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International Journal of Surgery & Surgical Techniques
ISSN: 2578-482X

Artificial Intelligence Meets Surgical Robotics: From Robotic Assistance to Supervised Surgical Autonomy

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Mini Review

Volume 10 Issue 2

Received Date: July 23, 2026

Published Date: August 10, 2026

Abstract

Artificial intelligence (AI) is changing the role of surgical robotics from mechanically precise instruments toward increasingly intelligent systems capable of recognizing anatomy, interpreting operative scenes, predicting surgical events, and assisting with selected procedural tasks. Conventional robotic surgery has primarily depended on direct surgeon control, providing improved visualization, dexterity, motion scaling, and ergonomic advantages without independently making operative decisions. The integration of computer vision, machine learning, deep learning, multimodal sensing, and adaptive robotic control is now creating a transition toward intelligent and partially autonomous surgery. Recent experimental systems have demonstrated the ability of robots to perform selected soft-tissue tasks, including suturing and tissue manipulation, while newer AI architectures are beginning to support surgical planning, workflow recognition, error detection, and intraoperative guidance. Nevertheless, fully autonomous surgery remains a research objective rather than routine clinical practice. Major challenges include anatomical variability, limited high-quality surgical datasets, unpredictable tissue behavior, explainability, cybersecurity, human–machine interaction, regulatory approval, and responsibility for autonomous decisions. This mini review examines the evolution of AI-integrated robotic surgery, current levels of autonomy, major technological components, clinical opportunities, limitations, ethical considerations, and the likely pathway toward supervised surgical autonomy. The future of robotic surgery is unlikely to involve the replacement of surgeons; instead, it is more likely to develop around intelligent systems that augment human judgment while progressively automating well-defined and reproducible surgical tasks.

Keywords: Artificial Intelligence; Robotic Surgery; Autonomous Surgery; Surgical Robotics; Computer Vision; Machine Learning; Surgical Navigation; Intraoperative Decision Support; Surgical Automation

Introduction

Robotic surgery has progressed considerably since the introduction of early computer-assisted surgical systems. Modern robotic platforms have provided surgeons with high-definition visualization, articulated instruments, tremor filtering, motion scaling, and improved ergonomics. However, most currently deployed robotic systems remain fundamentally dependent on the surgeon. The robot acts primarily as an advanced interface through which the surgeon performs the operation rather than as an independent decision-making agent [1,2].

Artificial intelligence is beginning to change this relationship. Instead of simply transmitting a surgeon's movements to an instrument, AI can potentially interpret

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the surgical environment and determine what is happening within it. Computer vision algorithms can identify anatomical structures, recognize surgical phases, track instruments, and detect changes in tissue. Machine-learning systems can analyze previous surgical demonstrations and learn patterns associated with successful manipulation. When these capabilities are integrated with robotic control, the result is an intelligent surgical system capable of perception, prediction, planning, and, in carefully controlled circumstances, autonomous action [3,4].

The distinction between robotic assistance and robotic autonomy is important. A robot that filters tremor or improves instrument positioning is assisting the surgeon. A system that recognizes tissue, develops an operative plan, and executes a defined task with limited intervention from the surgeon represents a substantially different technological concept. The latter requires reliable perception, decision-making, motion planning, feedback control, and safety mechanisms.

Recent literature suggests that the immediate future of AI in robotic surgery is likely to involve supervised autonomy, rather than completely independent operations [3]. In this model, the surgeon remains responsible for the procedure while the robotic system performs selected repetitive or technically demanding components. This approach could provide a practical bridge between conventional robotic assistance and higher levels of autonomy.

From Robotic Assistance to Surgical Autonomy

The evolution of surgical robotics can be understood as a gradual movement from mechanical assistance toward increasing decision-making capability. At the lowest level, the robot does not make meaningful decisions. It executes commands generated by the surgeon. This describes most commercially available robotic surgical systems. At higher levels, the robot can assist with specific physical or cognitive functions. Eventually, a system may be capable of performing an individual surgical task autonomously, while more advanced systems could potentially plan and execute multiple sequential tasks [5].

A commonly used conceptual framework describes autonomy across several levels. At Level 0, there is no autonomy. At Level 1, the system provides assistance to the surgeon. Level 2 involves autonomous performance of a specific task, while Level 3 represents conditional autonomy in which the system can plan and adapt during execution. Higher levels involve increasingly independent planning and execution of multiple surgical activities [5]. This progression is important because surgery is fundamentally different from structured industrial automation. Human tissue is deformable, heterogeneous, and constantly changing. Anatomical structures may vary substantially between patients, and bleeding, smoke, fluid, instrument obstruction, and unexpected tissue movement can rapidly change the operative field. Consequently, simply transferring industrial robotic autonomy into the operating room is not sufficient. Surgical robots must be capable of responding to uncertainty.

The most realistic near-term pathway therefore involves task-specific autonomy. Examples include autonomous camera positioning, tissue retraction, needle handling, suturing, knot tying, or other predefined subtasks. A surgeon could supervise these functions and intervene whenever necessary. This concept is supported by recent work showing that autonomous surgical systems can perform selected soft-tissue procedures in experimental environments. For example, the Smart Tissue Autonomous Robot (STAR) demonstrated autonomous laparoscopic intestinal anastomosis in a porcine model, using three-dimensional imaging and machine-learning-based tissue tracking to generate and execute surgical plans under supervision [6].

Artificial Intelligence as the Perceptual Layer of Robotic Surgery

One of the greatest limitations of conventional surgical robots is their limited understanding of the operative environment. A robot may accurately move an instrument, but movement alone does not mean that the machine understands what the instrument is touching. AI-based computer vision provides an important solution. Deep-learning systems can analyze surgical video and identify instruments, anatomical structures, tissue boundaries, surgical phases, and procedural events. These capabilities are important because autonomous surgery requires a robot to continuously answer several questions:

Where am I?
What anatomical structures are present?
What tissue am I manipulating?
What surgical step is currently being performed?
What should happen next?
Is the planned action safe?

Recent advances in foundation models and increasingly sophisticated surgical datasets are accelerating this area [3]. AI can potentially transform the operative video stream from a passive recording into an active source of information for the robotic controller.

This capability has already demonstrated clinical relevance. In 2026, surgeons in London reported an AI-assisted brain-tumor operation in which an AI system analyzed live surgical video and helped identify critical anatomical

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structures during the procedure. The system provided real-time visual guidance rather than independently performing the operation, illustrating an important intermediate stage between conventional surgery and autonomous intervention [7].

Computer vision may also support surgical education. Automated recognition of procedural phases can provide objective feedback regarding operative performance, while AI-based analysis of surgical video could potentially identify inefficient movements, prolonged operative stages, or deviations from expected workflows [3]. However, surgical vision remains difficult. Blood, smoke, tissue deformation, poor illumination, occlusion, and differences between patients can reduce algorithmic performance. An AI system trained primarily on one hospital's surgical videos may also perform poorly when exposed to different equipment, surgical techniques, or patient populations. Therefore, generalization remains one of the most important problems in surgical AI.

AI-Driven Surgical Planning and Decision Support

AI-integrated robotics involves more than recognizing anatomy. A genuinely intelligent surgical system must also support planning. Preoperative imaging from computed tomography, magnetic resonance imaging, ultrasound, and other modalities can be processed using AI to construct patient-specific anatomical models. These models may help surgeons understand tumor location, vascular anatomy, tissue relationships, and potential surgical approaches. Three-dimensional reconstruction can then be integrated into robotic platforms or navigation systems. The result is a more personalized surgical plan rather than a procedure based solely on generalized anatomical assumptions.

Intraoperatively, the plan may need to change. Tissue deformation can make preoperative images inaccurate, particularly during abdominal, thoracic, or neurosurgical procedures. Real-time imaging and computer vision can therefore be combined with preoperative models to update the surgical map during the procedure. AI can also function as an intraoperative decision-support system. Rather than telling the surgeon what to do independently, it may highlight structures at risk, predict possible complications, identify deviations from an expected surgical sequence, or suggest alternative actions. This distinction is clinically important. Surgical decisions involve patient-specific factors that may not be fully represented in training data. An AI system may recognize a pattern but still lack the broader clinical context required to make an appropriate decision. Therefore, AI should initially function as a second layer of intelligence that complements, rather than replaces, surgical expertise.

Autonomous Soft-Tissue Surgery

Autonomous surgery is particularly challenging in soft tissues because tissues deform when manipulated. The target does not remain in a fixed position, and the relationship between the instrument and tissue continuously changes. Despite these difficulties, experimental research has demonstrated meaningful progress. The STAR system represents an important example. In a preclinical porcine study, the system performed laparoscopic intestinal anastomosis using three-dimensional imaging, tissue tracking, and autonomous suturing. The robot generated multiple plans and executed the selected plan while adapting to tissue movement [6]. More recent work has extended the concept. A 2026 review of AI-enabled robotic surgery described experimental systems capable of autonomous soft-tissue tasks and highlighted the development of systems that can perform complex sequences while adapting to anatomical variation [4].

These developments are significant because suturing is not simply a matter of moving a needle from one location to another. The robot must identify tissue edges, estimate tissue deformation, select appropriate needle trajectories, control force, and continuously adjust its actions. Nevertheless, experimental success should not be confused with clinical readiness. A controlled animal model is substantially different from a human operation involving unexpected bleeding, scar tissue, anatomical anomalies, previous surgery, or rapidly changing operative conditions. The logical next step is therefore not immediate full autonomy but constrained autonomy, where the robot operates within predefined boundaries and the surgeon retains continuous oversight.

Human–Robot Collaboration

The future of robotic surgery will probably depend as much on human–machine interaction as on robotic hardware. A completely autonomous system raises difficult questions about trust and responsibility. Conversely, a system that constantly requires the surgeon to confirm every action may provide little practical advantage. An effective AI surgical assistant should therefore understand the surgeon's intent while maintaining appropriate independence for predefined tasks. For example, the surgeon might instruct a robotic system to prepare a specific anatomical area for suturing. The AI could identify the tissue, determine an appropriate trajectory, perform the suturing sequence, and then stop for confirmation. If unexpected anatomy is encountered, the system could immediately return control to the surgeon.

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This model creates a shared-control environment.
Such systems may offer several potential advantages:
Reduction of repetitive manual workload.
More consistent execution of standardized tasks.
Reduction in technical variability.
Improved visualization and anatomical recognition.
Real-time alerts for potentially dangerous situations.
Objective assessment of surgical performance.
Potential extension of advanced surgical capabilities to resource-limited settings.
Importantly, however, surgeon training will need to evolve. Surgeons operating AI-integrated systems must understand not only surgical anatomy and technique but also the capabilities and limitations of the AI.

Potential Clinical Applications

AI-integrated robotic surgery has potential across multiple specialties.

General Surgery

General surgery may become an important testing ground because procedures such as intestinal anastomosis involve repetitive, structured tasks. Autonomous suturing and tissue manipulation may eventually reduce technical variability [6].

Urological Surgery

Urology has been an early adopter of robotic surgery. AI could support prostate segmentation, nerve identification, surgical planning, and automated assessment of procedural performance. The 2026 literature specifically identifies urology as an important area for AI-enabled robotic innovation [4].

Neurosurgery

Neurosurgery presents a particularly attractive application because of the need for extremely precise anatomical localization. AI-assisted identification of critical structures may help surgeons navigate complex anatomy. The recent clinical demonstration of real-time AI assistance during brain-tumor surgery illustrates the potential of this approach [7].

Orthopedic Surgery

Robotic systems are already used for planning and executing precise bone cuts and implant positioning. AI may further improve patient-specific planning and adapt surgical execution to individual anatomy.

Surgical Oncology

AI-integrated robotics may assist with tumor localization, margin assessment, lymph-node identification, and preservation of critical structures. Combining imaging, pathology, and intraoperative information could eventually facilitate more individualized cancer surgery.

Advantages of AI-Integrated Robotic Surgery

The primary argument for AI integration is not technological novelty but the possibility of improving surgical consistency and safety. Human surgeons naturally vary in technical performance. Experience, fatigue, stress, and individual technique can influence operative performance. AI systems, when properly validated, may perform narrowly defined repetitive tasks with greater consistency. Another advantage is continuous monitoring. An AI system can analyze the operative field continuously without fatigue. It may identify an anatomical structure that is difficult to recognize visually or detect a deviation from an expected procedural sequence. AI can also facilitate objective assessment. Surgical video contains a large amount of information that is currently underused. Automated analysis could support training programs by providing quantitative feedback rather than relying exclusively on subjective assessment. Robotic systems can additionally provide highly controlled movements. When combined with AI-based perception, this precision could become more meaningful because the robot would not simply move accurately—it could potentially determine where and why it should move.

Limitations and Safety Concerns

Despite the enthusiasm surrounding autonomous surgery, several barriers must be addressed before widespread clinical implementation.

Data Quality

AI systems depend heavily on training data. Surgical datasets are often relatively small compared with datasets available in other fields. Privacy restrictions, institutional differences, inconsistent annotation, and variations in surgical technique make dataset development difficult.

Anatomical Variability

Patients do not have identical anatomy. An algorithm trained on typical cases may encounter an unexpected vessel, abnormal tissue, adhesions, or previous surgical changes. An autonomous system must be able to recognize when its assumptions are no longer valid.

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Explainability

Surgeons need to understand why an AI system recommends a particular action. A black-box system that produces an unexplained decision may be difficult to trust in a high-risk environment.

Failure Management

A safe autonomous robot must know when it is uncertain. Detecting failure may be as important as executing the correct action. Research is increasingly focusing on failure detection and anomaly recognition as safeguards for autonomous robotic surgery [8].

Cybersecurity

Connected surgical robots introduce cybersecurity concerns. Unauthorized access, manipulation of data, or interference with robotic control could potentially have serious consequences. Security therefore needs to be incorporated into system design rather than treated as an afterthought.

Regulatory Challenges

Robotic systems capable of adaptive or autonomous behavior are substantially different from conventional medical devices. Regulators must evaluate not only hardware reliability but also software performance, AI updates, training data, failure modes, and human oversight. The IDEAL Robotics framework emphasizes structured development, comparative evaluation, long-term monitoring, human factors, ethics, economics, and patient perspectives in the evaluation of surgical robotic technologies [2].

Ethical Considerations

Autonomous surgery introduces ethical questions that extend beyond technical performance. The first is responsibility. If an autonomous system makes an inappropriate decision, responsibility may involve the surgeon, hospital, manufacturer, software developer, or a combination of these parties. The second is patient consent. Patients should understand whether AI is being used to assist their surgeon and, particularly, whether the system is permitted to perform autonomous tasks. The third is algorithmic bias. AI systems developed from limited populations may perform differently across demographic or geographic groups. Ensuring representative training data is therefore essential. Finally, there is the question of human expertise. Increased automation should not result in surgeons losing fundamental technical skills. Training programs may need to develop a balance between manual surgical competency and the ability to supervise intelligent systems. The appropriate goal should therefore be augmentation rather than replacement. Human judgment remains essential when unexpected clinical circumstances arise.

Future Directions

The next phase of surgical robotics will likely involve the convergence of several technologies rather than the development of one isolated innovation. First, multimodal AI systems may combine surgical video, preoperative imaging, instrument position, force sensing, patient physiology, and operative history. Such integration could give robots a richer understanding of the surgical environment. Second, foundation models may allow surgical AI to generalize across procedures rather than requiring a separate algorithm for every narrowly defined task. However, their reliability in safety-critical environments will need rigorous testing. Third, digital twins could provide patient-specific simulations before surgery. A virtual representation of the patient's anatomy could allow the surgical team and robotic system to test alternative approaches before entering the operating room. Fourth, adaptive robotics may enable systems to respond to tissue movement and unexpected anatomical changes. This could be particularly important in soft-tissue procedures.

Finally, evaluation frameworks will become increasingly important. As autonomy increases, researchers will need standardized metrics for safety, accuracy, consistency, surgeon workload, patient outcomes, and economic value. The most plausible future is therefore not an operating room in which autonomous robots independently perform complete operations. Instead, the near-term future is likely to involve surgeon-led procedures supported by intelligent robotic systems that autonomously perform carefully selected subtasks [4].

Conclusion

AI-integrated robotic surgery represents an important transition in the evolution of surgical technology. Conventional robotic systems have already transformed minimally invasive surgery by improving visualization, dexterity, and ergonomics. The integration of AI adds a new dimension: the ability to perceive, interpret, predict, and potentially act within the surgical environment. Experimental autonomous systems have demonstrated that selected surgical tasks can be performed by robots with limited human intervention, while recent clinical applications of real-time AI assistance demonstrate that intelligent surgical guidance is moving from laboratory research toward patient care. However, autonomous surgery remains an emerging technology rather

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than a replacement for conventional surgical expertise.

The most realistic pathway is progressive and supervised. AI will first support visualization, planning, workflow recognition, and decision-making; subsequently, it will perform selected repetitive tasks under surgeon oversight; and only after extensive validation might more complex autonomous functions become clinically acceptable. The central question is therefore not whether robots will replace surgeons, but how intelligently surgeons and robots can work together. If developed responsibly, AI-integrated robotics could improve consistency, reduce technical variability, and support safer and more personalized surgery while keeping clinical judgment at the center of patient care.

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