: a systematic review and perspectives.[29]	Chevalier *et al.*	2025	Review

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[23] B. SCHMIDT, J.T. LEPPERT, *Costs of Robotic-Assisted Radical Prostatectomy 1 Year After Surgery: Pay Now and Save Later?*, in *JAMA Network Open*, 4, 2021, e212548.

[24] M. MAES-CARBALLO, M. GARCÍA-GARCÍA, I. RODRÍGUEZ-JANEIRO, *et al.*, *A systematic review of robotic breast surgery versus open surgery*, in *Journal of Robotic Surgery*, 17, 2023, 2583.

[25] R. BANDOPADHYAY, *Perioperative considerations for robotic-assisted thoracic surgery*, in *British Journal of Hospital Medicine*, 85, 2024, 1.

[26] G.P. GUERRINI, G. ESPOSITO, P. MAGISTRI, *et al.*, *Robotic versus laparoscopic gastrectomy for gastric cancer: The largest meta-analysis*, in *International Journal of Surgery*, 82, 2020, 210.

[27] S.W. WONG, Z.H. ANG, P.F. YANG, *et al.*, *Robotic colorectal surgery and ergonomics*, in *Journal of Robotic Surgery*, 16, 2022, 241.

[28] H. LI, Z. Han, H. Wu, *et al., op cit.*

[29] O. CHEVALIER, G. DUBEY, A. BENKABBOU, *et al.*, *Comprehensive overview of artificial intelligence in surgery: a systematic review and perspectives,* in *Pflugers Archiv-European Journal of Physiology*, 477, 2025, 617.

Introduction to Artificial Intelligence for General Surgeons: A Narrative Review.[30]	Lee *et al.*	2025	Review
Machine learning perioperative applications in visceral surgery: a narrative review.[31]	Hossain *et al.*	2024	Review
The Future of Artificial Intelligence in Surgery.[32]	Hamilton *et al.*	2024	Review
Current and future applications of artificial intelligence in surgery: implications for clinical practice and research.[33]	Morris *et al.*	2024	Review
Artificial intelligence in surgery.[34]	Varghese *et al.*	2024	Review
Artificial intelligence in surgery: A research team perspective.[35]	Mohamadipanah *et al.*	2022	Retrospective observational study
Investigating the Ethical and Data Governance Issues of Artificial Intelligence in Surgery: Protocol for a Delphi Study.[36]	Lam K *et al.*	2021	Qualitative / Consensus-based
Artificial intelligence and pediatric surgery: where are we?[37]	Miyake *et al.*	2024	Review

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[30] B. LEE, N. Narsey, *Introduction to Artificial Intelligence for General Surgeons: A Narrative Review*, in *Cureus*, 17, 2025, e79871.

[31] I. HOSSAIN, A. MADANI, S. LAPLANTE, *Machine learning perioperative applications in visceral surgery: a narrative review*, in *Frontiers in Surgery*, 11, 2024, 1493779.

[32] A. HAMILTON, *The Future of Artificial Intelligence, in Surgery* in *Cureus*, 16, 2024, e63699.

[33] M.X. MORRIS, D. FIOCCO, T. CANEVA, *et al.*, *Current and future applications of artificial intelligence in surgery: implications for clinical practice and research*, in *Frontiers in Surgery,* 11, 2024, 1393898.

[34] C. VARGHESE, E.M. HARRISON, G. O'GRADY, *et al.*, *Artificial intelligence in surgery*, in *Nature Medicine*, 30, 2024, 1257.

[35] H. MOHAMADIPANAH, C. PERUMALLA, S. YANG, *et al., Artificial intelligence in surgery: A research team perspective,* in *Current Problems in Surgery*, 59, 2022, 101125.

[36] K. LAM, F.M. IQBAL, S. PURKAYASTHA, *et al.*, *Investigating the Ethical and Data Governance Issues of Artificial Intelligence in Surgery: Protocol for a Delphi Study*, in *JMIR Research Protocols*, 10, 2021, e26552.

[37] Y. MIYAKE, G. RETROSI, R. KEIJZER, *Artificial intelligence and pediatric surgery: where are we?*, in *Pediatric Surgery International*, 41, 2024, 19.

Applications of artificial intelligence in surgery: clinical, technical, and governance considerations.[38]	Mascagni *et al.*	2024	Narrative Review
Critical view of safety assessment in sentinel node dissection for endometrial and cervical cancer: artificial intelligence to enhance surgical safety and lymph node detection (LYSE study).[39]	Pavone *et al.*	2025	Observational Study
AI chatbots in surgery: What does the future hold?[40]	Goldenberg *et al.*	2024	Letter to the Editor / perspective piece
Future of Artificial Intelligence in Surgery: A Narrative Review.[41]	Amin *et al.*	2024	Narrative Review
Artificial Intelligence in Surgery: The Future is Now.[42]	Guni *et al.*	2024	Review
Bringing Artificial Intelligence to the operating room: edge computing for real-time surgical phase recognition.[43]	Choksi *et al.*	2023	Experimental / applied technical study
AI's potential in LC for detecting anatomical landmarks, distinguishing safe	Fernicola *et al.*	2024	Review

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[38] P. Mascagni, D. Alapatt, L. Sestini, *et al., Applications of artificial intelligence in surgery: clinical, technical, and governance considerations*, in *Cirugía Española (English Edition)*, 102, 2024, S66.

[39] M. Pavone, B. Baby, E. Carles, *et al., Critical view of safety assessment in sentinel node dissection for endometrial and cervical cancer: artificial intelligence to enhance surgical safety and lymph node detection (LYSE study)*, in *International Journal of Gynecological Cancer*, 35, 2025, 101789.

[40] C.B. Goldenberg, B.J. Kirby, P.A. Albrecht, *et al., AI chatbots in surgery: What does the future hold?,* in *Journal of Plastic, Reconstructive & Aesthetic Surgery*, 88, 2024, 310.

[41] A. Amin, S.A. Cardoso, J. Suyambu, *et al., Future of Artificial Intelligence in Surgery: A Narrative Review*, in *Cureus*, 16, 2024, e51631.

[42] A. Guni, P. Varma, J. Zhang, *et al., Artificial Intelligence in Surgery: The Future is Now* in *European Surgical Research,* 2024.

[43] S. Choksi, S. Szot, C. Zang, *et al., Bringing Artificial Intelligence to the operating room: edge computing for real-time surgical phase recognition*, in *Surgical Endoscopy, 37,* 2023, 8778.

from unsafe zones, and recognizing surgical phases.[44]			
Artificial intelligence in surgery: the emergency surgeon's perspective (the ARIES project).[45]	De Simone *et al.*	2022	Review
Situating Artificial Intelligence in Surgery: A Focus on Disease Severity.[46]	Korndorffer *et al.*	2020	Retrospective observational and experimental study
Potential and Promise: Artificial Intelligence in Pediatric Surgery.[47]	Sinha *et al.*	2024	Review

Table 2

3. Results

Starting from the analysis of the results about the robotic surgery, Williamson *et al.* conducted a review aimed at showing how these surgical techniques can enhance traditional laparoscopy.[48] The study outlines current trends and encourages discussion on using robotic systems to enhance laparoscopy. In some surgeries, robotics offered better management of complex cases, improved ergonomics (notably in obese patients), and superior 3D vision, but involved longer operating times and higher costs than laparoscopy. For example, in liver surgery, while laparoscopy remains the most common minimally invasive technique, robotic liver resections (RLR) have emerged as a promising alternative. Studies indicate that RLR may offer a safer and more ergonomic approach, especially for complex cases involving major resections or lesions in postero-superior liver segments. Rocca *et al.* evaluated the role of robotic surgery in managing colorectal liver metastases (CRCLM).[49] Their findings show that robotic surgery is safe and effective, with blood loss and complication rates comparable to or better than open and laparoscopic procedures. Scognamiglio *et al.* suggest that robotic surgery could soon become a viable alternative to laparoscopy, especially for complex liver, esophageal, and pancreatic surgeries.[50] Minimally invasive hepatobiliary and pancreatic surgery provides better short-term outcomes than open surgery but is technically challenging. Awad et Al analyzed the use of robotic approach in abdominal wall repair. When

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[44] A. Fernicola, G. Palomba, M. Capuano, *et al.*, *Artificial intelligence applied to laparoscopic cholecystectomy: what is the next step? A narrative review*, in *Updates in Surgery*, 76, 2024, 1655.

[45] B. De Simone, E. Chouillard, A.A. Gumbs, *et al.*, *Artificial intelligence in surgery: the emergency surgeon's perspective (the ARIES project)*, in *Discover Health Systems*, 1, 2022, 9.

[46] J.R. Korndorffer, M.T. Hawn, D.A. Spain, *et al.*, *Situating Artificial Intelligence in Surgery: A Focus on Disease Severity*, in *Annals of Surgery*, 272, 2020, 523.

[47] A. Sinha, S. Bhatt, *Potential and Promise: Artificial Intelligence in Pediatric Surgery*, in *Journal of Indian Association of Pediatric Surgeons*, 2024, 400.

[48] T. Williamson, S.E. Song, *op. cit.*

[49] A. Rocca, A. Scacchi, M. Cappuccio, *et al., op. cit.*

[50] P. Scognamiglio, B.O. Stüben, A. Heumann, *et al., op. cit.*

compared to laparoscopic surgery, robotic operations tended to result in fewer complications as well, although the difference was not statistically significant with longer operating times and shorter length of hospital stay.[51] Always considering abdominal surgery, minimally invasive surgery (MIS) is increasingly used to treat gastric cancer (GC). While laparoscopic gastrectomy (LG) offers advantages over open surgery, it remains technically challenging. Robotic gastrectomy (RG) is gaining popularity worldwide and may overcome some limitations of LG. The metanalysis from Guerrini *et al.* compared surgical and oncological outcomes between RG and LG. Results showed that RG had longer operating times but less blood loss and fewer severe surgical complications. Oncologically, RG retrieved more lymph nodes, though resection margins and recurrence rates were similar between RG and LG. Overall, RG and LG were comparable in safety, feasibility, and oncological effectiveness, with RG showing some improved short-term surgical outcomes.[52] In colorectal surgery laparoscopy improves outcomes but is challenging for rectal cancer, leading to more open surgeries. Robotics may overcome pelvic technical difficulties while maintaining oncologic safety and minimally invasive benefits with longer operative times and higher costs.[53] Zhang *et al.* analyzed robotic bariatric surgery (RBS) and found it associated with lower 90-day mortality and longer operative times compared to laparoscopic bariatric surgery (LBS). Other safety and effectiveness outcomes were comparable. RBS may offer future advantages pending long-term, comprehensive evaluations.[54] In revisional bariatric procedures, RBS in connected with fewer complications, shorter hospital stays, and less need for conversion to open surgery.[55] Anyomih *et al.* examined the use of the robotic approach in emergency surgical settings, for procedures such as cholecystectomy and colectomy and hospital stays were significantly shorter in the robotic surgery group.[56] Liu *et al.* compared robotic surgery versus laparoscopic surgery in thyroid neoplasms' treatment.[57] Robotic surgery appears to be a safe and viable option that minimizes intraoperative trauma and enhances quality of life, though its longer duration and reduced lymph node removal require careful consideration. In other surgeries such as breast surgery, robotic appears to be better in aesthetic results and patient satisfaction with bigger costs and operative time. At the same time robotic-assisted thoracoscopic surgery is gaining popularity for lung and mediastinal procedures due to better outcomes, less pain, and faster recovery compared to thoracotomy. Its minimally invasive approach offers greater precision but also presents physiological and logistical challenges, especially in patients with complex conditions, requiring careful perioperative management. Robotic-assisted surgery has transformed also gynaecologic oncology over the past 15 years, expanding patient access to minimally invasive benefits such as less blood loss, shorter hospital stays, fewer wound complications, and faster recovery. While cost-effectiveness and long-term out-

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[51] L. Awad, B. Reed, E. Bollen, *et al.*, *Does robotic surgery have a role in abdominal wall reconstruction? A systematic review and meta-analysis*, in *Journal of Plastic, Reconstructive & Aesthetic Surgery*, 106, 2025, 353.

[52] G.P. Guerrini, G. Esposito, P. Magistri, *et al.*, *op. cit.*

[53] F.Rondelli, A. Lucarini, G.M. Garbarino, *et al.*, *Comparison of Laparoscopic and Robotic Lateral Lymph Node Dissection for Rectal Cancer: A Systematic Review and Meta-analysis of Short- and Long-term Outcomes*, in *Annali Italiani di Chirurgia,* 96*,* 2025, 847.

[54] Z. Zhang, L. Miao, Z. Ren, *et al.*, *op. cit.*

[55] A.M. Velardi, P. Anoldo, S. Nigro, *et al.*, *op. cit.*

[56] T.T.K. Anyomih, A. Mehta, D. Sackey, *et al.*, *op. cit.*

[57] H. Liu, Y. Wang, C. Wu, *et al.*, *op. cit.*

comes remain debated due to limited trials, robotic technology's advanced features like 3D vision and improved ergonomics are widely valued.[58]

And what about costs?

Assessing the cost-effectiveness of robotic-assisted surgery (RAS) is complex, particularly in emergency settings due to case variability. Myla *et al.* highlight a lack of studies on the economic impact of RAS in acute care.[59] This review examines its cost-effectiveness in elective surgery, with potential applications to urgent contexts. Some studies suggest lower costs compared to laparoscopy, attributed to reduced use of materials and disposable instruments, shorter operative times due to increased proficiency, and decreased hospitalization, readmissions, and recovery times. Rodrigues Martins *et al.* and Schmidt *et al.* the robotic approach for one of the first uses that has been made of it, the urological. [60], [61] In the first one study, costs rose with higher ASA scores, longer surgeries, greater use of clip packs, and extended hospitalization, but dropped by 11.5% when using four instead of five robotic instruments. The second one study compared costs of open vs robotic-assisted radical prostatectomy (RARP) using one-year claims data. While RARP had higher initial hospitalization costs, the gap narrowed by six months and shifted to a $383 saving at one year, suggesting long-term cost advantages.[62] Finally in colorectal surgery evidence shows similar surgical quality and outcomes between robotic and laparoscopic methods, with robotics offering fewer conversions and less surgeon fatigue but longer operative times and higher costs. Finally, robotic surgery offers ergonomic benefits for surgeons, including improved visualization with 3D vision and surgeon-controlled cameras, better posture from a seated position, and enhanced instrument manoeuvrability with greater freedom of movement and tremor reduction. However, drawbacks include lack of tactile feedback, visual and mental fatigue from longer surgeries, and workflow interruptions. Most ergonomic disadvantages may be reduced with experience and technological advances. While many studies are lab-based, more clinical research is needed to explore these ergonomic benefits, focusing on visualization, posture, instrument control, and issues like port placement and robotic arm collisions.

Regarding the second focus of our paper, Li et al highlight that over the past twenty-five years, research on artificial intelligence applied to surgery has shown steady growth, confirming its transition from an emerging technology to a well-established component of surgical innovation.[63] At the same time the analysis conducted by Hossain *et al.* highlighted a steady growth in the literature on AI in surgery, with a significant acceleration starting from 2018.[64] In general AI is progressively acquiring a strategic role in all phases of the surgical pathway — preoperative, intraoperative, and postoperative — contributing to improved diagnostic accuracy, operational efficiency, and patient safety. An example is its application in the management of thoracoabdominal trauma, providing tangible benefits in the preoperative phase [diagnosis and triage], intraoperative phase [safety and decision support], and postoperative phase [risk

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[58] K.H. Clair, K.S. Tewari, *op. cit.*

[59] K. Myla, N. Bou-Ayash, W.C. Kim, *et al.*, op. cit.

[60] Y.M. Rodrigues Martins, P. Romanelli de Castro, A.P. Drummond Lage, *et al.*, *op. cit.*

[61] B. Schmidt, J.T. Leppert, *op. cit.*

[62] K.H. Clair, K.S. Tewari, *op. cit.*

[63] H. Li, Z. Han, H. Wu, *et al.*, *op. cit.*

[64] I. Hossain, A. Madani, S. Laplante, *op. cit.*

assessment and complication management].[65] However, the adoption of AI in emergency surgery is progressing more slowly compared to other fields, due to the complex decision-making involving multiple clinical and human factors. The findings of an article by Morris *et al.* highlight that AI holds significant potential to enhance both surgical training and clinical decision-making but with some difficulties in understanding and interpreting AI algorithm mechanisms and the risk of inaccurate predictions.[66] The crucial role of artificial intelligence as a tool to improve accuracy, efficiency, and standardization in the evaluation of surgical performance, with future prospects for integrating video data to further refine the predictive capabilities of models, emerged from the study conducted by Mohamadipanah *et al.*[67] Machine learning and deep learning algorithms have proven effective in predicting postoperative complications, estimating mortality, preventing readmissions, and optimizing hospital length of stay. Five main application areas have emerged: predictive modelling of surgical risks; preoperative simulations through augmented reality and digital twins; real-time intraoperative decision support; safety monitoring using systems like the OR Black Box; partial automation of procedures via intelligent robotics. These tools show potential to transform the current surgical paradigm into a data-driven clinical ecosystem. Additionally, multidimensional AI models for home monitoring of activities of daily living (ADLs) suggest new possibilities for personalized postoperative care. Promising results have also emerged in the pediatric field. Artificial intelligence is transforming pediatric surgery by enhancing diagnosis, planning, perioperative care, training, and doctor-patient communication.[68] A relevant example of artificial intelligence's application is in the treatment of colorectal cancer. As highlighted by the study of Mascagni et al., AI is demonstrating a transformative impact throughout the entire care pathway. In diagnostics, AI would significantly improve the detection and classification of polyps during colonoscopy, with expected benefits in reducing mortality and healthcare costs. In the preoperative phase, predictive algorithms assist in assessing tumor invasion and lymph node risk, facilitating more targeted surgical decisions. AI also enhances the safety of endoscopic dissection and personalized surgical planning, improving intraoperative precision and reducing the risk of complications. However full integration of AI in surgery requires a multidisciplinary approach focused on safety, transparency, and appropriate use. Postoperatively, predictive models assist in preventing complications and optimizing follow-up, thereby improving clinical efficiency and patient management. A clear example of how artificial intelligence can be applied in surgery is provided by Pavone *et al.* in the field of gynecology. Their study explored the feasibility of using video-based assessments to evaluate the Critical Views of Safety (CVS) criteria for sentinel lymph node dissection in patients with endometrial or cervical cancer. The CVS approach is designed to standardize the evaluation of surgical quality, enhance the accuracy of sentinel lymph node identification, and ultimately improve patient outcomes.[69] The researchers collected surgical videos from patients undergoing minimally invasive sentinel lymph node dissection for cervical and endometrial carcinoma. They proposed three CVS criteria—lateral pararectal space, lateral paravesical space, and internal iliac artery—based on anatomical landmarks deemed essential to identify before proceeding with sentinel node dis-

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[65] B. Lee, N. Narsey, *op. cit.*
[66] M.X. Morris, D. Fiocco, T. Caneva, *et al.*, *op. cit.*
[67] H. Mohamadipanah, C. Perumalla, S. Yang, *et al.*, *op. cit.*
[68] Y. Miyake, G. Retrosi, R. Keijzer, *op. cit.*
[69] M. Pavone, B. Baby, E. Carles, *et al.*, *op. cit.*

section, as established by previous expert consensus. Introducing video-based assessment of these criteria provides a foundation for testing the feasibility of artificial intelligence algorithms capable of automatically identifying and documenting the CVS in surgical recordings. This represents an important first step toward developing AI systems that can autonomously assess and record these safety views in both laparoscopic and robotic surgeries. Beyond identifying anatomical structures during laparoscopic cholecystectomy (LC), artificial intelligence has also been trained to recognize surgical phases. Fernicola *et al.* in their review highlighted AI's potential in LC for detecting anatomical landmarks, distinguishing safe from unsafe zones, recognizing surgical phases using surgical videos. [70] Best performance was seen for Calot's triangle dissection, clipping/cutting, and gallbladder dissection, while preparation was often misclassified as Calot's dissection. Accuracy decreased with increasing procedural complexity (92% for low vs. 81% for high complexity) and was influenced by adverse events such as major bile leak (77%). Cross-hospital testing revealed variations in accuracy (79–90.6%) due to differing devices and techniques. Such semantic and temporal segmentation could help prevent bile duct injury, enhance surgical training, and eventually enable real-time decision support in the operating room. In education, AI supports the analysis of surgical performance and personalized training. Furthermore, the automated annotation of laparoscopic cholecystectomy videos has significantly increased the efficiency of video review, allowing the analysis of approximately 50 videos per hour. Correct identification of the Critical View of Safety was observed in less than 10% of cases, with a higher frequency of clear visualization of the hepatocystic triangle in less severe procedures. The agreement between AI annotations and clinical evaluations exceeded 75%, reaching 99% for intraoperative events, which were significantly associated with the severity of the pathology and the failure to achieve proper exposure of the CVS. Notably, the frequency of intraoperative events was more than double in the more severe cases. [71]

4. Discussion

Robotic surgery and artificial intelligence represent two of the most significant modern innovations in the surgical field, each contributing in unique ways to the evolution of clinical practice.

The robotic system enables 3D surgery without assistant-held instruments, unlike traditional laparoscopy, which relies heavily on assistants. A clear gap exists in technical capabilities and applications, with some procedures positioned between the two methods. Robotic surgery has been proposed for emergency procedures; its role compared to traditional laparoscopy remains debated. Current evidence shows that robotic assistance is technically feasible in urgent general surgery and achieves outcomes comparable to laparoscopy, especially in clinically stable patients. Considering the economic problems, the "easier" is the surgery the more this problem is felt. One of these surgeries is abdominal wall reconstruction. While robotic procedures tend to be more expensive than laparoscopic surgery, the total cost may be offset by quicker patient recovery and a lower rate of complications compared to open surgery. Also, in bariatric surgery the use of robotic surgery appears to be more expansive such as in the paper of Velardi *et al.* [72] In urological surgery hospitalization costs were mainly driven by robotic surgical supplies,

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[70] A. Fernicola, G. Palomba, M. Capuano, *et al.*, *op. cit.*

[71] J.R. Korndorffer, M.T. Hawn, D.A. Spain, *et al.*, *op. cit.*

[72] A.M. Velardi, P. Anoldo, S. Nigro, *et al.*, *op. cit.*

operating room time, patient health status, and length of stay. Reducing instrument use was the most impactful modifiable factor for lowering costs. Similar patterns are seen in other urologic procedures, though robotic approaches often have higher short-term costs. The findings support that, despite early scepticism and high purchase costs, robotic prostatectomy has not imposed undue long-term financial burdens, underscoring the importance of balancing innovation with cost-effectiveness in surgical care. High-quality comparative studies between robotic-assisted surgery and laparoscopy are needed to justify costs and assess patient benefits.

Considering operative time compared to open surgery, Robotic surgery involves longer operative time as in the paper of Liu at al.[73] Always in this paper we have the problem of results; fewer lymph nodes retrieved, higher postoperative thyroglobulin levels before radioactive iodine ablation, similar complication rates. Longer operative time are described in papers about gastric and bariatric robotic surgery. In line with bigger costs and longer operative times Maes-Carballo *et al.* explained the possibility of breast robotic approach.[74] Despite higher costs and longer operation times, robotic surgery is expected to grow, especially in specialized canters. It offers similar outcomes to open surgery, with potential for improved precision as technology advances. Robotic platforms have redefined minimally invasive surgery by enhancing precision, reducing surgeon fatigue, and improving patient recovery times. At the same time, AI is transforming contemporary surgery towards data-driven and personalized models, although challenges related to standardization, clinical validation, and interdisciplinary collaboration persist. Ethical and legal aspects, such as medical liability, algorithmic bias, privacy, and inequality of access, require stringent regulation These critical issues also emerge in the Australian context, where clinical use of AI remains limited, albeit with promising prospects, particularly in surgical training. AI holds great potential to enhance both surgical training and clinical decision-making processes, yet concerns persist regarding users' understanding and interpretation of algorithms and the risk of predictive errors. The introduction of AI in surgery represents a paradigmatic evolution compared to previous innovations, extending the surgeon's sensory enhancement to the cognitive domain. This includes preoperative support for risk assessment, resource management, and complication prediction, as well as intraoperative guidance through augmented reality and robotics. The role of AI in standardizing and objectively evaluating surgical performance is crucial, with prospects for integrating video data to further refine predictive capabilities. Furthermore, AI has enabled an objective assessment of surgical skills with high precision and significant correlation with traditional evaluation methods.[75] AI represents a significant breakthrough in modern surgery, offering tangible clinical benefits alongside vast potential yet to be fully explored and consolidated. Achieving full integration of AI into the surgical pathway requires rigorously addressing technical, ethical, educational, and regulatory challenges, while promoting a multidisciplinary approach focused on safety, transparency, and appropriate use.[76] Next-generation robots will integrate surgeon-guided movements with personalized surgical plans from preoperative 3D segmentation. Advances in cloud computing, big data, and AI are driving the development of smart robotic systems, with surgical

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[73] H. Liu, Y. Wang, C. Wu, *et al.*, *op. cit.*

[74] M. Maes-carballo, M. García-García, I. Rodríguez-Janeiro, *et al.*, *op. cit.*

[75] T. Kinoshita, M. Komatsu, *Artificial Intelligence in Surgery and Its Potential for Gastric Cancer* in *Journal of Gastric Cancer,* 23, 2023, 400.

[76] N. Kenig, J. Monton Echeverria, A. Muntaner Vives, *Artificial Intelligence in Surgery: A Systematic Review of Use and Validation*, in *Journal of Clinical Medicine,* 13, 2024.

technology companies partnering with major tech firms to create advanced intelligent robots.[77] While its integration offers significant benefits, it also raises complex ethical concerns.[78] Precisely with regard to the ethical problem, the works of Ricci *et al.*[79] and Damato *et al.*[80] address, from different perspectives, the delicate balance between individual autonomy, medical intervention and ethical-legal responsibility. On the one hand, the topic of human enhancement as an exercise of freedom beyond therapy is discussed, raising the need for clear rules for a conscious and non-discriminatory use of enhancement technologies. On the other, the problem of compulsory medical treatment in serious eating disorders is analysed, where the patients would be compromised and informed consent is difficult to evaluate. The centrality of human dignity emerges as a guiding criterion for balancing the right to treatment, personal freedom and the limits of medical intervention. In both cases, it is noted that the tools for measuring awareness, will, and decision-making capacity are often imperfect, and that greater interdisciplinary understanding (medical, psychological, ethical, legal) is needed; the constraint of respect for dignity emerges, which must be the guiding criterion for regulating what is permitted, what is obligatory and what is prohibited. On the other hand, the educational and formative value of innovations must also be considered; robotic surgery mixed to the new technologies, plays a crucial role in training future surgeons by offering varied exercises to develop basic motor skills like joystick handling, pedal use, camera control, and energy application, before advancing to complex tasks such as suturing and dissection. Its key benefit is supporting self-assessment, allowing learners to quickly gain autonomy by identifying and correcting mistakes early. Although simulation training requires significant investment in equipment and staff, it is essential due to the increasing use of robotic techniques alongside traditional surgery. Well-structured education is necessary to ensure a safe and effective transition to clinical practice.[81] Robotic-assisted surgical training is rapidly evolving, with approaches like online platforms, hands-on sessions, and advanced simulators developed over the past decade to address the growing demand for skilled robotic surgeons. Early validation studies show promising results, but there remains a need for specialized simulation modules for specific surgical fields. Future research should compare training methods to help establish a standardized curriculum for education and certification.[82] Robotic surgery demands both technical and non-technical expertise, making the learning curve for certain procedures longer than expected. Structured training programs play a key role in supporting surgeons during this phase and can lead to outcomes comparable to those of experienced professionals. However, only a few validated curricula currently exist. To ensure patient safety and optimize results, the development of standardized and comprehensive training programs is essential. While training opportunities are expanding, an addi-

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[77] M. Bhandari, T. Zeffiro, M. Reddiboina, *Artificial intelligence and robotic surgery: current perspective and future directions*, in *Current Opinion in Urology,* 30*,* 2020, 48.

[78] J.E. Knudsen, U. Ghaffar, R. Ma, *et al.*, *Clinical applications of artificial intelligence in robotic surgery*, in *Journal of Robotic Surgery,* 18, 2024, 102.

[79] L. Ricci, B. Di Nicolò, P. Ricci, *et al., The exercise of rights beyond therapy: on Human Enhancement,* in *BioLaw Journal*, 1, 2019, 497.

[80] F.M. Damato, P. Ricci, R. Rinaldi, *Informed consent and compulsory treatment on individuals with severe eating disorders: a bio-ethical and juridical problem*, in *La Clinica Terapeutica,* 174, 2023, 365.

[81] L. Bresler, M. Perez, J. Hubert, *et al.*, *Residency training in robotic surgery: The role of simulation*, in *Journal of Visceral Surgery,* 157, 2020, S123.

[82] R. Chen, P. Rodrigues Armijo, C. Krause, *et al.*, *A comprehensive review of robotic surgery curriculum and training for residents, fellows, and postgraduate surgical education*, in *Surgical* Endoscopy, 34*,* 2020, 361.

tional challenge is the potential over-reliance on automated or semi-automated systems. There is a risk that younger surgeons may develop reduced proficiency in fundamental open or laparoscopic techniques, which remain essential in complex or emergent situations where robotic platforms may not be available. Despite the promising advantages described, it is important to acknowledge that much of the available evidence remains heterogeneous and often derived from single-center or retrospective studies. This raises the risk of overestimating the clinical benefits of robotic platforms and AI-based tools, especially when long-term outcomes are not consistently reported. A more cautious interpretation is therefore required when translating current findings into broad clinical recommendations. We also note that on September 17, 2025, Italy approved the first national law on artificial intelligence in the EU, integrating the European AI Act with internal rules to regulate the development and use of AI. One of the main focuses is healthcare, where the law aims to ensure the centrality of the physician, data security, and algorithm transparency, even in the most advanced clinical applications such as AI-assisted surgery. The legislation provides for: traceability of automated decisions, to protect patients; enhancement of clinical data for research, while respecting privacy; development of AI tools to support diagnoses and surgical procedures, always under human supervision.

With this regulatory framework, Italy intends to encourage the adoption of AI in healthcare by ensuring ethics, safety, and responsibility, and promoting innovation in surgical practices through reliable and regulated technologies. In conclusion, sometimes we could question us “where are we going?”; we still can’t answer but travel appears to be so beautiful.

5. Conclusions

Robotic surgery and artificial intelligence are transforming surgical practice by integrating cognitive technology and predictive tools. The da Vinci system has improved precision, ergonomics, and training, with the greatest benefits seen in complex procedures. Its use is increasing in general and emergency surgery, although high costs and longer operating times still limit its applicability in simpler interventions. Ethical, legal, and economic issues also remain open, requiring procedure-specific evaluations and more standardized cost–benefit analyses.

Future developments point to greater integration between advanced robotics and AI, with systems becoming increasingly autonomous. However, the surgeon’s central role remains essential, as do the principles of patient autonomy, informed consent, and freedom of therapeutic choice. The adoption of technologies that enhance or replace human capabilities calls for clear regulation that distinguishes between support and substitution. In this regard, the recent Italian law on artificial intelligence (which mandates traceability, safety, and human oversight in healthcare) is a significant step forward.

Robotics and AI should be regarded as tools that serve the individual and play a key role in training future surgeons, provided they are embedded in validated, multidisciplinary educational programs. The ongoing transformation therefore requires a constant balance between technological innovation, patient dignity, and ethical responsibility.