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Review Article

From Robotic Assistance to Surgical Intelligence: Artificial Intelligence–Enabled Precision, Autonomy, Digital Twins and Human-Centred Governance in Next-Generation Surgery

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ABSTRACT

The integration of artificial intelligence (AI) with robotic surgery is transforming conventional robot-assisted procedures into increasingly intelligent, adaptive, and data-driven surgical systems. This review examines the evolution of robotic surgery from mechanically assisted intervention toward AI-enabled surgical intelligence, with particular emphasis on machine learning, deep learning, computer vision, multimodal data integration, digital twins, augmented reality, predictive analytics, and progressive robotic autonomy. Particular attention is given to AI-assisted patient-specific surgical planning, three-dimensional anatomical reconstruction, intraoperative navigation, tissue recognition, surgical workflow analysis, force-responsive robotic manipulation, automated skill assessment, and task-level autonomous surgery. The review further explores the emerging concept of human–AI–robot collaboration, in which artificial intelligence functions as a surgical co-pilot while the surgeon retains clinical authority and responsibility. Ethical, regulatory, legal, cybersecurity, data-governance, economic, and healthcare-equity considerations are also examined because these factors will determine the safe and sustainable translation of intelligent robotic systems into routine clinical practice. Emerging technologies, including multimodal foundation models, digital twins, risk-adaptive autonomy, continuous learning, tele-robotics, and intelligent operating-room ecosystems, are evaluated as potential drivers of the next generation of precision surgery. Overall, the evidence indicates that the future of robotic surgery is unlikely to involve wholesale replacement of surgeons; rather, it is expected to develop through increasingly sophisticated collaboration between human expertise, AI-based intelligence, and robotic precision. Responsible integration of these technologies could ultimately facilitate safer, more precise, personalized, adaptive, and equitable surgical care.

Keywords: *Artificial intelligence; Robotic surgery; Computer vision; Human–AI–robot collaboration; Precision surgery.*

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Introduction

Surgery has undergone a remarkable technological transformation over the past several decades, progressing from conventional open procedures dominated by direct manual manipulation toward minimally invasive, computer-assisted, robot-assisted, and increasingly intelligent surgical environments. The introduction of laparoscopic techniques reduced surgical access trauma, while robotic platforms subsequently addressed several limitations of conventional minimally invasive surgery by improving visualization, instrument articulation, ergonomics, motion scaling, and tremor filtration. Robotically assisted surgical systems are now used across multiple specialties, including urology, gynecology, general surgery, cardiothoracic surgery, oncology, and orthopedics. The U.S. Food and Drug Administration describes robotically assisted surgical devices as computer-assisted systems that enable surgeons to control surgical instruments through small incisions and emphasizes their role in minimally invasive and technically complex procedures. The evolution described in the present project report similarly illustrates the progression from early systems such as the PUMA 560 and AESOP to contemporary platforms such as da Vinci, MAKO, ROSA, and other image- and navigation-assisted robotic systems.

Although conventional robotic surgery substantially enhances the physical capabilities of the surgeon, most established platforms remain fundamentally dependent on human control. In this paradigm, the robot acts primarily as a sophisticated extension of the surgeon's hands and eyes rather than as an independent clinical decision-making entity. The emergence of artificial intelligence (AI), however, is progressively altering this relationship. Machine learning (ML), deep learning, computer vision, natural language processing, predictive analytics, reinforcement learning, and multimodal data analysis are enabling surgical systems to interpret complex clinical information, recognize anatomical structures, assess surgical workflow, provide decision support, and potentially perform selected procedural subtasks under human supervision. The attached report characterizes this transition as a movement from tele-manipulation toward intelligent, adaptive, and context-aware robotic assistance.

The convergence of AI and surgical robotics is particularly important because surgery generates a complex combination of heterogeneous and time-sensitive information. Preoperative imaging, electronic health records, laboratory investigations, patient-specific anatomical characteristics, intraoperative video, instrument kinematics, tissue characteristics, physiological parameters, and postoperative outcomes can collectively provide a multidimensional representation of the surgical episode. AI algorithms can potentially transform these data into clinically meaningful information before, during, and after an operation. Recent literature indicates that AI is being investigated for preoperative planning, prognostication, image interpretation, intraoperative navigation, tissue and instrument recognition, force and tactile assessment, detection of surgical margins, workflow analysis, and automated assessment of surgical skills. Consequently, the modern operating room is increasingly evolving from a predominantly procedure-centred environment into a data-rich, computationally augmented ecosystem.

One of the most significant developments in this transformation is the integration of AI with computer vision and augmented reality (AR). Conventional surgical imaging provides surgeons with visual information, but interpretation remains dependent on human perception and experience. AI-enabled computer vision can potentially identify anatomical structures, surgical instruments, pathological regions, tissue planes, and procedural phases in real time. When integrated with AR, patient-specific anatomical information derived from preoperative imaging may be superimposed onto the operative field, thereby providing additional guidance during dissection, navigation, and decision-making. Recent reviews describe this integration as an important pathway toward precision surgery because AI can process large volumes of preoperative and intraoperative information while AR can translate computational outputs into clinically relevant visual guidance.

The concept of precision surgery therefore represents an important bridge between robotic technology and personalized medicine. Rather than applying a standardized operative strategy to every patient, AI-enabled systems may facilitate patient-specific planning by integrating anatomical, clinical, imaging, and potentially biological information. Such systems could assist surgeons in determining optimal approaches, anticipating anatomical variations, estimating procedural risks, selecting implant parameters, and tailoring operative strategies. The attached report emphasizes that AI-based planning and robotic platforms can support patient-specific surgical planning, real-time feedback, and individualized treatment approaches, while emerging technologies such as digital twins may provide virtual representations of patients for simulation and planning.

Digital twins represent a particularly promising frontier in this context. A surgical digital twin can be conceptualized as a computational representation of a patient's relevant anatomy, physiology, clinical information, and procedural characteristics that can be used to simulate or evaluate potential interventions.

Although clinical implementation remains an evolving field, the integration of digital twins with AI and robotic platforms could create a feedback-oriented surgical ecosystem in which procedures are modeled before intervention, dynamically monitored during surgery, and evaluated after the procedure. Such an approach may ultimately facilitate predictive rather than merely reactive surgical care. The project report identifies digital-twin-assisted surgical planning as one of the emerging technologies capable of extending AI-enabled robotics beyond conventional robotic assistance.

An equally important transition is the gradual movement from robotic assistance toward partial autonomy. Autonomous robotic surgery does not necessarily imply complete replacement of the surgeon. Instead, surgical autonomy can be conceptualized as a continuum ranging from manual teleoperation and AI-enhanced assistance to shared control, supervised autonomy, and, potentially, highly autonomous execution of defined surgical tasks. Recent research has demonstrated experimental or early-stage autonomous performance of selected tasks, including suturing, tissue manipulation, anastomosis, knot tying, and other repetitive procedural components. Nevertheless, current evidence indicates that fully autonomous surgery remains limited, and human supervision continues to be central to patient safety and clinical accountability. The attached report likewise identifies supervised and semi-autonomous systems as an emerging direction while emphasizing the continued importance of human monitoring.

The movement toward increasing autonomy also introduces a fundamental change in the relationship between the surgeon and the machine. In conventional surgery, responsibility for operative decisions is relatively straightforward because the surgeon directly determines and executes the intervention. In AI-assisted environments, however, algorithms may contribute to planning, prediction, navigation, classification, or execution. This raises critical questions concerning human oversight, explainability, informed consent, responsibility for adverse outcomes, algorithmic bias, data ownership, cybersecurity, and legal liability. Recent literature specifically identifies privacy, informed consent, bias, surgeon autonomy, equitable access, and liability associated with autonomous systems as major ethical concerns. The World Health Organization similarly emphasizes that AI in healthcare must be developed and deployed with attention to transparency, accountability, human rights, equity, privacy, and appropriate governance.

The regulatory environment is also evolving alongside technological development. AI-enabled medical devices require evaluation not only of their hardware performance but also of software behaviour, intended use, data quality, validation, cybersecurity, and, in some cases, the consequences of adaptive or continuously learning algorithms. The FDA maintains an evolving list of AI-enabled medical devices authorized for marketing in the United States, reflecting the increasing integration of AI into medical-device development and regulatory practice. For surgical robotics, this issue becomes particularly complex because an error in an algorithmically influenced system may have immediate physical consequences for a patient. Accordingly, future regulatory frameworks will need to balance innovation with rigorous clinical validation, traceability, transparency, cybersecurity, and clearly defined human oversight.

Despite substantial technological progress, the clinical translation of AI-enabled robotic surgery remains constrained by several challenges. High acquisition and maintenance costs, specialized infrastructure, limited availability of high-quality annotated datasets, differences in surgical techniques, inadequate external validation, interoperability problems, cybersecurity threats, and the absence of universally accepted performance metrics may limit widespread adoption. The attached project specifically identifies high implementation costs, data privacy, algorithmic bias, cybersecurity, interoperability, legal liability, and limited long-term randomized clinical evidence as important barriers. These challenges are especially important in low- and middle-income healthcare systems, where expensive robotic platforms may remain concentrated in tertiary and metropolitan institutions, potentially increasing rather than reducing existing inequalities in access to advanced surgical care. The report therefore appropriately identifies affordability, accessibility, standardized training, and healthcare equity as essential components of future implementation.

Importantly, the future of intelligent surgery should not be framed simply as a competition between humans and machines. The more clinically realistic model is likely to be a human–AI–robot collaborative ecosystem in which computational systems augment rather than replace professional expertise. Surgeons contribute contextual understanding, clinical judgment, ethical reasoning, communication, adaptability, and responsibility, whereas AI and robotic systems can contribute computational speed, pattern recognition, quantitative analysis, precision, reproducibility, and continuous data processing. The attached report explicitly concludes that AI-powered robotic systems are more appropriately regarded as cooperative tools that enhance clinical performance rather than technologies intended to completely replace surgeons.

Against this background, there is a need for a contemporary review that moves beyond a conventional description of robotic platforms or isolated applications of AI. Existing reviews have addressed clinical applications, intraoperative enhancement, autonomous surgery, and ethical considerations individually, but the rapidly evolving field requires an integrated framework connecting technological capability with clinical translation, patient-specific precision, progressive autonomy, digital-twin-enabled simulation, human–machine collaboration, regulatory governance, economic feasibility, and healthcare equity. Recent reviews have similarly emphasized the need for further research and ethical safeguards before widespread implementation of AI in robotic surgery.

Therefore, this review aims to critically examine the transition from conventional robot-assisted surgery toward next-generation surgical intelligence. Particular emphasis will be placed on the evolution of robotic systems; AI, ML, deep learning, and computer vision technologies; preoperative AI-enabled planning; intraoperative navigation and decision support; AR and multimodal sensing; surgical education and skill assessment; digital twins and personalized surgical simulation; semi-autonomous and autonomous surgical tasks; postoperative predictive monitoring; and the emerging human–AI–robot relationship. In parallel, the review will critically evaluate data quality, algorithmic bias, explainability, cybersecurity, interoperability, clinical validation, regulatory requirements, legal responsibility, cost-effectiveness, workforce transformation, and global healthcare equity. Such an integrated perspective is essential for determining whether intelligent robotic surgery can progress from technological innovation to safe, clinically meaningful, economically sustainable, and ethically responsible routine healthcare.

Ultimately, the transformation from the scalpel to the intelligent surgical platform should not be understood merely as a technological replacement of one instrument by another. It represents a broader transition from manually executed, procedure-centred surgery toward data-driven, predictive, personalized, and increasingly adaptive surgical care. The convergence of robotics, AI, computer vision, augmented reality, digital twins, multimodal sensing, and advanced analytics has the potential to establish a new paradigm in which surgical systems continuously integrate patient-specific information, support clinical reasoning, improve procedural precision, and progressively automate selected tasks under appropriate human supervision. Realizing this potential, however, will depend not only on technological sophistication but also on rigorous evidence generation, responsible governance, affordability, interoperability, professional education, and preservation of human-centred clinical decision-making.

Evolution from Robot-Assisted Surgery to Surgical Intelligence

The development of robotic surgery represents a progressive transition from mechanically assisted procedures toward increasingly data-driven and intelligent surgical systems. Early surgical robots were principally designed to overcome the limitations of human dexterity, improve instrument control, and facilitate minimally invasive access. Over time, technological advances in three-dimensional visualization, motion scaling, articulated instruments, image guidance, haptic technologies, and computer-assisted navigation transformed robotic systems from experimental devices into clinically established platforms. The evolution described in the attached report demonstrates that contemporary robotic surgery is no longer restricted to mechanical assistance but increasingly incorporates artificial intelligence (AI), machine learning (ML), computer vision, augmented reality (AR), predictive analytics, and autonomous functions.

From telemanipulation to intelligent robotic platforms

The fundamental principle of first-generation robotic surgery was telemanipulation, whereby the surgeon controlled robotic instruments through a computerized interface. This architecture provided several advantages over conventional laparoscopic instruments, including enhanced degrees of freedom, improved ergonomics, tremor filtration, motion scaling, and stable three-dimensional visualization. However, the robot remained dependent on continuous surgeon input and had little or no capacity to independently interpret the operative environment.

The subsequent generation of robotic platforms introduced increasingly sophisticated sensing and navigation capabilities. Optical cameras, force sensors, positional encoders, electromagnetic tracking, and other forms of intraoperative sensing generated large volumes of data that could be analyzed computationally. This accumulation of surgical data created the foundation for AI integration. Contemporary research recognizes that surgical robots are particularly suitable for AI applications because they continuously generate information from instruments, sensors, surgical video, patient anatomy, and procedural workflow.

The resulting paradigm can therefore be conceptualized as a continuum:

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Manual surgery → minimally invasive surgery → robot-assisted surgery → computer-assisted surgery → AI-augmented surgery → semi-autonomous surgery → potentially autonomous surgical systems.

This progression is important because increasing intelligence does not necessarily imply increasing replacement of the surgeon. Rather, it represents a gradual redistribution of tasks between the human operator and computational system. Recent systematic analysis of FDA-cleared surgical robots proposed a five-level autonomy framework ranging from robot assistance (Level 1) to full autonomy (Level 5), illustrating that surgical autonomy should be understood as a spectrum rather than a binary characteristic.

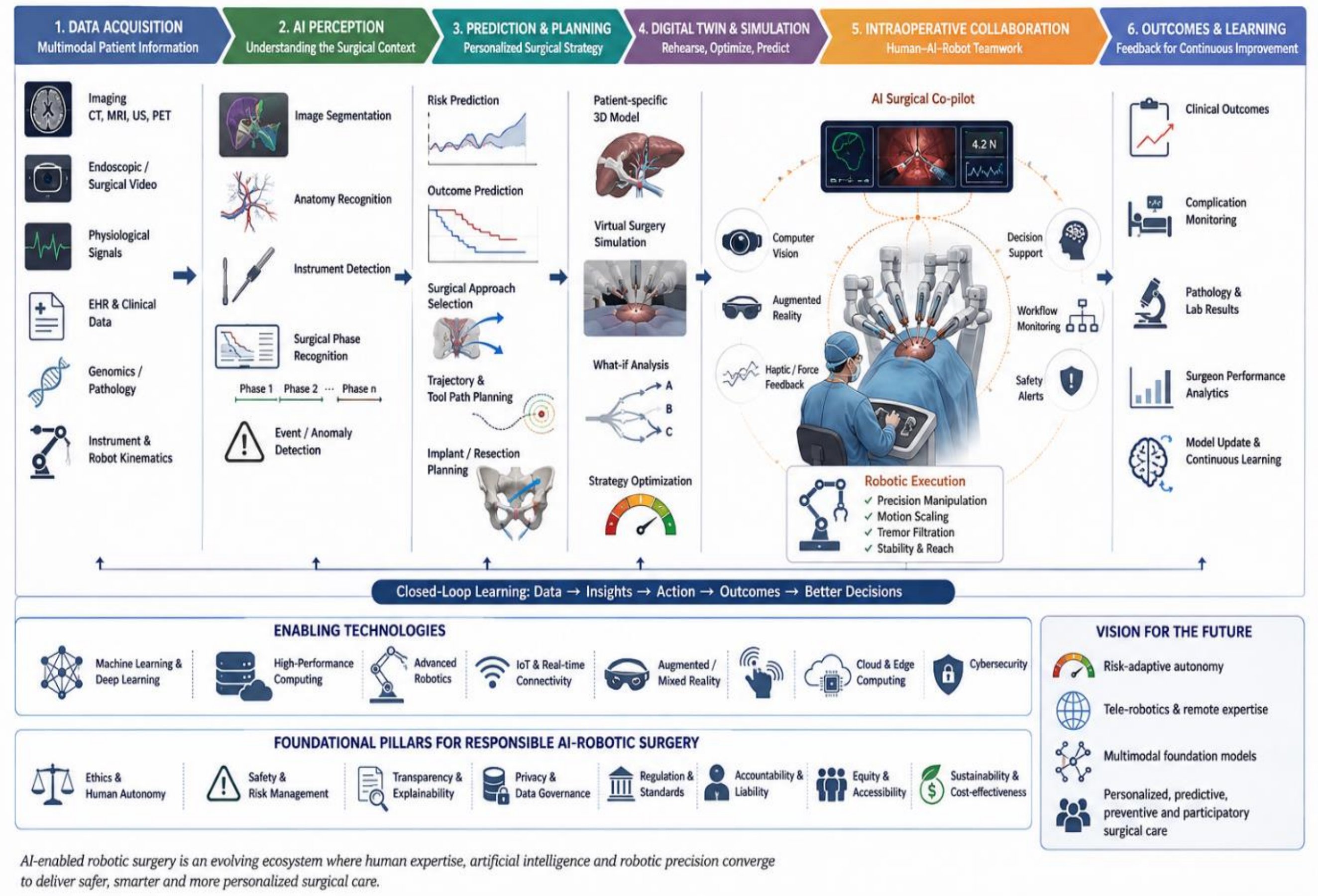

Figure 1: From Robotic Assistance to Surgical Intelligence: Integrated Framework of AI-Enabled Precision, Autonomy, and Personalized Surgery.

Artificial intelligence as the computational layer of robotic surgery

AI represents a major technological layer that distinguishes contemporary intelligent robotic surgery from conventional computer-assisted surgery. Machine learning algorithms can identify patterns within large datasets, whereas deep learning approaches, particularly convolutional neural networks and related architectures, have demonstrated considerable potential for image interpretation and surgical video analysis. Computer vision allows robotic systems to recognize instruments, anatomical structures, tissue characteristics, surgical phases, and procedural events.

The clinical applications of AI in robotic surgery are increasingly extending beyond preoperative decision support. Recent evidence describes applications involving intraoperative force and tactile measurements, detection of positive surgical margins, automation of selected surgical steps, and automated assessment of surgeon performance using operative video and instrument-kinematic data.

This transformation can be represented through three interconnected AI functions:

1. **Perception** – understanding the patient and operative environment through imaging, video, and sensor data.
2. **Prediction and reasoning** – estimating surgical risks, identifying patterns, anticipating procedural events, and supporting decision-making.

3. **Action** – translating computational outputs into navigation, instrument control, or supervised execution of defined surgical tasks.

The integration of these capabilities creates the foundation for what may appropriately be termed "surgical intelligence." In contrast to conventional automation, surgical intelligence involves the continuous interaction of perception, contextual interpretation, prediction, decision support, and controlled action.

Computer vision and real-time intraoperative understanding

Among AI technologies, computer vision has emerged as one of the most important components of intelligent surgery. Surgical procedures generate continuous video streams containing complex anatomical and procedural information. Human surgeons interpret these images using experience and contextual awareness, whereas AI-based computer vision systems can computationally process visual information at high speed.

Potential applications include:

- anatomical structure identification;
- surgical instrument detection and tracking;
- tissue classification;
- surgical phase recognition;
- identification of pathological regions;
- detection of surgical margins;
- estimation of tissue deformation;
- recognition of complications;
- assessment of procedural progress; and
- real-time guidance of robotic instruments.

Such capabilities could allow robotic systems to become increasingly context-aware. Instead of simply executing movements commanded by the surgeon, future systems may recognize what the surgeon is attempting to accomplish, where the relevant anatomical structures are located, and whether the current action is consistent with the planned surgical strategy.

The attached report similarly emphasizes the contribution of AI, computer vision, and augmented reality to real-time visual information, surgical navigation, instrument recognition, and precision manipulation.

AI-enabled preoperative planning and patient-specific surgery

The benefits of AI are not restricted to the operating room. Preoperative planning represents another important area in which computational intelligence can influence surgical outcomes. Medical imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasound, and three-dimensional reconstruction provide detailed anatomical information. AI algorithms can assist with segmentation, classification, anatomical reconstruction, risk prediction, and identification of clinically relevant structures.

The combination of AI-derived anatomical models with robotic planning can potentially create a patient-specific operative strategy before the first incision is made. Instead of relying exclusively on generalized anatomical assumptions, surgeons may increasingly use individualized computational models to determine optimal access routes, implant positioning, resection margins, tissue trajectories, and anticipated surgical difficulties.

This is particularly relevant to orthopedic robotic surgery. Systems such as MAKO and ROSA use patient-specific anatomical information and computer-assisted planning to facilitate implant positioning and alignment. The attached report describes improved component alignment, soft-tissue balancing, and reduced variability associated with robotic knee procedures.

The future direction, however, extends beyond navigation. AI could integrate imaging with demographic, physiological, laboratory, genomic, and historical clinical information to produce a multidimensional surgical risk profile. Such a system could potentially estimate the probability of complications and recommend alternative operative strategies before surgery begins.

Augmented reality and multimodal surgical guidance

The integration of AI with augmented reality provides another mechanism for translating computational information into clinically useful intraoperative guidance. AR can superimpose digitally generated anatomical structures, surgical trajectories, boundaries, or other information onto the surgeon's visual field. When these representations are generated from patient-specific imaging and continuously updated through AI, the distinction between preoperative planning and intraoperative navigation becomes increasingly blurred.

Such integration may allow surgeons to visualize structures that are not directly apparent in the operative field while simultaneously receiving computationally generated information about tissue characteristics, anatomical boundaries, and procedural risks.

The concept is consistent with the emerging field of digital-twin-assisted surgery, in which patient-specific digital representations can be used for planning, simulation, and potentially real-time intraoperative guidance. Recent work proposes that digital twins could integrate physical patient data with AI models and provide dynamic information to clinicians or surgical robots.

Digital twins: the next layer of personalized surgical intelligence

Digital twins may represent one of the most important emerging technologies in the transition from AI-assisted surgery toward genuinely adaptive surgical systems. A surgical digital twin can be understood as a dynamic virtual representation of a patient's relevant anatomical and physiological characteristics that can be updated using new clinical information.

Unlike a static three-dimensional anatomical model, a digital twin is intended to represent a dynamic relationship between the physical patient and computational model. Recent literature identifies potential applications across preoperative planning, intraoperative guidance, postoperative monitoring, and surgical education.

This closed-loop architecture could ultimately support a form of adaptive surgery, in which the surgical strategy is continuously informed by new intraoperative information rather than remaining entirely fixed after preoperative planning.

However, current evidence remains predominantly developmental. A 2026 narrative review concluded that digital-twin applications in surgery remain largely at proof-of-concept or early clinical deployment stages, with further validation, standardized protocols, and resolution of technical and ethical challenges required before widespread adoption.

From robotic assistance to semi-autonomous surgical tasks

One of the most transformative aspects of AI-integrated robotics is the possibility of delegating selected surgical tasks to robotic systems. Importantly, autonomy in surgery should not be interpreted as an immediate transition toward completely surgeon-independent operations. Instead, autonomy can develop incrementally.

Early research has explored autonomous performance of specific tasks such as suturing, knot tying, tissue manipulation, anastomosis, and other repetitive or structurally defined procedures. A systematic review of autonomous robotic surgery noted that several experimental and clinical applications have already demonstrated varying degrees of autonomy, while most systems remain far from fully autonomous surgery.

This distinction is clinically important. Surgical procedures occur within highly variable biological environments, where tissue deformation, bleeding, anatomical variation, unexpected pathology, and patient movement can challenge predefined algorithms. Consequently, the most realistic near-term model is likely to be supervised autonomy, in which AI and robotic systems perform constrained tasks while the surgeon retains authority to intervene.

Surgical education and AI-generated performance feedback

The influence of AI and robotics extends beyond clinical procedures to surgical education. Traditional assessment of surgical competency frequently depends on subjective expert observation, procedure counts, and global rating scales. Robotic platforms provide a rich source of objective information, including instrument trajectories, motion patterns, time, force, economy of movement, and procedural errors.

AI can analyze these data to generate quantitative assessments of technical performance. Recent literature has highlighted automated assessment using surgical video and instrument kinematics as an important application of AI in robotic surgery.

This creates the possibility of a new model of surgical education in which trainees receive continuous, data-driven feedback rather than relying solely on periodic assessment by supervisors. Virtual reality, robotic simulation, AI-based coaching, and digital twins could eventually be integrated into personalized training environments.

Such systems may enable a trainee to practice a procedure repeatedly on a patient-specific virtual model, receive AI-generated feedback regarding technical errors, and progress only after demonstrating predefined competencies. The attached report also identifies AI-based surgical simulation and advanced training technologies among the future directions of intelligent surgery.

Emergence of the "surgical co-pilot" paradigm

Collectively, these developments suggest that the next generation of robotic surgery may be better conceptualized as a surgical co-pilot system rather than simply a surgical robot. In this model, the AI system continuously analyzes information while the surgeon maintains clinical authority.

A future surgical co-pilot could potentially:

- summarize relevant patient information before surgery;
- generate individualized operative plans;
- identify high-risk anatomical structures;
- provide real-time visual and haptic alerts;
- monitor surgical workflow;
- predict potential complications;
- assess tissue and instrument interactions;
- recommend alternative strategies;
- document procedural events automatically;
- evaluate surgical performance; and
- assist with postoperative risk prediction.

Recent literature increasingly frames AI-enabled surgical systems as collaborative technologies that augment surgeons rather than simply automate them. A 2026 review of AI "companions" in surgery similarly proposes a progression toward systems supporting administrative, strategic, intraoperative, educational, and emergency functions, although the authors emphasize that clinical value and real-world effectiveness still require rigorous evaluation.

The emerging surgical intelligence ecosystem

The convergence of these technologies indicates that the future operating room is likely to function as an interconnected surgical intelligence ecosystem rather than a collection of independent devices. Such an ecosystem may integrate:

Table 1: Technological layer and function.

Technological layer	Function
AI/ML	Prediction, classification and decision support
Computer vision	Real-time perception and anatomical recognition
Robotics	Precise and reproducible physical execution
AR/XR	Visualization and human–machine interaction
Digital twins	Patient-specific simulation and adaptive modeling
Sensors/haptics	Force, motion and tissue feedback
Cloud/edge computing	Real-time data processing
Surgical analytics	Performance and outcome evaluation
Autonomous control	Supervised execution of selected tasks

The significance of this architecture lies in its potential to create a closed-loop surgical system. Information obtained from the patient can be processed by AI, translated into a surgical recommendation, delivered through an AR or robotic interface, and subsequently fed back into the computational model. In principle, this creates a continuous cycle of sense → interpret → predict → assist → act → evaluate → learn.

However, this vision should not be confused with established clinical reality. Many components remain under investigation, and the evidence base is heterogeneous. The current literature strongly supports the potential of AI for intraoperative enhancement and surgical assessment, while autonomous execution and comprehensive digital-twin integration remain less mature.

Translational gap: from technological feasibility to clinical utility

A critical issue emerging from the current literature is the distinction between technical capability and clinical value. Demonstrating that an algorithm can recognize an anatomical structure or that a robot can autonomously perform a particular maneuver does not necessarily establish that the technology improves patient outcomes.

For clinical translation, intelligent robotic systems must demonstrate measurable benefits in domains such as:

- operative safety;
- complication reduction;
- functional recovery;
- quality of life;
- procedure duration;

- hospital stay;
- long-term outcomes;
- reproducibility;
- cost-effectiveness; and
- equitable accessibility.

This translational gap is particularly important for emerging technologies such as digital twins. Current reviews identify substantial promise but also emphasize the need for standardized protocols, clinical validation, interoperability, and evaluation of real-world effectiveness before widespread implementation.

Artificial Intelligence Architecture in Intelligent Robotic Surgery: From Data Acquisition to Autonomous Decision-Making

The convergence of artificial intelligence (AI) and robotic surgery is transforming the conventional robot-assisted operating room into a data-driven computational environment. Whereas earlier robotic platforms primarily translated surgeon movements into highly precise instrument motions, contemporary systems increasingly incorporate machine learning (ML), deep learning, computer vision, multimodal data processing, predictive analytics, augmented reality (AR), and intelligent control. This transition is particularly important because surgery generates heterogeneous data across the entire perioperative pathway, including medical imaging, electronic health records, laboratory investigations, surgical video, instrument trajectories, force measurements, physiological parameters, and postoperative outcomes. AI provides the computational framework through which these diverse datasets can be transformed into predictions, recommendations, visual information, and, increasingly, controlled robotic actions. Recent reviews characterize this development as extending AI applications across preoperative, intraoperative, and postoperative surgical care rather than restricting AI to a single phase of the procedure.

The attached project similarly identifies machine learning, deep learning, computer vision, augmented reality, predictive analytics, and robotic systems as interconnected technologies supporting the transition toward intelligent surgery. It emphasizes that AI can analyze extensive datasets for preoperative planning, while deep learning and computer vision can support image interpretation, anatomical recognition, instrument identification, and intraoperative navigation. Accordingly, the architecture of intelligent robotic surgery can be conceptualized as a multilayered system comprising data acquisition, data processing, perception, prediction, decision support, human–machine interaction, robotic control, and continuous feedback.

Data acquisition: the foundation of surgical intelligence

The quality and diversity of input data fundamentally determine the performance of an AI-enabled surgical system. Unlike conventional clinical decision-support systems that may primarily depend on structured patient records, intelligent robotic surgery requires integration of multimodal information obtained before, during, and after an operation.

Preoperative data may include:

- computed tomography (CT);
- magnetic resonance imaging (MRI);
- ultrasound;
- positron emission tomography (PET);
- digital pathology;
- laboratory investigations;
- demographic information;
- medication history;
- previous operative records;
- physiological parameters; and
- patient-specific anatomical measurements.

Intraoperative information can include high-definition surgical video, endoscopic images, instrument position and velocity, force and torque measurements, tissue deformation, physiological monitoring, and surgeon–robot interaction data. Postoperative information may subsequently include complications, pathological findings, recovery trajectories, readmissions, and long-term outcomes.

This creates the possibility of a continuous perioperative data loop, in which information obtained before surgery contributes to planning, intraoperative data update the surgical strategy, and postoperative outcomes are subsequently incorporated into future predictive models. The development of robust surgical data infrastructures is increasingly regarded as an important prerequisite for realizing the potential of AI in surgery.

However, surgical datasets are inherently challenging. They frequently contain heterogeneous imaging protocols, differences in surgical techniques, variable annotation quality, incomplete clinical information, and substantial inter-institutional variation. These factors can influence algorithmic generalizability and may result in models performing well in the development environment but less reliably when transferred to another hospital, population, robotic platform, or surgical technique.

Machine learning as the predictive engine

Machine learning provides the principal analytical framework for extracting patterns from surgical datasets. Supervised learning can be used when datasets contain predefined labels, such as anatomical structures, surgical phases, complications, or pathology status. Unsupervised learning can identify previously unrecognized patterns within complex datasets, while reinforcement learning provides a framework through which an agent can learn actions by interacting with an environment and receiving feedback.

In robotic surgery, ML has potential applications across the perioperative pathway. Preoperatively, algorithms may predict operative difficulty, complications, length of hospital stay, or postoperative outcomes. Intraoperatively, ML can analyze surgical video, instrument movements, tissue characteristics, and physiological signals. Postoperatively, predictive models can potentially identify patients at increased risk of complications or delayed recovery.

The clinical significance of this capability lies not simply in automation but in anticipatory decision support. A conventional robotic system executes an instruction, whereas an intelligent system may increasingly anticipate the likely next surgical event, recognize deviation from the expected workflow, and provide an appropriate warning or recommendation.

Deep learning and surgical image interpretation

Deep learning has become particularly influential in surgical AI because of its capacity to analyze complex high-dimensional data. Convolutional neural networks and related architectures have been extensively investigated for image classification, segmentation, detection, and recognition.

In surgery, deep learning can potentially identify anatomical structures and pathological regions within operative images, classify tissues, recognize surgical instruments, determine procedural phases, and detect abnormal events. Computer vision is especially relevant to minimally invasive surgery because laparoscopic and robotic procedures generate continuous digital video streams suitable for computational analysis. A recent review of AI in minimally invasive surgery highlights real-time image recognition, intraoperative navigation, postoperative analysis, and automated surgical skill assessment as major areas of development.

Recent scoping evidence further demonstrates increasing interest in AI-based analysis of invasive surgical videos, although substantial heterogeneity remains in datasets, annotation methods, AI architectures, and outcome measures. This heterogeneity highlights the need for standardized surgical video datasets and reporting frameworks before AI models can be reliably compared across institutions.

Computer vision: enabling robotic perception

Computer vision represents the perceptual layer of intelligent robotic surgery. A robot cannot safely perform increasingly complex tasks without understanding the physical environment in which those tasks occur. In the surgical setting, this environment is highly dynamic because tissues deform, blood can obscure anatomy, instruments move continuously, and anatomical structures vary between patients.

Instrument tracking is particularly important for robotic control. By continuously estimating the position and orientation of surgical instruments relative to anatomical structures, computer vision can support collision avoidance, motion planning, and precision manipulation.

Anatomical segmentation is equally important. AI-generated segmentation can transform conventional two-dimensional images into three-dimensional representations that can subsequently be integrated into robotic navigation or AR systems. This creates a computational bridge between medical imaging and physical surgical action.

Multimodal AI and the integration of heterogeneous surgical information

A major limitation of early AI systems was their dependence on a single data modality. Surgical decision-making, however, rarely depends on one source of information. A surgeon simultaneously interprets imaging, operative video, patient history, laboratory findings, physiological changes, instrument behaviour, and contextual information.

The resulting computational model could potentially provide a more comprehensive representation of the surgical state than any individual data stream. This is particularly relevant to the development of general-purpose or foundation models for surgical robotics. Recent work has proposed vision–language–action architectures capable of integrating multiple forms of surgical information with robotic control, potentially allowing greater generalization across tasks.

The importance of this development should not be underestimated. Traditional robotic automation is generally task-specific, meaning that an algorithm trained to perform one procedure or surgical gesture may have limited ability to generalize to another. Foundation-model approaches attempt to overcome this limitation by learning broader representations from large and diverse datasets.

Nevertheless, surgical robotics presents unique challenges for foundation models. Biological tissues are deformable, surgical environments are highly variable, and errors can have immediate consequences. Furthermore, large open-source surgical datasets remain relatively scarce compared with datasets available in other AI fields.

Reinforcement learning and adaptive robotic control

Reinforcement learning (RL) provides another important component of the emerging AI architecture. In conventional programming, the desired robotic trajectory is explicitly defined. In reinforcement learning, an agent learns actions through interaction with an environment and optimization of a predefined reward function.

For surgical robotics, RL could theoretically be used to optimize:

- instrument trajectories;
- tissue manipulation;
- camera positioning;
- suturing;
- knot tying;
- navigation;
- force application; and
- task sequencing.

However, direct trial-and-error learning in living patients is clinically unacceptable when inappropriate actions may cause tissue injury. Consequently, reinforcement learning for surgery generally requires simulation environments, demonstrations, offline datasets, constrained learning, or human-supervised approaches.

This requirement makes surgical simulation particularly important. High-fidelity simulators and digital twins could provide controlled environments in which AI agents learn and test strategies before deployment in clinical settings.

Surgical video as a continuous source of intelligence

Surgical video represents one of the richest sources of information available to an intelligent surgical system. Unlike static preoperative images, video captures the dynamic progression of a procedure.

AI-based video analysis can potentially determine:

- what surgical phase is occurring;
- which instruments are being used;
- where instruments are positioned;
- which anatomical structures are visible;
- what surgical action is being performed;
- whether the procedure is following the expected workflow; and
- whether an abnormal event has occurred.

This capability may eventually enable real-time surgical workflow intelligence. For example, an AI system could recognize that a procedure has entered a high-risk stage and provide an automated warning or retrieve relevant patient-specific information. Recent literature specifically identifies surgical video and instrument kinematics as important sources for automated technical skill assessment and intraoperative feedback.

However, surgical video analysis faces important methodological challenges. Variations in camera angle, lighting, blood, smoke, anatomical appearance, instrument type, surgeon technique, and procedural sequence can substantially affect algorithmic performance. Consequently, external validation across institutions is essential.

Natural language processing and conversational surgical intelligence

Although computer vision and robotic control receive substantial attention, natural language processing (NLP) represents another potentially important component of intelligent surgery. NLP can allow AI systems to interpret clinical notes, radiology reports, operative documentation, pathology reports, and other textual information.

In an integrated surgical environment, a conversational AI system could potentially retrieve relevant patient information, summarize imaging findings, identify contraindications, explain procedural options, and provide context-sensitive information to the surgical team.

The emerging combination of language models with visual and robotic systems is particularly significant. Vision–language–action architectures are being explored as a potential pathway toward robots that can associate verbal instructions with visual perception and physical action.

Nevertheless, language-based systems should not be permitted to independently generate clinically consequential instructions without appropriate validation and human oversight. Hallucination, contextual misunderstanding, incomplete information, and uncertainty in generative models remain important safety considerations.

AI-enabled decision support during surgery

The ultimate purpose of surgical AI is not simply to recognize structures or classify images but to transform computational information into clinically meaningful decisions. AI-enabled decision support can potentially provide surgeons with real-time estimates of risk, predicted tissue characteristics, recommended trajectories, or alerts concerning deviations from the planned procedure.

A clinically useful decision-support architecture should ideally satisfy four conditions:

1. **Timeliness** – information must be generated rapidly enough to influence the current surgical decision.
2. **Accuracy** – recommendations must meet clinically acceptable performance thresholds.
3. **Interpretability** – surgeons should understand the basis and limitations of the recommendation.
4. **Actionability** – the information should meaningfully influence a clinical decision or robotic action.

The integration of AI with AR is particularly promising because computational outputs can be directly visualized within the operative environment. Previous work has proposed dynamic overlay of preoperative anatomical information onto the robotic surgical field to assist with identification of structures and dissection planes.

From decision support to robotic action

The transition from AI-generated recommendations to physical robotic action represents one of the most technically and ethically significant steps in surgical intelligence.

The inclusion of the surgeon within this loop is particularly important for current clinical systems. It creates a human-in-the-loop architecture, whereby AI can provide computational assistance while the surgeon retains responsibility and authority.

As autonomy increases, the surgeon's role may evolve toward supervisory control. The recent LASR framework illustrates this progression from robot assistance through task autonomy and conditional autonomy toward high-level and full autonomy. Importantly, a 2024 systematic review found that among 49 FDA-cleared surgical robots evaluated, 86% were categorized as Level 1, 8% as Level 2, and only 6% as Level 3, with no identified systems reaching Levels 4 or 5.

This evidence provides an important reality check against exaggerated claims surrounding autonomous surgery. Despite rapid technological development, clinically deployed surgical robotics remains predominantly surgeon-controlled.

Foundation models and the possibility of general-purpose surgical intelligence

One of the most innovative developments in the field is the emergence of foundation-model approaches. Traditional surgical AI models are typically trained for narrowly defined tasks. A model might recognize surgical instruments but be unable to interpret tissue characteristics, understand verbal instructions, or control a robotic arm.

Foundation models seek to develop broader representations that can be adapted to multiple downstream tasks. In surgical robotics, this could eventually allow a single multimodal model to process video, language, anatomical information, and robotic state while generating context-dependent actions.

A recent Nature Machine Intelligence perspective proposes vision–language–action models as a potential route toward increased autonomy in robot-assisted surgery. However, the authors identify major obstacles, including limited large-scale open surgical datasets, difficulty modelling deformable biological tissue, and the high safety requirements associated with robotic experimentation.

This development could fundamentally alter the architecture of surgical robots. Rather than programming every surgical action independently, future systems may learn generalized representations of surgical procedures from large collections of demonstrations and subsequently adapt these representations to individual patients and tasks.

The closed-loop intelligent operating room

The ultimate architecture emerging from these technologies is a closed-loop intelligent operating room. In such an environment, data are not merely collected and analyzed independently; they continuously influence subsequent actions.

The closed-loop architecture represents an important conceptual distinction between computer-assisted surgery and surgical intelligence. In the former, computers assist specific tasks; in the latter, computational systems continuously perceive, interpret, predict, support, and learn from the surgical process.

Data quality, explainability and model generalizability

Despite considerable technological promise, the performance of intelligent robotic surgery ultimately depends on the quality of the underlying data and algorithms. Poorly annotated datasets, demographic underrepresentation, institutional biases, inconsistent imaging protocols, and differences in surgical technique can lead to models that do not generalize adequately.

Algorithmic transparency is another major concern. Deep learning systems can generate highly accurate predictions while providing limited explanation of how a particular conclusion was reached. In high-risk surgical environments, a recommendation that cannot be appropriately interpreted or challenged may be difficult to integrate safely into clinical practice.

The issue becomes even more important as autonomy increases. A model used merely to provide supplementary information may tolerate a different degree of uncertainty from a model controlling a surgical instrument. Therefore, acceptable AI uncertainty should decrease as the consequences of automated action increase.

A proposed framework for next-generation surgical intelligence

Based on the technological trajectory identified in the attached report and recent literature, next-generation intelligent robotic surgery can be conceptualized through six interconnected layers:

Table 2: Layer, core technologies and primary functions.

Layer	Core technologies	Primary function
Layer I: Data	Imaging, EHR, video, sensors, laboratory data	Patient and surgical information acquisition
Layer II: Perception	Computer vision, segmentation, detection	Understanding anatomy and operative environment
Layer III: Intelligence	ML, deep learning, foundation models	Prediction, classification and contextual reasoning
Layer IV: Planning	Digital twins, simulation, predictive analytics	Patient-specific strategy development
Layer V: Action	Robotic control, navigation, AR, haptics	Precise execution and intraoperative assistance
Layer VI: Governance	Human oversight, validation, regulation, cybersecurity	Safe and responsible clinical deployment

This framework highlights that autonomous surgical capability should not be evaluated solely according to the mechanical capabilities of a robotic platform. True surgical intelligence requires successful integration across all six layers.

Critical perspective

The current trajectory suggests that AI will increasingly influence every stage of the surgical pathway, but the transition toward autonomous surgery should be approached cautiously. Recent evidence demonstrates considerable progress in intraoperative AI, surgical video analysis, automated skill assessment, and task-level robotic autonomy. Nevertheless, most clinically deployed robotic systems remain at low autonomy levels, and fully autonomous surgery has not yet become established clinical practice.

Therefore, the most plausible near-term future is not a surgeonless operating room but an intelligent collaborative operating room in which AI continuously processes multimodal information, robotic systems provide increasingly sophisticated physical assistance, and surgeons retain ultimate clinical authority.

The attached report reaches a compatible conclusion, emphasizing that AI-powered robotic surgery should augment clinical expertise rather than replace human judgment and that future development will require interdisciplinary collaboration among clinicians, engineers, researchers, and policymakers.

Clinical Applications of AI-Enabled Robotic Surgery: From Precision Procedures to Personalized Interventions

The clinical translation of artificial intelligence (AI)-enabled robotic surgery is expanding from conventional minimally invasive procedures toward increasingly complex, image-guided, data-driven, and partially automated interventions. The central advantage of integrating AI with robotic platforms lies not simply in replacing manual surgical movements, but in combining robotic dexterity, computational perception, predictive analytics, patient-specific planning, and real-time feedback. The attached report identifies orthopedic surgery, hernia repair, thoracic surgery and lung transplantation, cardiac surgery, neurosurgery, colorectal surgery, and other complex procedures as important areas in which robotic and AI technologies are increasingly being investigated.

This clinical transformation can be understood as a progression from robot-assisted execution toward AI-augmented precision surgery, in which information generated before and during an operation continuously influences surgical planning and execution. Recent literature similarly identifies intraoperative enhancement, force and tactile sensing, surgical-margin detection, automated surgical steps, video-based skill assessment, and personalized surgical feedback among the principal emerging applications of AI in robotic surgery.

Robotic-assisted orthopedic surgery and precision joint replacement

Orthopedic surgery represents one of the most mature applications of computer-assisted and robotic surgical technologies. Total knee arthroplasty (TKA), unicompartmental knee arthroplasty (UKA), and other joint-replacement procedures require accurate bone preparation, implant positioning, alignment, and soft-tissue balancing. Even small deviations from the intended surgical plan may influence implant biomechanics, functional recovery, wear, and revision risk.

The attached report identifies robotic-assisted knee replacement as an important application because robotic platforms provide patient-specific planning, improved bone preparation, and intraoperative assessment of soft-tissue balance. Contemporary systems such as MAKO, ROSA Knee, and CORI combine three-dimensional anatomical modelling with computer-assisted navigation and robotic guidance. The MAKO system, for example, uses CT-based patient-specific planning and incorporates haptic constraints intended to prevent bone preparation beyond predefined boundaries.

AI adds an additional layer to this established robotic architecture. Algorithms can potentially analyze preoperative imaging, estimate alignment and implant parameters, predict postoperative function, and identify patient-specific anatomical variations. Intraoperatively, AI-assisted systems may integrate optical tracking, force information, and soft-tissue measurements to assist with real-time adjustment of the surgical plan.

This model has the potential to reduce inter-surgeon variability while retaining surgeon oversight. Importantly, however, improved radiographic alignment should not automatically be interpreted as equivalent to improved long-term clinical outcomes. Longitudinal studies remain necessary to establish whether increasing robotic precision consistently translates into superior patient-reported outcomes, implant survivorship, and cost-effectiveness.

Robotic hernia repair and intelligent abdominal wall reconstruction

Robotic surgery has increasingly been applied to inguinal and ventral hernia repair. The principal advantages of robotic platforms include enhanced visualization, articulated instruments, improved access to confined anatomical spaces, and improved surgeon ergonomics. The attached report describes robotic approaches as increasingly utilized for inguinal and ventral hernias and reports encouraging findings regarding precision, recovery, and postoperative outcomes.

The integration of AI may further expand these capabilities. Computer vision can potentially identify abdominal wall structures, mesh boundaries, hernia defects, and critical anatomical landmarks. Motion tracking can provide objective information regarding instrument trajectories, while biomechanical modeling can help characterize abdominal wall behaviour.

An especially interesting development is the integration of dynamic imaging and biomechanical modelling. Instead of treating the abdominal wall as a static structure, future AI systems may model its behaviour during respiration, movement, and changes in intra-abdominal pressure. Such information could potentially contribute to individualized mesh selection, positioning, and tension optimization.

The attached report also describes the emergence of AI-assisted guidance, motion tracking, autonomous support, and multimodal sensing in robotic hernia surgery. These developments suggest that future abdominal wall reconstruction may increasingly involve patient-specific computational modeling rather than purely anatomical repair.

Robotic thoracic surgery and lung transplantation

Thoracic surgery presents unique technical challenges because procedures frequently involve confined anatomical spaces and delicate structures such as pulmonary vessels, bronchi, and mediastinal tissues. Robotic systems provide enhanced visualization and articulated instrument movement, potentially facilitating complex procedures through smaller incisions.

The attached report identifies robotic lung transplantation as an emerging application. Robotic systems can facilitate pneumonectomy, donor lung implantation, vascular and bronchial anastomosis, and other technically demanding steps through minimally invasive access.

AI may further contribute through preoperative imaging analysis, three-dimensional reconstruction, surgical planning, computer vision, gesture recognition, and intraoperative decision support. In particular, AI-assisted imaging may help evaluate recipient anatomy and support individualized transplant planning.

The report also describes recent clinical experience with robotic lung transplantation and notes encouraging short-term survival and functional outcomes, while emphasizing that standardized approaches and further validation remain necessary. These findings are promising but should be interpreted cautiously because robotic transplantation remains a highly specialized procedure with relatively limited clinical experience compared with conventional transplantation.

AI and robotic assistance in cardiac surgery

Cardiac surgery represents another important field for robotic and AI integration. The restricted operative field, proximity of vital structures, and need for highly precise tissue manipulation make computer-assisted technology particularly attractive.

Robotic platforms have been employed in minimally invasive cardiac procedures, including selected coronary, valve, and structural interventions. AI may extend these applications by supporting image interpretation, anatomical segmentation, surgical planning, intraoperative navigation, and procedural prediction.

The attached report specifically identifies AI-assisted guidance and robotic systems as increasingly relevant to complex cardiac and thoracic procedures.

One important future direction is multimodal cardiovascular modelling, whereby preoperative echocardiography, CT, MRI, electrocardiographic information, haemodynamic parameters, and intraoperative imaging are integrated into a patient-specific computational model.

Such models could potentially assist with:

- valve sizing and positioning;
- vascular navigation;
- coronary anatomy assessment;
- prediction of procedural risk;
- intraoperative imaging interpretation; and
- postoperative outcome prediction.

However, because cardiac procedures involve rapidly changing physiological conditions, AI systems must demonstrate exceptionally high reliability before being permitted to influence autonomous or semi-autonomous physical actions.

Neurosurgical robotics: precision within anatomically critical environments

Neurosurgery represents one of the areas in which robotic precision may offer particularly important benefits because surgical interventions frequently occur adjacent to highly sensitive neurological structures. Robotic and image-guided technologies can support stereotactic procedures, navigation, biopsy, electrode placement, and selected spinal interventions.

AI can potentially contribute by integrating MRI, CT, functional imaging, and intraoperative data to generate patient-specific anatomical maps. Computer vision and image registration may assist in compensating for anatomical changes that occur during procedures.

The attached report identifies neurosurgical applications as an area in which AI-guided robotic systems may reduce the risk of injury to critical brain and spinal structures.

The future direction is likely to involve AI-assisted navigation rather than complete autonomous neurosurgery, particularly because neural tissue is highly sensitive and unpredictable. AI may function as an intelligent safety layer that identifies critical structures, predicts risk, and alerts surgeons when planned trajectories approach predefined boundaries.

Colorectal surgery and AI-guided anatomical navigation

Colorectal surgery is another field in which AI and robotic technology can provide complementary advantages. Robotic platforms facilitate precise dissection in anatomically restricted regions, particularly during procedures involving the pelvis.

The attached report describes AI-assisted navigation in transanal total mesorectal excision (TaTME), including real-time visualization using MRI-based overlays. This represents an important example of how preoperative imaging can be transformed into intraoperative guidance.

AI-based computer vision may also assist in recognizing anatomical landmarks, identifying tissue planes, tracking instruments, and assessing surgical progress.

One particularly promising application is AI-assisted identification of the mesorectal plane, where computer vision could potentially distinguish tissue characteristics and provide real-time visual guidance. Such technologies may contribute to reducing inadvertent injury and improving consistency between surgeons.

AI-enabled robotic stapling and tissue-response assessment

The integration of sensing with robotic instruments represents an important transition from simple mechanical automation to intelligent physical interaction with biological tissue.

The attached report describes AI-assisted robotic stapling systems that incorporate feedback mechanisms to evaluate tissue compression before staple deployment. According to the report, the system can assess applied force and tissue response and adjust compression accordingly before firing.

This approach illustrates an important principle of surgical intelligence:

The robot does not merely perform a predefined movement; it measures the biological response to that movement and modifies its action accordingly.

This feedback-based architecture could potentially be expanded to other surgical instruments. Force sensing, tactile feedback, tissue deformation analysis, and machine-learning models could eventually allow robotic systems to distinguish different tissue properties and adjust their behaviour accordingly.

Such capabilities may be particularly valuable in procedures where inappropriate force can result in bleeding, tissue tearing, inadequate sealing, or postoperative complications.

Eye tracking and cognitive augmentation

Another emerging application is eye-tracking technology. Conventional laparoscopic surgery frequently requires an assistant to manipulate the camera while the surgeon controls instruments. Eye-tracking systems offer a potential alternative by detecting the surgeon's gaze and automatically adjusting the camera toward the region of interest.

The attached report describes eye-tracking systems capable of detecting the surgeon's gaze and dynamically adjusting camera positioning.

Although relatively simple compared with autonomous robotic surgery, this technology represents an important form of cognitive augmentation. By reducing the need for manual camera control, it can potentially reduce cognitive workload and allow the surgeon to maintain greater attention on the operative task.

Integration with AI could make this system more sophisticated. Rather than responding exclusively to gaze direction, future camera systems could combine gaze, surgical phase, instrument position, and anatomical context to predict where visualization will be required next.

AI-assisted surgical education and objective skill assessment

Robotic platforms generate large quantities of objective performance data, making them valuable tools for surgical education. Traditional surgical assessment relies substantially on expert observation and subjective rating. AI can potentially transform this process by converting surgical video and instrument-kinematic information into quantitative performance metrics.

Potential parameters include:

- instrument path length;
- instrument velocity;
- number of unnecessary movements;
- tissue-handling force;
- procedural time;
- instrument collisions;
- camera movement;
- error frequency; and
- sequence of surgical actions.

The attached report specifically identifies automated assessment of surgical skills using intraoperative video and instrument-kinematic data as an emerging AI application.

Autonomous and semi-autonomous task execution

One of the most significant clinical developments is the transition from AI-based decision support toward autonomous execution of defined surgical tasks.

A landmark example is the Smart Tissue Autonomous Robot (STAR), which demonstrated autonomous intestinal suturing in a porcine model. The attached report notes the 2016 demonstration of autonomous intestinal suturing and describes subsequent developments in AI-guided planning, intraoperative imaging, sensor analysis, and robotic control.

Importantly, these demonstrations do not indicate that fully autonomous surgery has become clinically established. Instead, they demonstrate the feasibility of task-specific autonomy under controlled conditions.

The distinction between task autonomy and procedural autonomy is critical. A robotic system may successfully perform suturing without being capable of independently managing an entire surgical operation. The latter requires continuous understanding of anatomy, pathology, bleeding, physiological status, unexpected findings, and changing procedural priorities.

Accordingly, the near-term clinical model is likely to involve supervised autonomy, where surgeons delegate specific repetitive or technically standardized tasks while maintaining overall procedural control.

AI in intraoperative prediction and surgical workflow optimization

Beyond direct instrument control, AI can analyze the progression of an operation and predict what is likely to occur next. Surgical workflow recognition can classify operative phases and identify deviations from expected procedural sequences.

Such capability may support:

- prediction of upcoming surgical steps;
- identification of prolonged procedural phases;
- early detection of complications;
- optimization of instrument preparation;
- automated documentation;
- operating-room resource management; and
- real-time alerts.

This represents a shift from reactive surgical assistance toward predictive surgical assistance.

The distinction is clinically meaningful. A conventional warning system responds after an adverse event has occurred, whereas a predictive AI system aims to identify risk before the event occurs.

Cross-specialty convergence and the emergence of platform intelligence

Although individual surgical specialties have different anatomical and procedural requirements, the underlying technological architecture is increasingly convergent. Computer vision, multimodal sensing, AI-based planning, robotic manipulation, augmented reality, and predictive analytics can potentially be adapted across multiple specialties.

This suggests that future surgical platforms may increasingly become technology-agnostic intelligence **layers** capable of supporting multiple robotic systems rather than being restricted to a single proprietary platform.

The attached report identifies interoperability as an important unresolved issue and argues that future intelligent medical robotics will require integrated data and resource platforms.

Such interoperability will be essential for preventing fragmented development in which every manufacturer develops isolated datasets, algorithms, interfaces, and control architectures.

Clinical maturity versus technological promise

The rapid expansion of AI-enabled robotic applications should not obscure the substantial difference between experimental feasibility and established clinical benefit. Some technologies, such as robotic-assisted knee arthroplasty and minimally invasive robotic surgery, have progressed substantially into routine clinical practice. Other technologies—including autonomous tissue manipulation, digital twins, AI-controlled surgical instruments, and fully autonomous procedures—remain at various experimental or early translational stages.

The attached report itself emphasizes that although AI and robotic systems have demonstrated substantial potential, clinical translation remains limited in several areas.

Accordingly, clinical adoption should be based on evidence demonstrating not merely technical accuracy, but meaningful improvement in patient-centered outcomes. Appropriate evaluation should include surgical safety, complications, recovery, functional outcomes, long-term survival or implant durability where relevant, cost-effectiveness, usability, and equity of access.

Integrative perspective: toward precision robotic surgery

The clinical applications discussed above demonstrate that AI-enabled robotics is evolving through several distinct but interconnected dimensions:

This progression represents a fundamental change in the meaning of surgical precision. Historically, precision referred primarily to the surgeon's ability to execute a movement accurately. In intelligent surgery, precision increasingly encompasses accurate perception, accurate prediction, accurate planning, accurate physical execution, and accurate adaptation to intraoperative changes.

The combination of AI and robotics therefore has the potential to transform surgery from a predominantly manually controlled intervention into an adaptive, data-driven therapeutic process. The attached report concludes that robotic platforms combined with AI can enhance visualization, dexterity, real-time feedback, patient-specific planning, workflow optimization, and postoperative recovery across multiple specialties.

Nevertheless, the ultimate value of these technologies will depend on whether increased technological sophistication produces demonstrable improvements in patient outcomes. The next generation of clinical research must therefore move beyond reporting technical feasibility and focus on prospective validation, external generalizability, long-term outcomes, cost-effectiveness, patient acceptance, and equitable implementation.

Table 3: Summary of clinical applications.

Surgical domain	Current robotic contribution	Emerging AI contribution	Future direction
Orthopedics	Navigation, bone preparation, implant positioning	Patient-specific planning, predictive modeling, soft-tissue analysis	Adaptive personalized arthroplasty
Hernia surgery	Articulated instruments, 3D visualization	Computer vision, biomechanical modeling, motion tracking	Intelligent abdominal-wall reconstruction
Thoracic surgery	Minimally invasive access and precise dissection	Imaging analysis, gesture recognition, navigation	Semi-autonomous tissue handling
Lung transplantation	Robotic pneumonectomy and implantation	AI-assisted imaging and planning	Integrated robotic transplant workflow
Cardiac surgery	Precision minimally invasive intervention	Multimodal imaging and risk prediction	Adaptive image-guided cardiac robotics
Neurosurgery	Stereotactic navigation and precision manipulation	Anatomical segmentation and trajectory prediction	Intelligent safety-guided navigation
Colorectal surgery	Precise pelvic dissection	AI navigation and tissue-plane recognition	Real-time anatomy-aware robotic surgery
Robotic stapling	Controlled mechanical deployment	Force/tissue-response feedback	Adaptive tissue-aware stapling
Surgical education	Simulation and objective kinematics	Automated skill assessment and coaching	AI-personalized competency training
Complex surgery	Enhanced dexterity and visualization	Workflow prediction and decision support	Supervised task autonomy

Overall, the clinical trajectory indicates that the most realistic near-term future is not autonomous surgery without surgeons, but increasingly intelligent collaboration between surgeon, AI, and robot. The attached evidence particularly supports this human-centred trajectory, while emphasizing that technological advancement must be accompanied by clinical validation, ethical accountability, affordability, and appropriate governance.

Precision Medicine and Personalized Surgery: The Role Of AI, Digital Twins and Patient-Specific Robotic Planning

This section would provide the conceptual centerpiece of the review by connecting AI-based prediction + medical imaging + digital twins + surgical simulation + robotic execution + postoperative learning into a unified model of next-generation precision surgery.

Precision Medicine and Personalized Surgery: Integrating AI, Digital Twins and Patient-Specific Robotic Planning

The convergence of artificial intelligence (AI), advanced imaging, robotics, augmented reality (AR), and digital-twin technologies is progressively redefining the concept of precision surgery. Conventional surgical planning is primarily based on anatomical imaging, clinical experience, standardized procedural pathways, and intraoperative judgment. Although these approaches remain fundamental, AI-enabled systems provide an opportunity to incorporate substantially larger quantities of patient-specific information into the planning and execution of an operation. The attached report identifies patient-specific planning, AI-assisted imaging, real-time feedback, digital twins, and predictive analytics as important components of the emerging precision-surgery paradigm.

From standardized procedures to individualized surgical strategies

The fundamental principle of precision medicine is that therapeutic decisions should account for individual biological, anatomical, clinical, and environmental variation rather than relying exclusively on population-level averages. In surgery, this principle translates into personalized procedural planning.

AI can potentially integrate medical images, clinical records, laboratory results, previous interventions, anatomical measurements, and outcome data to generate individualized predictions regarding operative complexity and postoperative risk. This information can subsequently be incorporated into robotic planning systems.

Patient-specific anatomical reconstruction

Three-dimensional reconstruction of patient anatomy represents an important bridge between diagnostic imaging and robotic intervention. CT and MRI datasets can be processed using AI-based segmentation algorithms to generate detailed three-dimensional representations of organs, vessels, tumors, bones, and other relevant structures.

When integrated with robotic platforms, these models can facilitate:

- individualized operative trajectories;
- identification of critical anatomical structures;
- implant positioning;
- tumor-margin planning;
- vascular mapping;
- surgical-access planning; and
- simulation of alternative surgical strategies.

This represents a fundamental shift from “planning around the average patient” toward “planning around the individual patient.”

Digital twins as dynamic surgical models

Digital twins represent a further evolution beyond conventional three-dimensional anatomical models. A digital twin is intended to provide a computational representation of a physical patient or relevant biological system that can be updated as new information becomes available.

In surgical medicine, a digital twin could potentially incorporate anatomical imaging, physiological parameters, previous treatment information, operative findings, and postoperative outcomes. The attached report identifies digital twins as a future technology capable of supporting individualized treatment planning and surgical simulation.

Virtual surgery before physical surgery

One of the most promising applications of digital twins is preoperative simulation. Surgeons could potentially evaluate different approaches on a virtual representation of the patient before selecting the optimal strategy.

For example, a virtual model could theoretically be used to compare:

- different surgical access routes;
- alternative implant positions;
- resection margins;
- vascular trajectories;
- robotic instrument approaches; and
- anticipated tissue interactions.

This could reduce uncertainty and provide surgeons with a better understanding of technically difficult anatomy before entering the operating room.

However, digital twins should currently be regarded as an emerging technology rather than an established standard of care. Their clinical value depends on the accuracy of the underlying model, quality of input data, ability to represent biological variability, and successful validation against real-world outcomes.

Intraoperative adaptation and real-time personalization

A major limitation of conventional preoperative planning is that the surgical environment may differ from the preoperative model. Tissue deformation, bleeding, patient positioning, organ movement, and unexpected anatomical findings can alter the operative environment.

AI-enabled robotic systems could potentially address this limitation through continuous data acquisition. Computer vision, force sensing, intraoperative imaging, and instrument tracking can provide updated information to the computational model.

This creates the possibility of dynamic surgical planning, in which the original plan is modified when clinically relevant changes occur.

Human–AI–Robot Collaboration and the Progressive Autonomy of Surgery

The development of increasingly capable robotic systems raises an important question: What should the role of the surgeon be when machines can perceive, predict, and perform selected surgical actions?

The available evidence suggests that the most clinically realistic trajectory is not immediate replacement of surgeons but progressive human–AI–robot collaboration. The attached report repeatedly emphasizes that AI and robotics should augment clinical expertise rather than eliminate human decision-making.

The autonomy continuum

Surgical autonomy should be understood as a continuum rather than a binary concept.

A useful conceptual model is:

1. **Manual control** – surgeon performs the procedure directly.
2. **Robot assistance** – robot improves dexterity and visualization.
3. **AI assistance** – AI provides information or recommendations.
4. **Shared control** – surgeon and robotic system jointly control selected movements.
5. **Task-level autonomy** – robot performs predefined surgical subtasks.
6. **Conditional autonomy** – robot performs more complex actions under supervision.
7. **High-level autonomy** – system manages substantial portions of the procedure.
8. **Full autonomy** – system independently plans and executes surgery.

Current clinical practice remains predominantly concentrated at the lower levels of this continuum. The attached report's discussion of autonomous systems similarly emphasizes gradual progression toward semi-autonomous assistance rather than immediate fully independent surgery.

The surgeon as supervisor and clinical decision-maker

As automation increases, the surgeon's role is likely to change rather than disappear. Surgeons may increasingly function as supervisors who:

- establish treatment goals;
- select appropriate patients;
- approve AI-generated plans;
- monitor robotic actions;
- intervene when unexpected events occur;
- manage complications;
- communicate with patients; and
- retain ultimate clinical responsibility.

This model is consistent with WHO guidance, which emphasizes that AI in healthcare should assist human decision-making and that human oversight must remain meaningful, particularly when decisions carry significant consequences.

Surgical co-pilots

The concept of the AI surgical co-pilot may represent an intermediate and clinically realistic stage between conventional robotic assistance and autonomous surgery.

A surgical co-pilot could continuously monitor:

- patient data;
- surgical video;
- robotic instrument trajectories;
- procedural phases;
- physiological variables; and
- preoperative plans.

It could then provide context-sensitive recommendations, warnings, or visual overlays without independently controlling the entire operation.

This architecture has the potential to preserve human judgment while reducing cognitive and technical workload.

Ethical, Legal, Regulatory and Cybersecurity Considerations

Technological capability alone cannot determine the future of intelligent robotic surgery. Because AI-enabled robotic systems can influence or potentially execute physical actions on patients, ethical and regulatory requirements are substantially more demanding than those associated with conventional information technologies.

The attached report identifies privacy, algorithmic bias, accountability, transparency, cybersecurity, legal liability, affordability, and human oversight among the principal challenges limiting responsible implementation.

Patient autonomy and informed consent

The increasing role of AI raises questions regarding informed consent. Patients should understand when AI is being used in their care, what function it performs, and the degree of human oversight involved.

The issue becomes particularly important as systems progress from decision support toward autonomous task execution. Consent processes may need to distinguish between:

- surgeon-controlled robotic assistance;
- AI-generated recommendations;
- AI-assisted navigation;
- supervised autonomous tasks; and
- highly autonomous procedures.

WHO identifies protection of human autonomy as a central ethical principle and states that machine autonomy should not undermine human control over healthcare decisions.

Algorithmic bias and health inequity

AI models learn from historical datasets. If training data are incomplete, unrepresentative, or systematically biased, algorithmic predictions may reproduce or amplify existing disparities.

This issue is particularly important in surgical AI because anatomical variation, demographic characteristics, disease prevalence, healthcare infrastructure, and surgical practice can differ substantially across populations.

WHO emphasizes that AI systems should be developed using accurate, complete, diverse and representative datasets and that developers should actively identify and mitigate bias.

Therefore, validation should extend beyond a single institution or population whenever possible.

Transparency and explainability

Surgeons must be able to understand the limitations of AI-generated recommendations. A highly accurate but completely opaque system may be difficult to trust when its recommendation conflicts with clinical judgment.

Explainability is particularly important when AI influences physical robotic action. The higher the potential harm associated with an incorrect decision, the greater the requirement for transparency, uncertainty estimation, and human override.

Liability and accountability

Responsibility becomes increasingly complex when an AI-enabled robotic system contributes to an adverse event.

Potentially responsible parties may include:

- the surgeon;
- healthcare institution;
- robotic manufacturer;
- AI developer;
- software provider; and
- maintenance or data-management provider.

Existing legal frameworks may not adequately address situations in which multiple human and computational agents jointly contribute to a surgical decision.

Consequently, future regulation should clearly define responsibility according to the degree of autonomy, intended use, human oversight, and system performance.

Data privacy and governance

AI-enabled surgery depends heavily on patient data, including imaging, video, physiological information, operative records, and potentially biometric information. These datasets require secure collection, storage, transmission, and processing.

WHO's recent work on health-data governance emphasizes that high-quality, representative and ethically sourced data are essential for reliable AI while strong governance is necessary to protect privacy and support responsible data sharing.

Federated learning, privacy-preserving computation, controlled-access databases, encryption, and robust institutional governance may become increasingly important in large-scale surgical AI development.

Cybersecurity

Cybersecurity represents a distinctive concern for connected robotic systems because compromise of an ordinary information system and compromise of a surgical robot have fundamentally different consequences.

Potential vulnerabilities include:

- unauthorized system access;
- manipulation of data;
- malicious alteration of AI outputs;
- communication interference;

- ransomware;
- software vulnerabilities; and
- compromised connected devices.

Cybersecurity should therefore be incorporated into robotic design from the earliest development stages rather than treated solely as a post-deployment concern.

Regulatory validation

AI-enabled robotic devices require rigorous evaluation before widespread clinical adoption. WHO recommends attention to intended use, lifecycle documentation, risk management, cybersecurity, external validation, data quality, and transparency in the regulation of AI for health.

For surgical robotics, validation should ideally evaluate at least four dimensions:

Algorithmic performance + robotic performance + clinical safety + patient outcomes.

A system should not be considered clinically successful merely because its algorithm demonstrates high classification accuracy in a laboratory dataset.

Economic Feasibility, Accessibility and Healthcare Equity

The economic dimension of intelligent robotic surgery is particularly important because sophisticated robotic platforms require substantial expenditure on acquisition, maintenance, disposable instruments, software, infrastructure, and workforce training.

The attached report identifies high installation and maintenance costs as a major barrier, particularly for developing and resource-limited healthcare systems.

The risk of a technological divide

If advanced robotic systems remain concentrated in high-income hospitals, their benefits may become disproportionately available to economically privileged populations. This creates a paradox: technologies designed to improve precision medicine could simultaneously increase healthcare inequality.

Equitable implementation therefore requires consideration of:

- acquisition costs;
- maintenance costs;
- training requirements;
- infrastructure;
- internet and computing capacity;
- availability of technical personnel;
- patient affordability; and
- regional healthcare priorities.

WHO specifically warns that AI development should not widen the digital divide and emphasizes equitable access across high- and low-resource settings.

Cost-effectiveness rather than technological novelty

Future evaluations should therefore focus on **value**, not simply innovation. Cost-effectiveness analyses should consider the complete care pathway, including:

- procedure duration;
- operating-room utilization;
- hospital stay;
- complication rates;
- readmissions;
- rehabilitation;
- revision procedures;
- maintenance;
- training; and
- long-term outcomes.

An expensive technology may still be economically justified if it produces substantial improvements in outcomes or reduces downstream costs. Conversely, technical superiority without meaningful clinical benefit may not justify widespread implementation.

Training, Workforce Transformation and the Future Surgeon

AI-enabled robotic surgery will require a transformation in surgical education. Future surgeons will need not only traditional anatomical and procedural expertise but also familiarity with robotic systems, AI limitations, data interpretation, human–machine interaction, and cybersecurity.

The attached report highlights the need for interdisciplinary training combining medicine, computer science, bioinformatics, and engineering.

From technical proficiency to technological literacy

Future surgical competency may encompass five domains:

1. **Clinical competence**

2. **Technical robotic competence**
3. **AI literacy**
4. **Data interpretation**
5. **Human–machine decision-making**

Surgeons should understand not only how to operate a robotic system but also when an AI recommendation may be unreliable.

AI-enabled simulation

Simulation represents an especially important component of future surgical education. AI can monitor trainee performance and provide quantitative feedback regarding movement efficiency, force, errors, timing, and procedural sequencing.

Digital twins could eventually allow training on anatomically realistic patient-specific models without exposing patients to unnecessary risk.

This could establish a new educational cycle:

Simulation → AI assessment → individualized feedback → adaptive training → competency verification → supervised clinical practice.

Future Directions: Toward the Autonomous, Adaptive and Connected Operating Room

The future development of AI-enabled robotic surgery is likely to be determined by the convergence of several technologies rather than by any single innovation.

Multimodal surgical foundation models

Future AI systems may integrate text, imaging, video, sensor data and robotic state information into unified models. The goal would be to develop systems capable of understanding surgical context rather than performing isolated classification tasks.

Such models could potentially support:

- surgical planning;
- intraoperative assistance;
- workflow recognition;
- complication prediction;
- robotic control;
- postoperative monitoring; and
- surgical education.

However, their clinical deployment will require extensive validation and strong safeguards. WHO's 2025 guidance on large multimodal models emphasizes the need to address governance, transparency, safety and responsible deployment as these systems expand into healthcare.

Adaptive autonomy

Future robotic systems are unlikely to have a single fixed level of autonomy. Instead, autonomy may dynamically change according to task complexity and risk.

For example:

Low-risk repetitive task → higher autonomy

Complex anatomical variation → increased surgeon control

Unexpected bleeding → immediate human takeover

This concept of risk-adaptive autonomy may be more clinically appropriate than unrestricted automation.

Continuous learning systems

Current medical AI models are generally trained, validated, deployed and subsequently updated through controlled processes. Future robotic systems may increasingly learn from accumulated procedural data.

However, continuous learning introduces additional regulatory challenges because system behaviour can change after deployment. Consequently, mechanisms will be required to ensure that model updates do not unexpectedly degrade safety.

Tele-robotics and geographically distributed surgery

The combination of robotics, high-speed communication and AI may expand access to specialist surgical expertise through remote assistance and tele-robotic procedures.

The attached report identifies telehaptic systems and advanced connectivity among future directions.

AI could potentially provide additional safety support by compensating for communication delays, monitoring instrument trajectories, and detecting unsafe movements.

The intelligent operating room

The ultimate evolution may involve an operating room in which multiple devices function as a coordinated intelligent ecosystem:

Patient monitoring + imaging + robotic platform + AI co-pilot + AR display + digital twin + surgical documentation + postoperative analytics.

Such integration could create a continuously connected surgical environment in which information is available to the appropriate clinical team at the appropriate time.

Research Gaps And Priorities For Clinical Translation

Despite rapid technological progress, several important gaps remain.

Lack of standardized datasets

Different institutions use different imaging protocols, robotic platforms, surgical techniques, annotation systems, and outcome definitions. Standardized multicenter datasets are needed to improve model generalizability.

Limited prospective clinical evidence

Many AI applications remain supported primarily by retrospective studies, simulation experiments, or single-center investigations. Prospective multicenter studies and randomized clinical trials are required to determine whether AI-enabled robotic systems improve meaningful patient outcomes.

Limited long-term evidence

Short-term improvements in operative metrics do not necessarily translate into better long-term outcomes. Studies should therefore examine recurrence, implant longevity, functional recovery, quality of life, survival, and revision rates where applicable.

Interoperability

AI systems, robotic platforms, imaging systems, electronic health records, and hospital information systems often operate within separate technical environments. Interoperability is therefore essential for creating integrated surgical intelligence.

Human factors

Future research should evaluate surgeon trust, cognitive workload, automation bias, situational awareness, communication, and appropriate responses to AI failure.

Equity and affordability

Technological innovation should be accompanied by implementation strategies appropriate for low- and middle-income healthcare systems. Otherwise, intelligent surgery may increase rather than reduce global healthcare disparities.

Proposed Translational Framework for Responsible Intelligent Robotic Surgery

Based on the evidence synthesized in the attached report and contemporary literature, a clinically responsible pathway for intelligent robotic surgery can be conceptualized as follows:

Data
↓
High-quality, representative multimodal patient data

↓
Perception
AI-based imaging, computer vision and sensor interpretation
↓
Prediction
Risk estimation, outcome prediction and workflow recognition
↓
Personalization
Patient-specific planning and digital-twin simulation

↓
Collaboration
Human–AI decision support and augmented reality

↓
Control
Robotic execution with appropriate human oversight

↓
Adaptation
Real-time response to changing anatomy and physiology
↓
Evaluation
Postoperative outcomes, safety and patient-reported measures
↓
Learning
Validated feedback into future models
↓
Governance
Continuous monitoring, accountability, cybersecurity and equity

This framework emphasizes an important principle: autonomy should be the result of validated clinical capability, not the objective of technological development by itself.

Conclusion

The convergence of artificial intelligence and robotic surgery represents one of the most consequential technological transformations in contemporary surgical medicine. Robotic systems have already improved visualization, dexterity, ergonomics, navigation, and precision across multiple surgical specialties. The integration of AI is now extending these capabilities toward computer vision, predictive analytics, patient-specific planning, surgical workflow recognition, automated skill assessment, real-time decision support, and supervised execution of selected surgical tasks. The attached report demonstrates this transition across orthopedic, abdominal, thoracic, cardiac, neurosurgical, colorectal, and other emerging applications.

The next stage of development is likely to involve the convergence of AI, robotics, digital twins, augmented reality, multimodal sensing, and advanced computational models. Together, these technologies could establish a new paradigm of surgical intelligence, in which the operating room becomes a continuously connected environment capable of perceiving, interpreting, predicting, assisting, adapting, and learning.

Nevertheless, technological sophistication should not be equated with clinical superiority. The central challenge is to demonstrate that AI-enabled robotic systems produce meaningful improvements in patient safety, functional outcomes, quality of life, efficiency, and equity. Current evidence remains uneven, particularly for autonomous surgery and digital-twin applications, and substantial gaps persist in external validation, interoperability, long-term outcome assessment, cybersecurity, regulatory oversight, and economic evaluation.

The future of surgery is therefore unlikely to be defined by the disappearance of the surgeon. Rather, it is more plausibly represented by a human-centred partnership among surgeon, artificial intelligence, robotic systems, and patient-specific computational models. Human clinical judgment, empathy, ethical reasoning, communication, and accountability remain indispensable, while AI and robotics can contribute computational scale, precision, reproducibility, continuous perception, and data-driven prediction. WHO guidance similarly emphasizes human autonomy, safety, transparency, accountability, equity, and sustainable development as foundational principles for responsible AI in healthcare.

Ultimately, the transition from scalpel to algorithm should not be interpreted as a transition from human medicine to machine medicine. It represents an evolution from predominantly manually executed surgery toward precision, predictive, personalized, and increasingly adaptive surgical **care**. The most successful systems will therefore be those that achieve an appropriate balance between automation and human oversight, innovation and regulation, precision and affordability, and computational intelligence and human values. If these principles are maintained, AI-enabled robotics may evolve from an advanced surgical tool into an integrated platform for safer, more personalized, and more equitable surgical medicine.

Future Perspectives

Future research should prioritize clinical translation rather than technological novelty. Multicenter prospective trials should compare AI-enabled robotic procedures with established surgical approaches using patient-centred endpoints. Standardized datasets and reporting frameworks should be developed to facilitate reproducibility and external validation. Digital twins should undergo rigorous validation before being used for high-stakes clinical decisions, while autonomous robotic systems should progress through carefully defined levels of supervised autonomy.

Equally important will be the development of risk-adaptive human oversight, whereby the degree of surgeon control corresponds to procedural complexity and potential harm. AI models should communicate uncertainty, enable rapid human override, and undergo continuous post-deployment surveillance.

The future operating room may ultimately become a learning ecosystem in which each procedure contributes validated information to improve subsequent planning, training, and patient care. However, this vision will only be sustainable if technological progress is accompanied by robust governance, transparent evaluation, cybersecurity, workforce education, patient participation, and equitable access. WHO's current policy work continues to emphasize that AI should augment human judgment rather than displace it and that implementation must address quality, equity, governance and accountability simultaneously.

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Conflict of Interest

None declared.

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