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Review article

ARTIFICIAL INTELLIGENCE ACROSS THE SURGICAL LEARNING CONTINUUM: CURRENT APPLICATIONS, EDUCATIONAL CHALLENGES AND FUTURE DIRECTIONS

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Abstract: Artificial intelligence (AI) is transforming surgical education through adaptive learning, simulation, computer vision, learning analytics, and decision support. This structured narrative review synthesizes AI applications across the surgical learning continuum, from undergraduate education and clinical clerkship through residency, fellowship, independent practice, and continuing professional development. A structured literature search of PubMed/MEDLINE, Scopus, and Google Scholar was conducted between May and June 2026, with evidence organized using the AI-assisted Surgical Learning Continuum. AI can support personalized learning, clinical reasoning, simulation, objective technical assessment, operative video analysis, automated feedback, performance analytics, and longitudinal competency tracking. Generative and multimodal AI may further enable interactive and adaptive learning. However, implementation is constrained by algorithmic bias, hallucinations and reliability concerns, data privacy, explainability, automation bias, faculty preparedness, and regulatory uncertainty. The evidence remains heterogeneous, and technical performance does not necessarily establish educational effectiveness or clinical reliability. AI should therefore augment rather than replace human educators, preserving mentorship, professional judgment, ethical reasoning, accountability, and patient-centered care. Future research should prioritize rigorous validation, meaningful educational outcomes, cost-effectiveness, and responsible implementation across diverse surgical training environments.

Keywords: artificial intelligence, surgical education, competency-based medical education, machine learning, computer vision, generative AI, surgical training, surgical learning continuum.

INTRODUCTION

Surgical education is shifting from traditional apprenticeship models toward competency-based medical education (CBME), driven by work-hour restrictions, technological advancement, and patient safety imperatives (1, 2). Concurrently, surgery is undergoing digital transformation. Operative video, robotic platforms, and electronic health records generate extensive datasets that artificial intelligence (AI)—including machine learning (ML), deep learning (DL), computer vision, natural language processing, and generative models—can analyze to support surgical learning and assessment (1, 3, 4). In this review, AI is used as the overarching term encompassing computational approaches such as ML and DL. Generative AI refers to systems capable of producing new content, while large language models (LLMs) are a major class of generative AI designed to process and generate human language.

AI applications such as automated performance analysis and adaptive tutoring can provide individualized learning and objective feedback (2, 3, 5), but the literature remains fragmented. Existing reviews often focus on specific technologies or individual training stages rather than the longitudinal development of surgical competence. Moreover, AI integration requires balancing educational benefits against algorithmic bias, limited transparency, data privacy concerns, and overreliance on automated systems (4, 6).

This review examines AI across the complete surgical learning continuum using a stage-based conceptual framework, providing an evidence-informed perspective on responsible implementation while emphasizing human expertise, mentorship, and clinical judgment.

MATERIAL AND METHODS

This structured narrative review examined AI across the surgical learning continuum, encompassing undergraduate education, clinical clerkship and internship, residency, fellowship, independent practice, and continuing professional development. A structured nar-

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rative approach was selected because of the broad scope, methodological heterogeneity, and rapidly evolving literature, and was informed by the SANRA framework.

A structured search of PubMed/MEDLINE, Scopus, and Google Scholar was conducted between May and June 2026. Searches combined controlled vocabulary, where applicable, with free-text terms related to AI, surgical education, and medical education. The database-specific search framework is summarized in Table 1. Eligible publications addressed AI applications in surgical education, training, assessment, professional development, or clinical learning. Original research, systematic and scoping reviews, narrative reviews, educational studies, consensus documents, and relevant guidance or policy publications were considered. Only English-language publications were included, with no predefined publication-date restrictions. Irrelevant, duplicate, and non-substantive publications were excluded. Reference lists of relevant publications were also screened for additional studies.

Two authors independently reviewed publications for relevance and assessed potentially eligible full texts; disagreements were resolved through discussion and consensus. As a structured narrative review, a formal PRISMA-based record-level screening process was not prospectively implemented; therefore, complete numbers of identified, duplicate, and excluded records were not systematically retained.

Given the heterogeneity of study designs, technologies, and outcomes, quantitative pooling was not appropriate. Evidence was synthesized narratively using the AI-assisted Surgical Learning Continuum, an author-developed conceptual framework. Findings were interpreted according to study design, methodological limitations, outcomes, external validity, and real-world applicability, with greater weight given to systematic reviews, prospective or validated studies, established guidance, and clearly defined educational outcomes.

The AI-assisted Surgical Learning Continuum is conceptual and hypothesis-generating and has not undergone Delphi consensus, external validation, or prospective empirical testing. No formal protocol was prospectively registered, and standardized risk-of-bias assessment was not undertaken because of the heterogeneous evidence base and narrative design. These limitations were considered in interpreting the findings and are acknowledged in the Discussion.

Evolution of Artificial Intelligence in Surgery and Surgical Education

The evolution of artificial intelligence (AI) in surgery has progressed from rule-based systems to machine learning, deep learning, computer vision, and generative AI, paralleling the digitization of surgical practice. Electronic health records, medical imaging, operative video, and robotic platforms now generate extensive datasets supporting clinical and educational applications (1, 7).

Table 1. *Database-specific search framework*

Parameter	Approach
Databases	PubMed/MEDLINE, Scopus, and Google Scholar
Search period	May–June 2026
Language	English
Date limits	No predefined restrictions
Additional searching	Reference lists of relevant publications
Database	**Search framework**
PubMed/MEDLINE	(“artificial intelligence” OR “machine learning” OR “deep learning” OR “computer vision” OR “generative AI” OR “large language model*” OR ChatGPT) AND (“medical education” OR “surgical education” OR “surgical training” OR simulation OR “competency-based medical education” OR “technical skills assessment” OR residency OR fellowship OR internship OR clerkship OR “continuing professional development”)
Scopus	TITLE-ABS-KEY (“artificial intelligence” OR “machine learning” OR “deep learning” OR “computer vision” OR “generative AI” OR “large language model*” OR ChatGPT) AND (“surgical education” OR “medical education” OR “surgical training” OR simulation OR “technical skills assessment” OR residency OR fellowship OR “continuing professional development”))
Google Scholar	“artificial intelligence” OR “machine learning” OR “deep learning” OR “generative AI” OR “large language models” combined with “surgical education,””surgical training,””-medical education,” simulation, residency, fellowship, or technical skills assessment.

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Machine learning enabled pattern recognition beyond predefined rules, while deep learning expanded the analysis of complex datasets such as medical images and operative videos. Computer vision and natural language processing further supported image interpretation, workflow recognition, and automated analysis. More recently, generative AI and large language models have introduced conversational learning, adaptive tutoring, content generation, and personalized educational support, although concerns regarding accuracy, bias, and academic integrity require appropriate oversight (3, 4, 8).

These developments have accompanied the emergence of Surgical Data Science, integrating surgery, computer science, engineering, and data analytics to transform clinical and procedural data into information that can improve patient care, operative performance, and surgical education (1, 4). Accordingly, AI applications now extend from clinical decision support and operative planning to performance analysis, technical-skills assessment, intelligent simulation, personalized learning, and competency evaluation across surgical specialties (2, 5, 8, 9).

This progression provides the foundation for examining AI across the surgical learning continuum, where it can support knowledge acquisition, skill development, competency assessment, and lifelong learning while complementing expert mentorship and clinical judgment (2, 3, 8, 9).

The Surgical Learning Continuum: A Conceptual Framework for AI-assisted Surgical Education

Surgical competence develops progressively, making a longitudinal continuum better suited to its assessment than episodic evaluation. Although apprenticeship and mentorship remain central, variable clinical exposure and subjective assessment highlight the need for more objective measures (1, 5). AI can complement traditional approaches by analyzing performance data and providing continuous, personalized feedback.

Across this continuum, AI applications evolve with the learner: supporting foundational knowledge in undergraduate education; clinical reasoning during clerkship; simulation and skill acquisition in residency; subspecialty refinement in fellowship; and performance analytics and decision support during independent practice and continuing professional development (CPD) (3, 4). This trajectory is illustrated in Figure 1.

Non-technical competencies, including communication, teamwork, professionalism, and ethical reasoning—remain essential. AI can synthesize simulation, portfolio, and clinical outcome data to help educators identify learning needs (2, 8), while requiring transparency, appropriate data governance, and algorithmic fairness (6, 10).

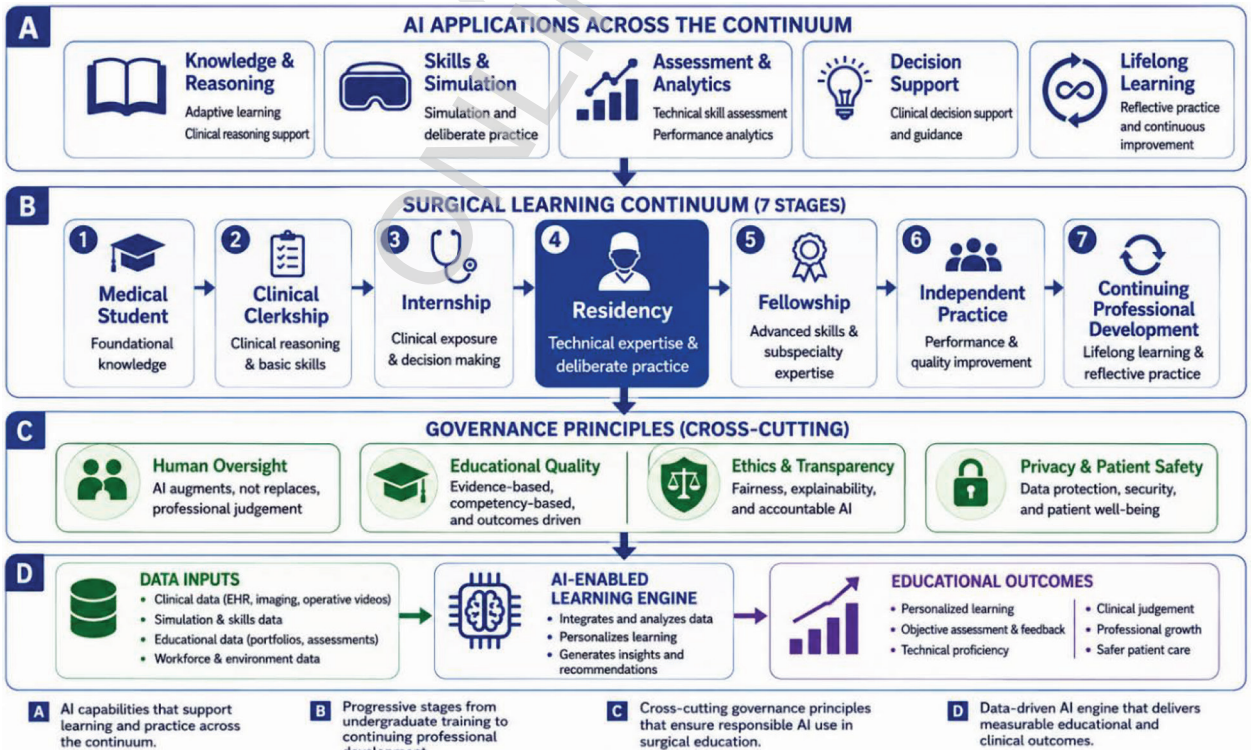

Figure 1. *The AI-assisted Surgical Learning Continuum: A conceptual framework illustrating the integration of artificial intelligence across progressive stages of surgical education and professional development*

Artificial Intelligence in Undergraduate Surgical Education

Artificial intelligence (AI) can support undergraduate surgical education through personalized learning, objective assessment, and early procedural-skills development. Although lectures, anatomy teaching, clinical exposure, and faculty feedback remain fundamental, increasing student numbers and variable opportunities for operative observation create a need for scalable, learner-centred approaches (2, 5).

Adaptive learning platforms can analyze performance, identify knowledge gaps, and adjust content according to individual progress, supporting personalized learning while allowing faculty to focus on higher-order reasoning and mentorship (5, 8). AI can also enhance anatomical and clinical learning through computer vision, three-dimensional reconstruction, image interpretation, and interactive visualization (3, 4).

Generative AI and large language models can support self-directed learning through explanations, clinical scenarios, formative questions, and interactive assistance. However, inaccurate information, fabricated references, and inconsistent reasoning require critical evaluation of AI-generated outputs and appropriate faculty oversight (4, 8).

AI-assisted simulation is particularly relevant to early technical-skills development. Computer vision and machine learning can assess instrument handling, hand movements, economy of motion, and procedural accuracy, providing immediate feedback and supporting deliberate practice. Selected studies have reported technical skill acquisition comparable to expert instruction for specific performance measures, although evidence remains limited to particular settings and outcomes (11, 12). Learning analytics may also identify learner needs but can overlook broader competencies and introduce unintended educational consequences (13).

Overall, AI may strengthen undergraduate surgical education through individualized learning and objective assessment. Responsible implementation requires reliable data, faculty readiness, appropriate infrastructure, and governance addressing bias, transparency, academic integrity, and overreliance on automated systems (4, 6, 14). Faculty oversight and professional judgment should remain central.

Artificial Intelligence During Clinical Clerkship and Internship

During clerkship and internship, learners transition to direct patient care, where AI can help standardize learning opportunities across clinical settings (2, 5). Machine learning and generative AI can support clinical reasoning by helping learners formulate differential diagno-

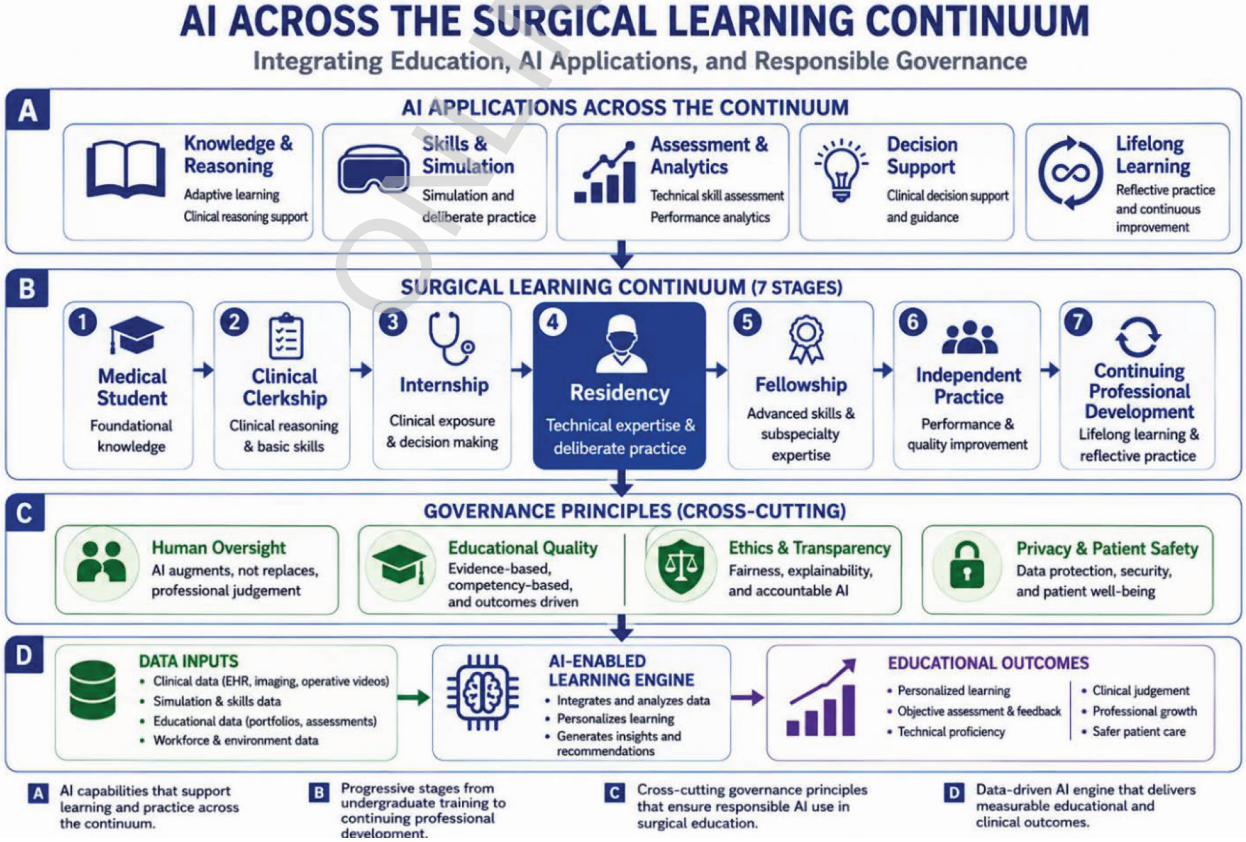

Figure 2. *Artificial Intelligence Applications Across the Surgical Learning Continuum*

ses, interpret investigations, and explore evidence-based management under faculty supervision (4, 8).

For operative preparation, AI platforms can provide procedural walkthroughs, annotated videos, and computer vision-based workflow recognition (3, 15). Integrated analytics from case logs, simulations, and portfolios can generate longitudinal performance profiles and help educators identify competency gaps requiring remediation (2, 5).

Learners may also gain early exposure to clinical decision-support systems and predictive models for perioperative complications (4, 16, 17). However, automation bias and population-specific bias require AI to be used as an educational scaffold rather than a substitute for independent clinical judgment or human supervision (6, 10, 14). As trainees progress to residency, its role increasingly shifts toward technical-skills assessment and workflow analysis (Figure 2).

Artificial Intelligence in Surgical Residency Training

Residency is the central phase of surgical skill acquisition, during which trainees progress from supervised participation toward independent practice. AI has particular potential at this stage because residency generates substantial structured and unstructured educational data, including operative videos, simulation performance, procedure logs, workplace-based assessments, and clinical outcomes. Integrating these data may support objective assessment, individualized feedback, and competency-based progression (2, 3, 5).

Key studies illustrating AI applications across surgical education—including technical-skills assessment, intelligent tutoring, curriculum optimization, and generative AIare summarized in Figures 3 A and 3B.

Technical Skills Assessment and Operative Video Analysis

Computer vision and machine learning can analyze operative videos to identify instruments, anatomical structures, and procedural phases, providing objective measures of motion economy and technical proficiency (3, 5, 9). Performance analysis across multiple procedures can provide longitudinal insights for targeted remediation, although automated metrics should be interpreted alongside expert assessment to capture broader clinical competence (5, 6).

Intelligent Simulation and Personalized Feedback

AI-enhanced simulation adapts task difficulty and feedback to learner performance, facilitating continuous deliberate practice with reduced constant faculty oversight (11, 12). Integrating simulation data with clinical logs creates comprehensive profiles that help educators detect competency gaps earlier (8, 13).

Competency-Based Progression and Learning Analytics

AI can aggregate performance data to support competency-based medical education (CBME) by identifying developmental patterns across training (2, 5). However, automated metrics may inadequately capture non-technical competencies such as clinical judgment, communication, teamwork, professionalism, and adaptability. Human oversight and expert interpretation therefore remain essential, particularly when AI-derived assessments inform high-stakes progression decisions (6, 10).

Study	Study Design	AI Technology / Application	Educational Setting	Level of Evidence*	Methodological Quality
Kirubarajan et al. (2)	Systematic scoping review	Multiple AI educational interventions	Undergraduate and postgraduate surgical education	Level II	Moderate
Morris et al. (3)	Narrative review	Broad AI applications in surgery	Clinical practice and surgical education	Level IV	Moderate
Varghese et al. (4)	State-of-the-art review	AI across surgical care	Entire surgical learning and practice ecosystem	Level IV	Moderate
Bilgic et al. (5)	Scoping review	AI applications across surgical education	Undergraduate, residency, and continuing education	Level II	Moderate
Hla & Hindin (8)	Narrative review	Generative AI and machine learning	Surgical education across training stages	Level IV	Moderate
Winkler-Schwartz et al. (11)	Machine-learning-based observational/validation study	Machine-learning assessment of virtual-reality surgical performance	Neurosurgical simulation training	Level III	Moderate–high
Fazlollahi et al. (12)	Randomized clinical trial	AI tutoring system for simulated surgical skills	Undergraduate surgical simulation	Level I	High
Fazlollahi et al. (13)	Educational cohort/intervention study	AI-guided curriculum optimization	Simulation-based surgical education	Level III	Moderate

***Figure 3A**. Study Characteristics and Evidence Profile Across the Surgical Learning Continuum*

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Study	Principal Findings	Educational Implications	Principal Limitations
Kirubarajan et al. (2)	AI-supported adaptive learning, intelligent tutoring, simulation, automated assessment, and learning analytics; evidence quality was variable.	AI has substantial educational potential but requires rigorous evaluation of evidence quality and implementation.	Heterogeneous interventions and outcomes; variable quality of underlying studies; limited evidence of transfer to clinical practice.
Morris et al. (3)	AI applications included computer vision, decision support, workflow analysis, operative video analytics, and educational assessment.	AI can support competency-based education and integration of data-driven learning tools.	Narrative methodology; potential selection bias; limited quantitative evaluation of educational outcomes.
Varghese et al. (4)	AI is increasingly integrated into perioperative care, decision-making, operative performance, education, and professional development.	Supports longitudinal integration of AI across the surgical learning continuum.	Predominantly conceptual synthesis; limited primary educational outcome data; rapidly evolving technology may limit durability of conclusions.
Bilgic et al. (5)	AI-supported simulation, technical skills assessment, personalized learning, curriculum development, operative video analysis, and competency evaluation.	Highlights broad educational applications and priorities for future research.	Heterogeneous AI technologies and outcomes; predominance of simulation-based studies; limited real-world validation.
Hla & Hindin (8)	Generative AI enables conversational learning, content generation, adaptive tutoring, and personalized support but raises concerns regarding accuracy, bias, and academic integrity.	Requires careful governance, critical evaluation, and faculty oversight.	Limited mature primary evidence; rapidly changing AI landscape; unresolved concerns regarding reliability, bias, privacy, and generalizability.
Winkler-Schwartz et al. (11)	Machine learning distinguished levels of surgical expertise using objective virtual-reality performance metrics.	Demonstrates feasibility of AI-based objective assessment of technical surgical skills.	Simulation-specific setting; limited generalizability; selected performance metrics may not capture broader surgical competence.
Fazlollahi et al. (12)	AI-guided tutoring achieved technical skill acquisition comparable to expert instruction while providing individualized feedback.	Supports AI tutoring as a potential adjunct to expert instruction.	Medical-student and simulation-based population; uncertain transfer to clinical practice; limited assessment of nontechnical skills.
Fazlollahi et al. (13)	AI-assisted curriculum design improved technical competency but highlighted risks of over-optimizing algorithm-selected performance metrics.	Emphasizes the need to balance AI personalization with comprehensive competency-based education.	Simulation-based assessment; limited external validation; potential over-optimization of selected technical metrics.

Abbreviation: AI, artificial intelligence. Source content and terminology retained from the supplied Table 2.

Figure 3B. *Educational Contributions and Limitations of Artificial Intelligence in Surgical Education*

AI may enhance residency training through objective performance analysis, intelligent simulation, personalized feedback, and longitudinal learning analytics, with particular value in supporting individualized learning and competency-based progression. However, AI-derived metrics should complement rather than replace expert assessment to ensure that progression decisions remain educationally valid and clinically meaningful (6, 10).

Artificial Intelligence in Fellowship and Advanced Surgical Training

Fellowship training marks the transition from general surgical competence to subspecialty expertise, emphasizing advanced techniques, complex clinical scenarios, procedural precision, and independent decision-making. At this stage, AI can support procedural planning, vision-based operative analysis, robotic skills assessment, performance analytics, and individualized refinement of expertise (3, 4).

Vision-based analysis is particularly relevant to advanced training. Deep learning can recognize surgical phases, anatomical structures, instruments, and critical procedural steps, allowing fellows to review annotated operative videos, compare performance with expert benchmarks, and identify technical variations that may be missed during conventional observation (3, 7). This can transform operative recordings into tools for technical refinement and reflective practice.

AI can also support preoperative planning by integrating imaging, pathology, laboratory findings, and patient-specific risk factors. Such systems may help fellows understand complex anatomy, anticipate operative challenges, and consider alternative strategies, particularly in anatomically demanding subspecialties such as colorectal surgery (4, 16, 18).

Robotic platforms provide additional opportunities through kinematic data on instrument movement, dexterity, efficiency, and ergonomics. Machine learning can identify inefficient movement patterns and track technical improvement, complementing expert supervision and deliberate practice (3, 19).

AI-assisted decision support may further enhance training through predictive estimates of postoperative complications, recurrence, functional outcomes, and treatment responses. These tools can encourage integration of quantitative risk estimates with clinical judgment, patient preferences, and evidence-based practice (6, 16). Applications across multiple surgical subspecialties further illustrate the expanding scope of these technologies (20–27).

Despite these advances, fellowship remains fundamentally dependent on expert mentorship and experiential learning. AI cannot fully assess intraoperative adaptability, leadership, communication, professionalism, or ethical decision-making, and its performance remains influenced by dataset quality, institutional variation, and algorithmic bias (6, 14). AI should there-

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fore support objective feedback and reflective learning while expert supervision guides higher-order assessment and graduated operative responsibility.

Artificial Intelligence in Independent Surgical Practice

The transition to independent practice expands AI's role from education to clinical decision-making, operative planning, performance assessment, quality improvement, and patient safety. By providing objective information on clinical practice and outcomes, AI may also support ongoing professional development (3, 4, 16, 19).

AI-assisted decision-support systems can integrate clinical, imaging, laboratory, and outcome data to support diagnosis, risk prediction, and treatment planning. Predictive models have been studied for postoperative complications, surgical-site infection, readmission, and other outcomes, potentially informing perioperative decision-making (4, 16, 17). Intraoperatively, computer vision can analyze surgical video, recognize anatomical structures and procedural phases, and assess workflow, while machine learning can evaluate instrument movements and technical performance, particularly in robotic and minimally invasive surgery (3, 4, 7).

AI may also support longitudinal assessment of surgical performance by integrating operative video, technical metrics, complications, and patient-reported outcomes. These data can complement case volume, morbidity and mortality review, peer assessment, and credentialing, supporting reflective practice, quality improvement, and targeted professional development (5, 19). Generative AI and large language models may assist with literature synthesis, guideline comparison, and evidence retrieval, although outputs require verification because of inaccurate or fabricated information (4, 8).

Despite these potential benefits, surgeons remain accountable for clinical decisions. Automation bias, variation in training data, and differences across populations and healthcare settings may affect AI performance. Responsible implementation therefore requires rigorous validation, transparency, appropriate governance, and meaningful human oversight (6, 10, 14, 19).

Continuing Professional Development and Lifelong Surgical Learning

AI supports lifelong learning by offering personalized access to evidence, adaptive educational modules, and performance analytics (3, 4, 8). Integrating clinical outcomes with educational platforms helps surgeons address specific practice gaps (4, 8). Nevertheless, the interpretation of AI-supported learning needs should remain integrated with clinical experience, peer review, and professional mentorship (6, 10).

Ethical, Educational, and Regulatory Challenges

Key challenges in integrating AI across surgical education include algorithmic bias, automation bias,

Challenge	Potential Impact	Recommended Mitigation
Automation bias	Excessive reliance on AI may weaken independent reasoning and critical thinking.	Maintain human oversight and require critical appraisal of AI outputs.
Algorithmic bias and dataset representativeness	Homogeneous datasets may produce biased performance across diverse populations and settings.	Use diverse, multicentre datasets with external validation.
AI hallucinations and factual inaccuracies	Fabricated references or incorrect information may disseminate inaccurate educational content.	Verify AI-generated content against reliable, peer-reviewed sources.
Academic integrity	Unregulated AI use may undermine authentic learning and assessment.	Establish clear institutional policies for acceptable AI use and disclosure.
Limited assessment of non-technical skills	Automated metrics may overlook communication, empathy, leadership, teamwork, and adaptability.	Use AI analytics as an adjunct to faculty assessment and workplace-based evaluation.
Data governance, privacy, and explainability	Sensitive clinical and learner data may be exposed, while opaque algorithms may reduce trust.	Implement secure data governance, anonymization, and transparent or explainable AI where feasible.
Regulatory uncertainty	Variable standards may lead to inconsistent implementation across institutions.	Develop professional guidelines, accreditation standards, and continuous validation.
Faculty preparedness	Limited AI literacy may hinder effective curriculum integration.	Provide faculty development and AI/digital literacy training.
Environmental impact and computational cost	Training and deploying large AI models can require substantial computational resources and energy, contributing to environmental burden and potentially increasing institutional costs.	Prefer efficient models and task-specific systems where appropriate; use shared infrastructure, monitor resource consumption, and consider environmental impact when selecting and deploying AI tools.

Abbreviation: AI, artificial intelligence.

Figure 4. *Ethical, Educational, and Regulatory Challenges of AI Across the Surgical Learning Continuum*

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data privacy, explainability, academic integrity, and limited evaluation of non-technical skills (6, 10, 14, 19, 28, 29). These challenges and mitigation strategies are summarized in Figure 4.

International Regulatory and Governance Frameworks

International regulatory frameworks increasingly shape the responsible integration of AI into healthcare and surgical practice. The European Union AI Act adopts a risk-based approach to AI governance, while the European Health Data Space emphasizes responsible health-data governance and ethical oversight (29–32). In the United States, evolving FDA approaches emphasize evaluation, transparency, lifecycle management, and post-market monitoring of AI-enabled technologies (33). International initiatives also highlight the need for clearly defined responsibilities, coordinated oversight, and collaboration among policymakers, developers, and healthcare providers (34, 35). These priorities reinforce the importance of addressing bias, privacy, transparency, accountability, and human oversight in healthcare AI (36).

Emerging Generative AI, Multimodal Models, and AI Agents

Recent advances have expanded generative AI beyond conventional text-based assistance. Models such as GPT-4o, Claude, and Gemini demonstrate increasingly capable language and reasoning, although performance varies across models and tasks (37). Multimodal foundation models integrate text, images, and audio, creating opportunities for interactive case discussions, simulated patient encounters, communication training, and personalized feedback (38). AI agents may further enable multistep educational workflows, including adaptive tutoring and simulation. However, technical performance does not necessarily translate into educational effectiveness or clinical reliability; prospective evaluation, faculty oversight, and validation in authentic learning environments remain essential.

DISCUSSION

This narrative review highlights the expanding role of AI across the surgical learning continuum, from undergraduate education to continuing professional development. Rather than replacing established educational models, AI is best understood as an adjunct that can support personalized learning, simulation, objective assessment, performance analytics, and access to educational resources. Its potential value lies in connecting these applications across successive stages of professional development rather than treating them as isolated technologies.

The role of AI evolves with increasing clinical responsibility. In early education, it can support knowledge acquisition, adaptive learning, simulation, and foundational procedural skills. During residency and fellowship, applications increasingly include operative video analysis, technical-skills assessment, personalized feedback, and competency-based progression. After formal training, AI may support clinical decision-making, reflective practice, performance analysis, and lifelong learning. This progression supports a continuous learning pathway in which AI applications are adapted to the needs and responsibilities of the learner.

An important opportunity is the integration of multimodal data from simulation, operative video, procedure logs, workplace-based assessments, and clinical outcomes. Longitudinal analysis could provide a more comprehensive picture of competency development and identify learning needs not apparent through episodic assessment. However, reliability depends on data quality, interoperability, external validation, and appropriate interpretation. AI-derived metrics should therefore be considered alongside expert assessment, particularly for educational progression and other high-stakes decisions (5, 6, 19).

Surgical competence extends beyond measurable technical performance. Clinical judgment, communication, teamwork, professionalism, leadership, adaptability, ethical reasoning, and empathy remain essential but are difficult to capture fully through algorithmic metrics. Experienced educators and mentors therefore remain central to contextual interpretation, professional development, and high-stakes decision-making. AI should augment, rather than displace, apprenticeship, mentorship, and reflective practice (2, 5, 6).

Despite rapid technological development, the evidence base remains heterogeneous. Many studies have small samples, single-centre designs, variable outcome measures, or limited external validation, while differences in datasets, algorithms, educational environments, and assessment methods hinder comparison. Future research should prioritize multicentre prospective studies, standardized outcomes, external validation, and longitudinal evaluation of whether AI-assisted education produces sustained improvements in competence, clinical performance, and patient outcomes (19).

Implementation also requires attention to bias, transparency, privacy, accountability, automation bias, and equitable access, particularly when AI informs competency progression, certification, or clinical care. Effective governance should ensure appropriate vali-

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dation, continuous monitoring, and meaningful human oversight (6, 10, 14, 19).

Overall, AI-assisted surgical education is likely to evolve toward a hybrid model combining technological capabilities with human expertise. AI can provide continuous data-driven insights, individualized learning opportunities, and scalable assessment, while educators remain essential for mentorship, contextual interpretation, professional development, and ethical decision-making. The goal should not be to automate surgical education, but to use AI responsibly to make learning more personalized, evidence-informed, and continuous throughout a surgeon's career.

Limitations

This review has several limitations. The literature on AI in surgical education is heterogeneous, with substantial variation in study design, technologies, educational settings, and outcome measures, limiting direct comparison. Many studies involve small samples, single institutions, or early-stage implementations, while external validation remains limited. The rapid evolution of AI may also render some findings outdated as technologies and educational practices develop. Finally, the long-term effects of AI-assisted education on surgical competence, clinical performance, and patient outcomes remain insufficiently established. These limitations underscore the need for larger multicentre studies, standardized outcomes, external validation, and longitudinal evaluation.

Future Directions and Research Priorities

Artificial intelligence (AI) is likely to become an increasingly important component of surgical education and clinical practice. Although advances have been made in simulation, video analysis, learning analytics, and clinical decision support, applications remain fragmented across individual tasks and specialties. Future efforts should focus on interoperable, evidence-based AI ecosystems supporting learning across the surgical continuum (3, 4).

Strengthening the evidence base is a major priority. Most studies remain observational, simulation-based, or proof-of-concept, while high-quality multicentre randomized trials are limited. Future research should use standardized educational outcomes and longer follow-up to determine whether AI improves operative performance, clinical decision-making, competency, patient outcomes, and cost-effectiveness (2, 5).

Future systems should emphasize transparency and multimodal integration. Explainable AI may provide interpretable feedback, while platforms integrating operative video, natural language processing, wearable sensors, robotic systems, electronic portfolios, and workplace-based assessments could support



Figure 5. *Roadmap for the Responsible Future Integration of Artificial Intelligence Across the Surgical Learning Continuum*

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more comprehensive competency assessment and personalized training (3, 6, 8, 16).

Rapid advances in generative AI, multimodal foundation models, AI agents, digital twins, federated learning, and synthetic data may enable intelligent tutoring, personalized feedback, high-fidelity simulation, privacy-preserving collaboration, and scalable education. However, their educational value requires rigorous validation, ethical governance, and collaboration among surgical educators, clinicians, and AI developers (3, 4, 6, 8, 19).

International collaboration will also be important. Representative datasets, harmonized validation standards, faculty development, curriculum integration, competency assessment, and appropriate regulatory oversight are needed for equitable, safe, and transparent adoption across diverse healthcare settings (4, 6, 10, 28).

Ultimately, AI's value should be judged not by technological sophistication alone but by its ability to improve learning, surgical competence, patient outcomes, and equitable access to education (Figure 5). Responsible implementation could position AI as a longitudinal tool supporting lifelong professional development.

CONCLUSION

Artificial intelligence (AI) can support surgical education through personalized learning, simulation, objective assessment, clinical decision support, and lifelong professional development. Its integration into competency-based education should enhance, rather than replace, surgical educators and clinical judgment. Responsible implementation requires rigorous validation, transparency, equitable governance, and human oversight. Ultimately, AI should augment surgical expertise and support personalized learning, objective competency assessment, and continuous professional development while contributing to safe, high-quality, patient-centred care.

Abbreviations

AI - Artificial Intelligence;
CBME - Competency-Based Medical Education;
CPD - Continuing Professional development;
DL - Deep Learning;
ML - Machine Learning

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Conflicts of Interest: The authors declare that there are no conflicts of interest.

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Ethical Clearance: Not applicable, as no animal or human studies were involved.

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Sažetak

VEŠTAČKA INTELIGENCIJA KROZ KONTINUUM HIRURŠKOG OBRAZOVANJA: AKTUELNE PRIMENE, OBRAZOVNI IZAZOVI I BUDUĆI PRAVCI

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Veštačka inteligencija (VI) transformiše hirurško obrazovanje kroz adaptivno učenje, simulacije, računarski vid, analitiku učenja i sisteme za podršku odlučivanju. Ovaj strukturisan narativni pregled objedinjuje primene VI kroz kontinuum hirurškog obrazovanja, od osnovnog obrazovanja i kliničke nastave, preko specijalizacije i subspecijalizacije, do samostalne prakse i kontinuiranog profesionalnog razvoja. Strukturisana pretraga literature u bazama PubMed/MEDLINE, Scopus i Google Scholar sprovedena je tokom maja i juna 2026. godine, pri čemu su dokazi organizovani prema konceptualnom okviru Kontinuuma hirurškog obrazovanja uz podršku veštačke inteligencije. VI može doprineti personalizovanom učenju, kliničkom rezo-

novanju, simulacijama, objektivnoj proceni tehničkih veština, analizi operativnih video-zapisa, automatizovanoj povratnoj informaciji, analitici performansi i longitudinalnom praćenju kompetencija. Generativna i multimodalna VI mogu dodatno omogućiti interaktivno i adaptivno učenje. Međutim, primenu VI ograničavaju algoritamska pristrasnost, halucinacije i pitanja pouzdanosti, zaštita privatnosti podataka, razumljivost odluka sistema VI, pristrasnost usled automatizacije, spremnost nastavnog kadra i regulatorna neizvesnost. Dokazi su i dalje heterogeni, a tehničke performanse ne predstavljaju nužno pokazatelj obrazovne efikasnosti ili kliničke pouzdanosti. Stoga VI treba da bude podrška, a ne zamena za nastavnike, uz očuvanje mentorstva, profesionalnog rasuđivanja, etičkog rasuđivanja, odgovornosti i pristupa usmerenog na pacijenta. Buduća istraživanja treba da daju prioritet rigoroznoj validaciji, relevantnim obrazovnim ishodima, isplativosti i odgovornoj primeni u različitim okruženjima hirurškog obrazovanja.

Ključne reči: veštačka inteligencija, hirurško obrazovanje, obrazovanje zasnovano na kompetencijama, mašinsko učenje, računarski vid, generativna veštačka inteligencija, hirurška obuka, kontinuum hirurškog obrazovanja.

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