Review

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# Artificial intelligence: revolutionizing robotic surgery: review

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**Abstract**

Robotic surgery, known for its minimally invasive techniques and computer-controlled robotic arms, has revolutionized modern medicine by providing improved dexterity, visualization, and tremor reduction compared to traditional methods. The integration of artificial intelligence (AI) into robotic surgery has further advanced surgical precision, efficiency, and accessibility. This paper examines the current landscape of AI-driven robotic surgical systems, detailing their benefits, limitations, and future prospects. Initially, AI applications in robotic surgery focused on automating tasks like suturing and tissue dissection to enhance consistency and reduce surgeon workload. Present AI-driven systems incorporate functionalities such as image recognition, motion control, and haptic feedback, allowing real-time analysis of surgical field images and optimizing instrument movements for surgeons. The advantages of AI integration include enhanced precision, reduced surgeon fatigue, and improved safety. However, challenges such as high development costs, reliance on data quality, and ethical concerns about autonomy and liability hinder widespread adoption. Regulatory hurdles and workflow integration also present obstacles. Future directions for AI integration in robotic surgery include enhancing autonomy, personalizing surgical approaches, and refining surgical training through AI-powered simulations and virtual reality. Overall, AI integration holds promise for advancing surgical care, with potential benefits including improved patient outcomes and increased access to specialized expertise. Addressing challenges and promoting responsible adoption are essential for realizing the full potential of AI-driven robotic surgery.

**Keywords:** artificial intelligence, computers, haptic technology, robotic surgical procedures, surgeons

## Introduction

Robotic surgery, a minimally invasive surgical technique utilizing computer-controlled robotic arms, has revolutionized modern medicine. Compared to traditional laparoscopic surgery, it offers enhanced dexterity, improved visualization, and reduced tremors, leading to several benefits for patients. These include smaller incisions, lesser blood loss, faster recovery times and reduced pain[1].

Artificial intelligence (AI) encompasses a range of intelligent technologies that can learn, reason, and make decisions without explicit programming. In the medical field, AI is finding increasing applications in various areas, including medical imaging analysis and diagnosis[2], drug discovery and development[3] and robot-assisted surgery[4].

The integration of AI into robotic surgery holds immense promise for further enhancing its precision, efficiency, and accessibility. This paper explores the current state of AI-driven robotic surgical systems, their advantages and limitations, and future directions for this transformative technology.

The development of robotic surgery can be traced back to the 1980s with the introduction of the PUMA robot[5]. Early robotic surgical systems were primarily used for telemanipulation, allowing surgeons to operate remotely. Subsequent advancements led to the creation of more sophisticated robotic arms with improved dexterity and control. The landmark FDA approval of the da Vinci Surgical System in 2000 marked a significant milestone in the field[6].

### HIGHLIGHTS

- Robotic surgery, known for its minimally invasive techniques and computer-controlled robotic arms, has revolutionized modern medicine by providing improved dexterity, visualization, and tremor reduction compared to traditional methods.
- AI applications in robotic surgery focused on automating tasks like suturing and tissue dissection to enhance consistency and reduce surgeon workload.
- AI integration holds promise for advancing surgical care, with potential benefits including improved patient outcomes and increased access to specialized expertise.

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The application of AI in healthcare has witnessed significant growth in recent years, fueled by advancements in machine learning algorithms and the availability of vast amounts of medical data. Early applications focused on tasks like analyzing medical images for cancer detection or predicting patient outcomes[7–9].

The initial integration of AI in robotic surgery focused on automating specific surgical tasks, such as suturing or tissue dissection. These applications aimed to improve consistency and reduce surgeon workload[4,10].

Current AI-driven robotic surgical systems incorporate various functionalities, including image recognition and segmentation: AI algorithms can analyze surgical field images in real-time to identify critical structures, blood vessels, and tumors, aiding surgeons in decision-making[11,12].

With motion control and path planning: AI can assist in planning and optimizing surgical instrument movements, leading to smoother and more precise procedures[13]. With haptic feedback: AI can enhance the sense of touch experienced by the surgeon through the robotic interface, providing valuable feedback on tissue texture and resistance[14,15].

## Methods

A comprehensive literature search for this narrative review was conducted using the PubMed, Embase and Google Scholar databases, focusing on peer-reviewed publications from January 2010 till May 2024 to ensure the inclusion of the latest developments in the field. The search employed the following terms: artificial intelligence and related terms, machine learning and related terms, and robotic or robot-assisted surgery and related terms. The selection process followed the PRISMA guidelines, as illustrated in Figure. Initially, 483 unique records were identified. After screening, 457 full-text articles were evaluated for their relevance, and 103 were chosen as representative of the most recent advancements in the field to be included in this narrative review. The search terms were reviewed and examined by two authors. Any disagreements were resolved through the involvement of an independent third author. The study methodology is illustrated in Figure 1.

## Review

The advancement of autonomous control in surgical robotic platforms holds promise for achieving greater precision, intelligent maneuvers, and avoidance of tissue damage. Although many autonomous robotic systems remain experimental, some have already made their way into clinical practice. Ongoing research aims to develop fully autonomous surgical systems capable of performing complex tasks on deformable soft tissues, such as suturing and intestinal anastomosis, within open surgical settings. Initial findings suggest that supervised autonomous procedures can surpass both expert surgeon-performed surgeries and robot-assisted approaches in terms of effectiveness and consistency. These strides in autonomous robotic surgery have the potential to enhance surgical outcomes and expand access to optimized techniques[16,17].

Despite initial skepticism among some surgeons, advances in AI and robotics are paving the way for increased autonomy in surgical procedures. While the absence of haptics has traditionally hindered the widespread adoption of robotic surgery, there is growing recognition within the surgical community of the true potential of robotics. Consequently, the integration of AI is becoming increasingly crucial, offering new avenues for enhancing surgical precision and outcomes[17–19].

The levels of autonomy in robotic surgery offer a progressive framework for understanding the evolving capabilities of surgical robots. As per Yang *et al.*'s[20] classification of the level of autonomy shown in the figure; At Level 0, exemplified by the da Vinci system, surgeons directly control robotic movements without any assistance or constraints[21]. Moving up to Level 1, robots begin to assist surgeons by providing virtual fixtures or active limitations to guide their actions, facilitated by technologies like tissue interface sensing and eye tracking[21].

Level 2 autonomy grants robots the ability to execute specific surgical tasks based on physician-provided guidelines, with control shifting from human operators to machines during task execution[21]. Examples include autonomous algorithms for tasks like tip retroflection in magnetic colonoscopy and tissue retraction systems using visual markers and fuzzy logic[19,22].

Advancements to Level 3 introduce perceptual abilities to robots, enabling them to plan and execute tasks independently within the surgical setting. Examples include flexible endoscopic robots navigating unstructured environments autonomously during procedures like colonoscopy[17,22,23].

Level 4 autonomy represents a significant leap, where robots interpret preoperative and intraoperative data to create intervention plans, execute actions, and adapt in real-time. While specific examples are limited, potential applications include intelligent tissue removal in cancer surgery, aiming to minimize damage to healthy tissue while targeting cancerous areas[21].

Level 5 autonomy, where robots perform surgery without human intervention, remains aspirational and has not yet been achieved. However, advancements across lower autonomy levels indicate a promising trajectory toward more sophisticated and independent robotic surgical systems[21].

The levels of surgical autonomy are illustrated in Figure 2.

Several examples illustrate the current state of autonomous robotic surgery interventions, particularly at level 3. One notable system is the Smart Tissue Autonomous Robot (STAR), designed by Axel Kriger, which has demonstrated the ability to match or even surpass human surgeons in bowel anastomosis[24]. STAR operates autonomously with human approval of the surgical plan, exhibiting remarkable efficacy in reducing errors and achieving smoother tissue reconstruction. The system assesses tissue thickness and structure to devise a suture insertion plan, then proceeds to sew autonomously after receiving human confirmation[24]. Continuous communication with the surgeon ensures adaptation to tissue deformation or unexpected changes throughout the procedure[24].

While advancements in autonomous suturing are promising, they are currently limited to anatomical phantoms or ex-vivo models, with full autonomy in suturing still a distant prospect[21]. Another autonomous system, TSolution One, specializes in bone carving according to a pre-established plan, particularly in hip and knee replacement surgeries[25]. Although effective in bone drilling, its inability to differentiate between tissue types necessitates manual relocation of soft tissues to prevent damage. However, long-term data on survival and outcomes are lacking, impeding the assessment of its cost-effectiveness[25].

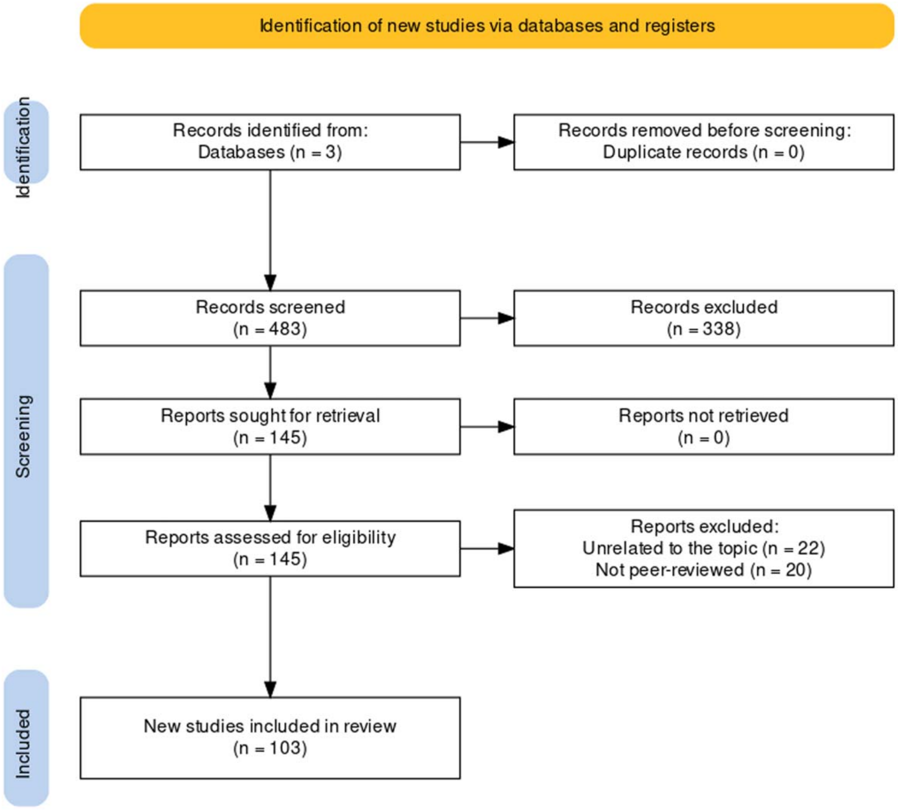

**Figure 1.** Flowchart of study methodology.

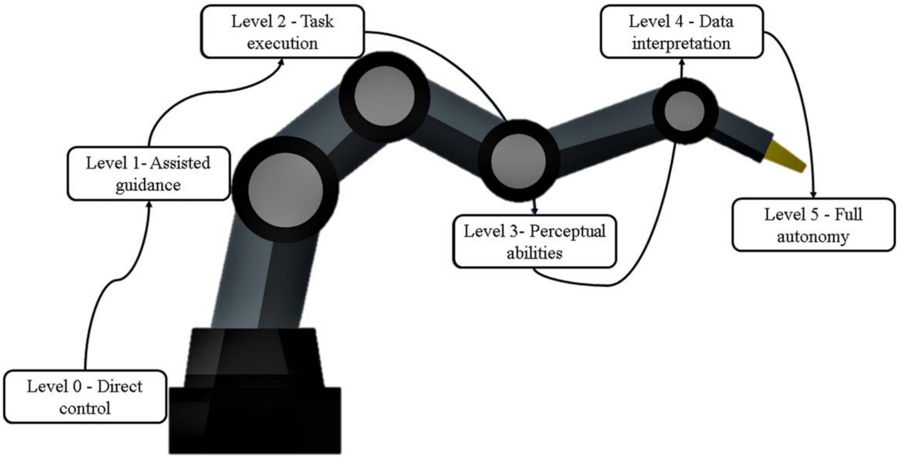

**Figure 2.** Levels of robotic autonomy.

Veebot represents another automated system specifically for blood sample collection. Employing infrared light and ultrasonography, Veebot identifies suitable veins for blood collection with a success rate comparable to human performance[26,27]. Similarly, the ARTAS system, a robotic graft harvesting device, enhances hair restoration surgery through follicular unit extraction, leveraging robotic precision for optimal harvesting[28].

The CyberKnife robot showcases advanced autonomous capabilities in performing radiosurgery for brain and spine malignancies under human supervision. Utilizing stereotactic principles and real-time imaging, the system continuously adjusts for minor patient posture variations during treatment, ensuring precise and effective radiation delivery[29].

These examples underscore the evolving landscape of autonomous robotic surgery, highlighting both achievements and ongoing challenges in integrating artificial intelligence into surgical practice.

Several AI algorithms are being explored for use in robotic surgery, including:

- Deep learning: This technique is particularly adept at image recognition and can be used to identify anatomical structures, predict bleeding risks, and even guide surgical instrument trajectories[30–34].
- Reinforcement learning: This approach allows AI systems to learn through trial and error, potentially enabling them to perform complex surgical tasks autonomously in the future[35].

The integration of AI in robotic surgery is a rapidly evolving field with numerous ongoing advancements. Here are some compelling case studies and examples across different surgical specialties.

### *Minimally invasive cardiac surgery*

AI-assisted robotic coronary artery bypass grafting (CABG): Studies are demonstrating the potential of AI to improve outcomes in minimally invasive cardiac surgery. A multicenter, retrospective study published in the Journal of Thoracic and Cardiovascular Surgery (JTCVS) by Cuartas *et al.* and Cao *et al.*[36,37] explored the use of AI-assisted robotic minimally invasive CABG. The results showed promising outcomes, with shorter operative times, reduced blood loss, and fewer complications compared to traditional techniques.

Research is ongoing to leverage AI for real-time risk stratification during cardiac surgery. This could involve analyzing various physiological parameters to predict potential complications and guide surgeons in making informed decisions. Bonatti *et al.* and Ralf *et al.*[38,39] highlight the potential applications of AI in this area.

### *Neurological procedures*

AI-powered Image Guidance for Brain Tumor Resection: Multiple studies[40–42] showcased the potential of AI for assisting in complex brain tumor surgeries. The study described a case where AI-powered image guidance helped surgeons achieve a more complete tumor resection during delicate brain surgery, potentially leading to improved patient outcomes.

AI is showing promise in assisting with delicate neurological procedures like brain tumor removal. A recent article in Nature Medicine highlighted a case where AI-powered image guidance helped surgeons achieve a more complete tumor resection during a complex brain surgery[40–42]

AI algorithms are being explored for pre-surgical planning and intraoperative navigation in neurological procedures. This could involve creating 3D models of the brain based on patient scans and utilizing AI for real-time visualization of critical structures during surgery.

### *Orthopedic surgery*

In orthopedic surgery, the initial application of AI concentrated on hip and knee procedures, employing data from the preoperative, intraoperative, and postoperative phases. The adoption of AI in shoulder surgery is more recent, with a growing number of reports but limited comprehensive studies[43].

Patient-specific instrumentation (PSI), which has been developed over an extended period and is now commonly used in shoulder surgeries like shoulder arthroplasty, contributes to successful outcomes by ensuring precise implant placement. Properly securing and aligning the glenoid component presents a major challenge in total shoulder arthroplasty (TSA), and PSI supports surgeons by facilitating preoperative planning. A meta-analysis of 12 studies involving 227 participants revealed that PSI greatly enhanced glenoid positioning and decreased component malpositioning from 68.6 to 15.3% compared to traditional methods[44].

Concurrently, robotic-assisted surgery has advanced significantly, especially in total knee arthroplasty (TKA) and total hip arthroplasty (THA). Platforms like the MAKO robotic arm-assisted system improve preoperative evaluations through CT scans, offering a 3D perspective of the joint that aids in accurate implant placement and virtual adjustments for balanced knee ligaments[45]. Research indicates that the MAKO system enhances the precision of component positioning, reduces post-operative pain and hospital stays, and improves functional outcomes[45,46]. For THA, the MAKO system has shown superior results with comparable complication rates to conventional methods, and patients report better outcomes and fewer instances of implant malpositioning[47,48].

In shoulder surgery, AI is also progressing in the diagnosis and treatment of conditions such as rotator cuff tears (RCT). Traditionally, orthopedists diagnose RCT by interpreting MRI data, but deep learning systems using 3D convolutional neural networks (CNN) have been created for automated, accurate diagnosis. These systems can identify RCT, determine tear sizes, and visualize tear locations. Additionally, AI algorithms can assess muscle atrophy to predict the reparability of extensive RCTs, improving diagnostic efficiency and objectivity by measuring factors like the supraspinatus muscle occupation ratio[49,50].

Research suggests AI can improve implant positioning and potentially reduce long-term complications in orthopedic surgery. Batailler *et al.* and Kayani *et al.*[51,52] investigated AI-assisted robotic TKA. The results demonstrated improved component positioning and alignment compared to conventional techniques, potentially leading to better implant longevity and patient outcomes.

AI-powered robotic systems are being utilized for complex orthopedic surgeries like hip and knee replacements. Research published in The Bone & Joint Journal found that AI-assisted robotic surgery for total knee arthroplasty resulted in improved implant positioning and potentially reduced long-term complications[51–53].

The integration of AI and robotic technologies in orthopedic surgery is revolutionizing preoperative planning, intraoperative accuracy, and postoperative results across a range of surgeries, including those for the hip, knee, and shoulder.

AI has the potential to personalize surgical approaches in orthopedics based on factors like patient anatomy and medical history. This could involve optimizing implant selection and surgical techniques for each individual patient.

### *Urology*

Robotic-assisted laparoscopic prostatectomy for prostate cancer with AI for improved tissue identification and nerve sparing[54]. The adoption of minimally invasive robotic surgery has seen a notable increase, especially for significant uro-oncological procedures. This innovation has profoundly transformed the surgical landscape, representing a major advancement toward the most effective and least invasive treatment options for patients. Modern robotic surgery systems typically employ a "master–slave" model, where surgeons control robotic arms remotely from an advanced console. This collaboration between human expertise and machine precision allows for meticulous monitoring and enhancement of surgical actions through AI[55].

Machine learning (ML) has been extensively applied across various medical domains, improving disease diagnosis accuracy, aiding therapy selection, facilitating patient monitoring, and assisting in primary prevention risk assessment. ML techniques are crucial for enhancing surgical systems, particularly through the automated analysis of patient imaging and precise tracking of surgical anatomy and instruments during the perioperative period[55,56].

Although no surgical system can yet perform operations entirely independently, robots have shown promising results in tasks such as anatomic tracking, suturing, and biopsy sampling[57]. The field of urology has seen an increase in the use of semi-autonomous surgical systems like Aquablation, with studies demonstrating the benefits of robotic assistance in therapeutic procedures[58]. Advances in selecting surgical candidates and the development of automated surgical robotic systems could significantly improve surgical precision and patient outcomes[55].

Robotic surgery leverages advanced 3D visualization to augment the surgeon's skills and accuracy. However, the absence of haptic feedback can negatively impact surgical outcomes[59]. Visual cues alone govern actions like dissection, pressure application, and tissue response evaluation, which can lead to issues such as excessive force on delicate tissues or insufficient force during knot-tying. For instance, excessive force during robotic radical prostatectomy (RARP) can damage neurovascular bundles, causing neuropraxia and delaying the recovery of sexual function, while insufficient force may lead to poor suture retention[55,59]. To address these issues, Dai *et al.*[59] developed an advanced warning system to detect suture breakage, incorporating biaxial shear detection and haptic feedback to alert the surgeon before a potential suture rupture. This system, integrated with the Da Vinci surgical system, provides vibrotactile feedback as suture tension approaches its limit, leading to a significant reduction in suture breakage and knot slippage and improved task consistency among inexperienced surgeons[59].

Additionally, Piana *et al.*[60] demonstrated the use of three-dimensional augmented reality (AR) guidance during kidney transplantation (KT) to enhance surgical navigation and safety for patients with atheromatic vascular disease. This technology, which does not require haptic input, utilizes high-accuracy CT scan imaging to create 3D virtual models that are overlaid onto the vasculature during robot-assisted kidney transplantation (RAKT) using the Da Vinci console[60].

Computer vision (CV), a subset of machine learning that focuses on image analysis, also holds promise for improving the diagnosis and identification of urologic conditions[61]. For example, CV algorithms applied to CT abdominal imaging data can accurately locate kidney stones, thanks to advanced image signal processing that allows the algorithms to discern even the smallest visual differences between abnormal and healthy anatomical structures[55,61,62]

### *Gastrointestinal surgery*

Robotic-assisted minimally invasive colorectal surgery with AI is being studied for enhanced visualization and improved surgical precision[63].

Robotic systems have shown significant effectiveness in colorectal cancer surgeries, particularly in complex procedures such as total mesorectal excision and complete mesocolon excision[1,64]. The robotic platform aids surgeons in performing vascular dissection, intracorporeal anastomoses, and lymphadenectomy, especially in anatomically challenging areas like those near critical vascular structures or the lateral pelvic walls[64]. Many medical centers now standardize the use of robotic assistance for rectal resections, reflecting the increased success and advantages of robotic surgery in these technically demanding colorectal procedures[1,65].

One major concern regarding the widespread adoption of robotic assistance in colorectal surgery has been the high cost. Nevertheless, substantial evidence consistently demonstrates the undeniable benefits of robotic surgery, particularly in left colectomies and various rectal procedures, often surpassing the capabilities of advanced 3D laparoscopic systems[15,66]. Robotic-assisted surgery can overcome the limitations of traditional laparoscopy, offering advantages such as reduced blood loss, shorter hospital stays, faster restoration of bowel function, favorable oncological outcomes, and a lower conversion rate to open surgery[1,66]. A meta-analysis by Trastulli *et al.*[67] confirmed that robotic colorectal surgeries result in fewer perioperative complications and surgical site infections compared to laparoscopic procedures[67].

A promising innovation in robotic rectal resections is the integration of Firefly technology, which is particularly beneficial during the low ligation of the inferior mesenteric artery (IMA) pedicle[68]. The precision offered by robots in retroperitoneal and pelvic dissection is crucial for accurate lymphadenectomy around the IMA[68].

The use of robotics in bariatric surgery has been advancing since Cadiere *et al.*[69] first reported a case in 1999[69]. Roux-en-Y gastric bypass is widely regarded as the most effective surgical procedure for severe obesity, and robotic surgery has emerged as a promising technology to enhance this procedure due to its documented advantages[70]. It is the most extensively studied robotic bariatric procedure[70]. Sleeve gastrectomy is also gaining popularity due to its low risk of complications, excellent outcomes, and perceived technical simplicity[71]. However, it involves specific challenges such as the risk of leakage along the staple line and the need for precise dissection in the left crus and hiatus area to mobilize the fundus[71]. Robotic surgery offers advantages over laparoscopic surgery, including endo-wrist capabilities that facilitate precise dissection and suturing of the staple line[71]. A systematic review by Cirocchi *et al.*[72] indicated that robotic bariatric surgery is increasingly used not only in redo cases but also in primary procedures, such as creating intracorporeal anastomoses during Roux-en-Y gastric bypass or managing complex resections in sleeve gastrectomy[72]. Robotic technology also improves the efficiency of closing enterotomies or gastrotomies, even when stapling is used for anastomoses[72].

In pancreatic surgery, a study of 250 robotic pancreatic resections showed that robotic-assisted surgery is feasible for both oncologic and benign conditions, with a low conversion rate to open surgery[73]. However, it is crucial to remember that robotic technology is a tool that ultimately relies on the surgeon's expertise[74]. The robotic platform enables surgeons to overcome the limitations of laparoscopy, especially in procedures like D2 lymphadenectomy[75]. The utility of the surgical robot is evident in tasks such as performing robotic-sewn anastomoses and navigating difficult dissections near the gastroesophageal junction and pyloric region, which is particularly advantageous in total gastrectomies[76].

A study by Oliveira *et al.*[77] in head and neck surgery also demonstrated AI-powered robotic systems for greater dexterity and potentially reduced postoperative complications in head and neck surgery[77].

These examples showcase the diverse applications of AI in robotic surgery and its potential to revolutionize surgical care across various disciplines. As research and development continue, we can expect even more advancements in this exciting field.

### *Advantages and limitations of AI integration in robotic surgeries*

#### Advantages

- Enhanced precision and accuracy: AI can assist surgeons in achieving greater precision during delicate procedures, potentially leading to improved surgical outcomes[78].
- Reduced surgeon fatigue: AI can automate repetitive tasks, minimizing surgeon fatigue and potentially improving focus during critical aspects of the surgery[79].
- Improved safety: AI-driven systems can provide real-time feedback on potential complications, such as bleeding or instrument clashes, aiding in preventing surgical errors[80,81].

Some AI features with their benefits are summarized in Table 1.

#### Limitations

- High development and implementation costs: The development and implementation of AI-driven robotic surgical systems are expensive, including the initial purchase cost, ongoing maintenance, and infrastructure upgrades. This can limit their accessibility, particularly for smaller hospitals and healthcare institutions in resource-constrained settings[84,85].
- Reliance on data quality: The effectiveness of AI algorithms heavily depends on the quality and quantity of training data. Biases in training data can lead to biased decision-making by the AI system, potentially exacerbating existing healthcare disparities[86].
- Ethical considerations: The increasing autonomy of AI in surgery raises ethical concerns regarding responsibility and liability in case of adverse events. Clear guidelines and regulations are needed to ensure patient safety and address medico-legal issues[87].

### *Challenges faced in implementing AI in robotic surgeries*

- Regulatory hurdles: Obtaining regulatory approvals for AI-driven robotic surgical systems can be a complex and time-consuming process, hindering their wider adoption[88,89]. Regulatory bodies need to establish clear guidelines for evaluating the safety and efficacy of these systems while fostering innovation.
- Integration with existing workflows: Integrating AI-powered robotic systems into existing surgical workflows can be challenging. This may require changes in surgical team dynamics and necessitate additional training for surgeons and surgical staff to adapt to the new technology[90,91].
- Cybersecurity concerns: The increasing reliance on AI systems in surgery raises cybersecurity concerns regarding potential hacking or malfunctions that could compromise patient safety. Robust security measures are essential to ensure the integrity and reliability of these systems[92,93].

#### Future directions

The integration of AI in robotic surgery is a rapidly evolving field with immense potential to transform surgical care. Here are some exciting future directions to consider:

- Enhanced autonomy: Advancements in AI could lead to the development of more autonomous robotic surgical systems, potentially enabling surgeons to perform complex procedures remotely or with minimal assistance[94,95]. However, careful consideration of ethical implications and ensuring surgeon oversight remain crucial.
- Personalized surgery: AI can be used to analyze patient data and tailor surgical approaches to individual needs, leading to more personalized and effective treatments[96,97]. This could involve factors like patient anatomy, medical history, and genetic variations.
- Improved surgical training: AI-powered simulations can provide surgeons with realistic training environments to practice complex procedures and refine their skills, potentially leading to improved surgical outcomes[98,99]. Virtual reality (VR) integrated with AI could further enhance the training experience.

Robotic-assisted technologies have fundamentally transformed how various tasks are executed, with one of the most significant advancements being the integration of artificial

**Table 1**

**AI features relevant to robotic surgery.**

| Feature | Description | Potential benefits |
|---|---|---|
| Enhanced precision with motion prediction[82] | AI can analyze a surgeon's movements and predict their next actions, allowing robotic instruments to anticipate and follow seamlessly | - Minimized reaction times - Improved surgical precision - Reduced tissue damage |
| Intraoperative tissue recognition with AI-powered vision[83] | AI algorithms can analyze real-time surgical video to identify critical anatomical structures and potential complications | - Improved surgical navigation - Reduced risk of accidental injury |
| Automated suturing and knot-tying[35] | Advancements in AI and robotics are leading to the development of automated suturing and knot-tying systems | - Reduced surgeon fatigue - Improved consistency of suturing - Potentially shorter surgical times |
| Personalized surgical planning with AI[78] | AI can analyze patient data (scans, medical history) to generate individualized surgical plans and predict potential outcomes | - Optimized surgical approaches - Improved patient selection for robotic surgery - Potentially better long-term results |

AI, artificial intelligence.

intelligence (AI)[100]. The incorporation of AI algorithms enhances the capabilities of robotic systems by enabling them to learn, adapt, and make decisions in real-time[100]. This enhancement allows robots to perform complex tasks with increased efficiency and precision. Machine learning algorithms also improve human-robot interaction, making robots more intuitive and responsive to user needs. Despite these advancements, there is currently no evidence that AI can independently recognize the critical tasks in robotic-assisted surgeries that determine patient outcomes. Therefore, extensive studies on large data sets and external validation are required to verify the efficacy of AI algorithms in robotic-assisted surgeries[100].

The increasing autonomy in robotic surgery has the potential to standardize surgical outcomes, making them less dependent on the surgeon's training, experience, and daily performance variations[24]. A survival study indicated that a developed robotic system could match the performance of an expert surgeon[24]. However, robotic-assisted surgeries have yet to be thoroughly explored in emergency settings, though initial experiences have been documented in the literature[101]. Two promising areas of ongoing research in this field are micro-robotics and telesurgery[102,103].

Micro-robotics research includes the development of portable capsule endoscopes for various diagnostic tasks, surgical applications, and targeted drug delivery[102,103]. These microrobots, which are millimeter-sized, can be guided by extracorporeal magnets to perform specific functions, such as applying a nitinol clip to stop chronic bleeding during a biopsy in porcine models[102,103]. Research in micro-robotics focuses on four key areas: miniaturized functionality, contained propulsion, consistent visualization, and precise telemanipulation[103].

The integration of AI in robotic-assisted technologies is advancing the field by improving the efficiency, accuracy, and user interaction of robotic systems. However, further research is necessary to validate the independent effectiveness of AI in critical surgical tasks. Increased autonomy in robotic surgery could lead to more standardized outcomes, and emerging areas like micro-robotics and telesurgery hold significant promise for future applications.

## Conclusion

The integration of AI into robotic surgery holds immense promise for revolutionizing surgical care. By enhancing precision, efficiency, and accessibility, AI has the potential to improve patient outcomes, reduce complications, and democratize access to specialized surgical expertise. However, addressing challenges related to cost, data quality, ethical considerations, and regulatory hurdles is crucial for the responsible and widespread adoption of this transformative technology. As AI continues to evolve, the future of robotic surgery is poised to become even more remarkable, paving the way for a new era of personalized, precise, and patient-centered surgical care.

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## Author contribution

All authors fulfill the ICMJE criteria for authorship. All authors reviewed the final version of the manuscript and approved it for submission and publication.

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Data are available upon reasonable request.

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