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Narrative Review

Artificial Intelligence in Robotic-Assisted Gynecological Surgery: A Narrative Review of Clinical Applications, Emerging Platforms, and Future Perspectives

Mohamed Abdelrahman[1,2,3]*, Rawia Ahmed[1,2], Mohamed Elshaikh[1], Elmuiz Haggaz[1,2] and Simon Colreavy[3]

[1]Royal College of Physicians of Ireland, Ireland
[2]Limerick Hospital Groups, Ireland
[3]University of Limerick, Ireland

***Corresponding Author:** Mohamed Abdelrahman, Royal College of Physicians of Ireland, Ireland.

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Abstract

Background: Robotic-assisted surgery represents the most technologically advanced modality of Minimally Invasive Gynecological Surgery (MIGS). The integration of Artificial Intelligence (AI) with robotic surgical platforms including the established da Vinci system and emerging platforms such as the Hugo RAS system offers unprecedented opportunities to enhance surgical precision, automate complex tasks, and provide real-time decision support. However, a focused synthesis of AI applications specifically within robotic gynecological surgery, encompassing both clinical outcomes and technological trajectories, is lacking.

Objective: To provide a focused narrative review of AI applications within robotic-assisted gynecological surgery, examining the current evidence on clinical outcomes, specific AI-enabled capabilities, emerging robotic platforms, and future technological directions.

Methods: A focused narrative review was conducted, drawing on evidence from a comprehensive systematic review of AI in MIGS (55 included studies, 48,951 patients) and supplementary targeted literature searches for robotic-specific AI applications in gynecology.

Results: AI-enhanced robotic gynecological surgery encompasses four principal domains: (1) intraoperative guidance and anatomical navigation; (2) surgical skill assessment and training; (3) predictive modeling for personalized surgical planning; and (4) semi-autonomous task execution. The da Vinci platform remains the dominant robotic system, with AI enhancements including Firefly near-infrared imaging and emerging computer vision modules. The Hugo RAS system represents a new generation of AI-integrated robotic platforms with promising early clinical results. Meta-analysis data from the broader systematic review demonstrate that robotic AI-assisted MIGS is associated with the greatest reductions in operative time (MD: -28.4 min) and blood loss (MD: -48.3 mL for myomectomy) compared to conventional approaches.

Conclusion: The convergence of AI and robotic surgery in gynecology is advancing rapidly, with current applications in decision support and performance analytics yielding measurable clinical benefits. The trajectory toward greater surgical autonomy is clear, but requires parallel development of ethical frameworks, regulatory standards, and training curricula to ensure safe and equitable implementation.

Keywords: *Artificial Intelligence; Robotic Surgery; Gynecology; da Vinci; Hugo RAS; Autonomous Surgery; Surgical Outcomes; Machine Learning; Computer Vision; Surgical Training*

Introduction

Robotic-assisted surgery has fundamentally transformed the practice of Minimally Invasive Gynecological Surgery (MIGS). Platforms such as the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA, USA) provide surgeons with enhanced three-dimensional visualization, wristed instrumentation with seven degrees of freedom, tremor filtration, and motion scaling, enabling complex procedures to be performed with greater precision and dexterity than conventional laparoscopy [1]. A systematic review and meta-analysis by Lenfant., *et al*. [2] confirmed that robotic-assisted hysterectomy is associated with reduced blood loss, shorter hospital stay, and lower conversion rates compared to open surgery, consolidating the clinical case for robotic MIGS.

The convergence of robotic surgery with Artificial Intelligence (AI) represents the next evolutionary step in this technological trajectory. AI algorithms trained on vast datasets of surgical videos, kinematic data, and patient outcomes have the potential to augment robotic platforms in several critical ways: providing real-time intra-operative guidance, automating routine surgical tasks, predicting and preventing complications, and objectively assessing surgical performance [3,4]. The recent emergence of new robotic platforms, including the Hugo RAS system (Medtronic), introduces additional opportunities for AI integration from the ground up, with modular architectures designed to accommodate intelligent software enhancements [5].

This narrative review synthesizes the current evidence on AI applications specifically within robotic-assisted gynecological surgery, drawing on data from a comprehensive systematic review of 55 studies (48,951 patients) and supplementary targeted literature. The review is organized around the principal clinical and technical domains of AI-robotic integration, with attention to specific gynecological procedures, emerging platforms, and the ethical and regulatory landscape.

Robotic platforms and AI integration

The da Vinci surgical system

The da Vinci Surgical System remains the global standard for robotic-assisted gynecological surgery, with over 7,000 systems installed worldwide and more than 10 million procedures performed to date. The platform's master-slave architecture, which translates the surgeon's hand movements into precise robotic arm motions at the patient side, provides the foundational infrastructure for AI integration. Current AI-enabled capabilities of the da Vinci system include Firefly near-infrared fluorescence imaging for real-time visualization of vascular structures and lymphatics, and the Intuitive Surgical Hub for data capture and analytics. Emerging AI modules under development include computer vision systems for anatomical structure identification, real-time performance analytics, and predictive algorithms for intraoperative event detection [6].

The Hugo RAS system

The Hugo RAS system (Medtronic) represents a new generation of robotic surgical platforms designed with modularity and AI integration as core design principles. Innocenzi., *et al*. [5] conducted a systematic review of the Hugo RAS system in gynecologic robotic surgery, reporting favorable early clinical outcomes across hysterectomy, myomectomy, and oncologic procedures. The system's open architecture facilitates the integration of third-party AI software modules, positioning it as a potentially more accessible platform for AI-driven surgical innovation. The competitive landscape created by the Hugo RAS system and other emerging platforms (e.g. CMR Surgical Versius, Avatera) is expected to accelerate AI development across the robotic surgery ecosystem.

AI applications in robotic gynecological surgery

Intra-operative guidance and anatomical navigation

The most immediately clinically impactful application of AI in robotic gynecological surgery is the provision of real-time intra-operative guidance. Computer vision algorithms, particularly CNNs, have been trained to identify critical anatomical structures within the robotic surgical field including the ureter, uterine vessels, bladder, and bowel—providing visual alerts to the surgeon when these structures are at risk of injury. This capability is particularly valuable in complex cases involving distorted anatomy, such as advanced endometriosis, large uterine fibroids, or post-inflammatory adhesions, where standard anatomical landmarks may be obscured [7].

Augmented reality (AR) systems, powered by AI, can overlay preoperative imaging data (CT or MRI scans) onto the live robotic video feed, creating a real-time anatomical map that enhances spatial orientation. Collins., *et al*. [8] demonstrated the feasibility of AR-guided laparoscopic surgery of the uterus, developing a system capable of accurately registering preoperative MRI data to the intra-operative laparoscopic view in real time. This technology has particular relevance for robotic myomectomy, where the precise localization of intramural fibroids relative to the uterine cavity and vascular supply is critical for surgical planning and execution.

AI-assisted endometriosis surgery represents a particularly compelling application. Zhao., *et al*. [9] demonstrated that AI could substantially enhance both diagnostic and therapeutic outcomes in minimally invasive surgery for endometriosis. Chen., *et al*. [10] provided proof-of-concept evidence for AI-based automatic visual recognition of endometriotic lesions during laparoscopy, with sensitivity and specificity approaching expert surgeon performance. When integrated with robotic platforms, such systems could provide real-time lesion mapping, guiding complete excision while minimizing damage to adjacent structures.

Surgical skill assessment and training

Robotic surgery generates a uniquely rich dataset: the kinematic data from the robotic arms, including tool position, velocity, acceleration, and applied force at sub-millimeter precision. AI algorithms—particularly LSTM networks and DNNs—have been applied to this kinematic data to develop objective metrics of surgical skill, moving beyond subjective expert assessment. Lam., *et al*. [11] conducted a systematic review of machine learning for technical skill assessment in surgery, demonstrating that AI-derived metrics from robotic kinematic data correlated strongly with expert assessment and discriminated between novice and expert surgeons with high accuracy.

Kankanamge., *et al*. [12] reviewed AI-based assessment of minimally invasive surgical skills using standardized objective metrics, identifying robotic kinematic analysis as the most technically mature approach, with commercial systems (e.g., Intuitive Surgical's Performance Analytics) already deployed in clinical training programs. Khalid., *et al*. [13] evaluated deep learning models for identifying surgical actions and measuring performance, demonstrating that DL-derived metrics could provide granular, action-level feedback to trainees a capability that traditional global rating scales cannot match. Levin., *et al*. [14] extended this approach to gynecological surgery specifically, demonstrating that automated surgical intelligence could reveal substantial time spent outside the patient's body during MIGS, providing actionable insights for efficiency improvement.

Predictive modeling and personalized surgical planning

Beyond intra-operative applications, AI is increasingly utilized for preoperative predictive modeling in robotic gynecological surgery. ML models, trained on large clinical datasets, can predict the probability of conversion from robotic to open surgery, estimate operative time, and forecast the risk of specific complications based on patient-specific factors. This predictive capability enables a more personalized surgical approach, allowing the surgical team to prepare appropriately and counsel patients more accurately regarding expected outcomes.

In the context of robotic hysterectomy, AI models can integrate preoperative imaging characteristics (uterine size, fibroid burden, adhesion score) with patient demographics and comorbidities to generate individualized risk profiles. Tinelli., *et al*. [15] reviewed AI applications in fibroid treatment, including robotic-assisted myomectomy, demonstrating that ML models could predict operative complexity and blood loss from preoperative ultrasound and MRI data with clinically useful accuracy. Walczak and Mikhail [16] demonstrated that artificial neural networks could predict estimated blood loss and transfusion requirements in gynecological surgery, enabling proactive preparation of blood products and activation of cell salvage protocols.

Semi-autonomous task execution

The most transformative and most distant application of AI in robotic gynecological surgery is the development of semi-autonomous or fully autonomous surgical systems capable of performing defined tasks without continuous human guidance. While full autonomy remains a long-term goal, significant progress has been made in autonomous subtask execution. Saadati and Amirmazlaghani [17] developed a system for automated surgical operation in endometriosis treatment through AI and robotic vision, demonstrating the feasibility of AI-guided autonomous tissue identification and manipulation in a controlled setting.

The broader robotic surgery literature provides important proof-of-concept evidence: the Smart Tissue Autonomous Robot (STAR), developed at Johns Hopkins University, demonstrated autonomous laparoscopic anastomosis with outcomes superior to human surgeons in preclinical models. While this research was not specific to gynecology, it establishes the technical feasibility of autonomous soft tissue surgery and provides a roadmap for gynecological applications. Wah [18] reviewed AI-powered robotic surgery and its transformative potential for surgical decision-making, noting that the integration of reinforcement learning with robotic platforms could enable systems to learn and optimize surgical strategies through simulated practice.

Application Domain	AI Technology	Clinical Benefit	Evidence Level
Intraoperative guidance	CNN, Computer Vision	Reduced iatrogenic injury, enhanced anatomical identification	Moderate (prospective cohort studies)
AR navigation	CNN + Image Registration	Improved spatial orientation in complex anatomy	Low-Moderate (feasibility studies)
Endometriosis lesion recognition	CNN (deep learning)	More complete lesion excision, standardized diagnosis	Low-Moderate (proof-of-concept)
Surgical skill assessment	LSTM, DNN (kinematic data)	Objective performance metrics, accelerated training	Moderate (validation studies)
Complication prediction	DNN, ML models	Proactive risk management, personalized planning	Moderate (retrospective cohorts)
Blood loss prediction	ANN, ML models	Preparation of blood products, reduced transfusion rates	Moderate (retrospective cohorts)
Semi-autonomous task execution	RL, hybrid DL	Potential for reduced operative time, enhanced precision	Low (preclinical/early feasibility)

Table 1: *Summary of AI applications in robotic gynecological surgery.*

CNN = Convolutional Neural Network; AR = Augmented Reality; LSTM = Long Short-Term Memory; DNN = Deep Neural Network; ANN = Artificial Neural Network; ML = Machine Learning; RL = Reinforcement Learning.

Ethical, regulatory, and training considerations

The integration of AI with robotic surgical platforms raises profound ethical and regulatory questions that must be addressed in parallel with technological development. Collins., *et al*. [19] developed a Delphi consensus statement on the ethical implications of AI in robotic surgical training, identifying key principles including transparency, accountability, patient autonomy, and equitable access. The question of liability in AI-assisted surgery when an AI recommendation contributes to an adverse outcome remains unresolved in most jurisdictions and requires urgent attention from legal and regulatory bodies.

Regulatory frameworks for AI-enabled medical devices are evolving. The US Food and Drug Administration (FDA) has developed a regulatory framework for AI/ML-based Software as a Medical Device (SaMD), which encompasses surgical AI systems. The European

Medical Device Regulation (MDR) similarly requires clinical evidence of safety and performance for AI-enabled surgical systems. The challenge for regulators is to develop frameworks that are sufficiently rigorous to ensure patient safety while not stifling innovation through excessive bureaucratic burden.

The training implications of AI-robotic integration are equally significant. As AI systems assume greater responsibility for intraoperative tasks, the competencies required of future gynecological surgeons will evolve. Surgeons will need to develop new skills in AI system oversight, intervention when AI recommendations are incorrect, and the ability to operate safely when AI systems fail. Training curricula must be redesigned to incorporate these competencies, and simulation platforms that include realistic AI interactions will be essential for safe skill acquisition [20].

Future perspectives

The trajectory of AI in robotic gynecological surgery points toward several transformative developments over the next decade.

First, the integration of multi-modal data streams combining surgical video, robotic kinematics, patient physiological monitoring, and electronic health record data into unified AI models will enable a more comprehensive understanding of the surgical situation and more accurate prediction of outcomes.

Second, the development of federated learning approaches, which allow AI models to be trained across multiple institutions without sharing patient data, will address the data scarcity problem while preserving privacy.

Third, the emergence of digital twins patient-specific computational models that simulate surgical procedures will enable preoperative rehearsal and intra-operative guidance with unprecedented precision.

Fourth, the convergence of AI with next-generation robotic platforms incorporating haptic feedback, variable stiffness instruments, and miniaturized sensors will create a new generation of intelligent surgical systems that are qualitatively more capable than current platforms.

Ultimately, the vision of AI in robotic gynecological surgery is not the replacement of the surgeon, but the creation of a collaborative human-AI surgical team in which each partner contributes their unique capabilities: the surgeon providing clinical judgment, ethical reasoning, and adaptive problem-solving; the AI providing tireless vigilance, pattern recognition across vast datasets, and real-time computational analysis. Realizing this vision requires sustained investment in research, infrastructure, and education, guided by a commitment to patient safety and equitable access.

Conclusion

The integration of Artificial Intelligence with robotic platforms in gynecological surgery is advancing rapidly across four principal domains: intra-operative guidance, surgical skill assessment, predictive modeling, and semi-autonomous task execution. Evidence from a comprehensive systematic review of 55 studies demonstrates that robotic AI-assisted MIGS is associated with the greatest clinical benefits among all AI modalities, including the largest reductions in operative time and blood loss. The emergence of new robotic platforms such as the Hugo RAS system, designed with AI integration as a core principle, will further accelerate this development. The gynecological surgery community must proactively engage with the ethical, regulatory, and educational challenges that accompany these technological advances, ensuring that the transformative potential of AI-robotic surgery is realized safely, equitably, and in the service of optimal patient outcomes.

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Conflict of Interest

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Ethical Approval

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