ISSN 0000-0000

REVIEW **Open Access**

Surgeon-in-the-Loop AI Systems in Robotic Surgery: Enhancing Precision, Efficiency, and Personalisation – A Short Narrative Review

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ABSTRACT

Surgeon-in-the-loop AI systems represent a significant advancement in robotic surgery by integrating artificial intelligence (AI) to enhance human capabilities while maintaining surgeon oversight. This narrative review summarises recent literature from 2023 to 2025 on their applications in general robotic surgery, focusing on areas such as reinforcement learning, image recognition, and real-time decision support. A thorough search of databases, including PubMed, Scopus, and Web of Science, identified key studies demonstrating improvements in precision, efficiency, and personalisation. The findings demonstrate AI's capacity to tailor its approach to a surgeon's preferences, offer intraoperative guidance, and minimise errors through the use of advanced imaging techniques. However, challenges remain, including data privacy concerns, algorithmic bias, and regulatory hurdles. Looking ahead, there is a need to balance the autonomy of these systems with ethical safeguards, as well as efforts to expand access to such technologies.
This review highlights the potential of surgeon-in-the-loop AI systems to revolutionise surgery and calls for interdisciplinary collaboration to address existing limitations.

Keywords: Artificial intelligence, robotic surgery, surgeon-in-the-loop, reinforcement learning, image recognition, ethical challenges, precision medicine

INTRODUCTION

The integration of artificial intelligence (AI) into robotic surgery has evolved from teleoperated systems, such as the da Vinci Surgical System, to intelligent platforms that collaborate with surgeons in real-time. Surgeon-in-the-loop AI systems maintain human control while leveraging AI to enhance precision, efficiency, and personalization. These systems employ reinforcement learning (RL), image recognition, and real-time analytics to adapt to surgeon techniques, provide decision support, and reduce errors, which contribute to an estimated 400,000 annual deaths in the US due to surgical complications [1].

Recent advancements (2023–2025) have focused on creating symbiotic human-AI interactions, addressing limitations like surgeon fatigue and variability in techniques [2,3]. This narrative review, adhering to ICMJE guidelines, explores these developments, their applications in general surgery, and associated challenges, aiming to guide clinicians, researchers, and policymakers.

METHODS

Literature was sourced from PubMed, Scopus, Web of Science, and Google Scholar using terms like "surgeon-in-the-loop AI," "AI robotic surgery," "reinforcement learning surgery," and "image recognition surgery." Inclusion criteria targeted peer-reviewed articles, reviews, and studies from January 2023 to August 2025, in English, focusing on general robotic surgery. Non-surgical AI or pre-2023 studies were excluded unless foundational. Searches retrieved 120 articles; 30 were selected for relevance and quality (Fig.1). Data extraction focused on personalization, decision support, imaging, efficiency, and challenges. No funding or conflicts influenced this review.

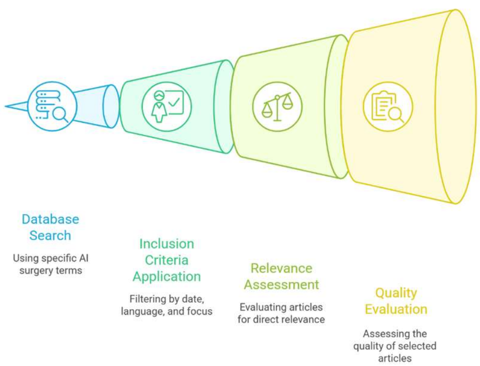

Fig.1: Article Selection Process

BACKGROUND ON SURGEON-IN-THE-LOOP AI SYSTEMS

Surgeon-in-the-loop AI systems position the surgeon as the primary decision-maker, with AI acting as an adaptive assistant. These systems integrate sensors for haptic feedback, cameras for visual input, and AI algorithms using deep learning, RL, and imitation learning [4]. RL optimizes actions based on rewards (e.g., successful suturing), while imitation learning mimics surgeon behaviors from procedure datasets [5]. In general surgery, applications include laparoscopy, orthopedics, and neurosurgery, where AI-enhanced robots reduce operative times and complications [6]. The evolution from level 0 (no autonomy) to level 3 (conditional autonomy under supervision) reflects increasing AI integration, with systems like the da Vinci incorporating AI extensions [7,8].

PERSONALIZED SURGICAL EXPERIENCE

AI systems personalize surgical workflows by adapting to individual surgeon preferences through RL and imitation learning. In ophthalmic surgery, RL agents trained on surgeon data improve task efficiency by 20–25%, adapting to hand movements and decision styles [9]. Imitation learning analyzes video datasets to predict surgeon intentions, enhancing robot responsiveness [10]. In urologic oncology, personalized AI adjusts to surgeon expertise, improving prostatectomy precision [11].
These systems customize haptic feedback and motion scaling, reducing cognitive load and aiding novice surgeons [12]. Studies show personalized interfaces shorten learning curves and improve ergonomic outcomes, fostering seamless human-robot collaboration [13].

REAL-TIME DECISION SUPPORT

AI provides intraoperative decision support by processing multimodal data—imaging, vitals, and patient records—for real-time recommendations. RL models predict complications like bleeding, suggesting optimal interventions [14]. A 2025 study reported a 30% reduction in error rates through AI-driven risk assessments in complex procedures [15]. In orthopedics, AI guides fracture reduction by simulating outcomes [16]. Digital twins, virtual patient replicas, enable preoperative planning and intraoperative adjustments [17]. In urologic surgery, AI overlays provide instant feedback, enhancing decision accuracy [18]. These capabilities improve safety and tailor interventions to patient-specific factors.

ENHANCED IMAGING AND RECOGNITION

Image recognition, powered by convolutional neural networks (CNNs), is central to surgeon-in-the-loop systems, identifying tissues and pathologies with high accuracy. AI processes endoscopic feeds for real-time tissue classification, integrating with augmented reality (AR) for incision guidance [19]. A 2024 study reported 95% accuracy in tissue identification, surpassing human assessment in low-visibility conditions [20]. RL enhances autonomous subtasks like suction, improving efficiency [21]. In oncology, AI reduces positive tumor margins by 20% through precise margin detection [22]. Robust models address challenges like varying lighting, ensuring reliability across procedures [23].

EFFICIENCY AND PRECISION

AI-driven robots enhance surgical efficiency and precision by automating repetitive tasks and optimizing workflows. Studies report 15–20% reductions in operative times through predictive analytics and motion compensation [24]. In minimally invasive surgery, AI minimizes tremor, achieving sub-millimeter accuracy and reducing complications [25]. RL frameworks, like those in the dVRL platform, improve suturing precision [26]. Postoperative AI monitoring via wearables detects early complications, further improving outcomes [27]. These advancements shorten recovery times and alleviate healthcare system burdens.

Challenges and Ethical Considerations

Technical challenges include the need for large, diverse datasets for AI training, constrained by privacy regulations like GDPR and HIPAA [28]. Algorithmic bias from unrepresentative data risks disparities, particularly for underrepresented groups [29].
Ethical concerns involve over-reliance on AI, potentially eroding surgeon skills, and accountability for errors [30]. Transparency in "black-box" models is critical, prompting

research into explainable AI (XAI) [31]. Regulatory hurdles, with only low-level autonomy FDA-cleared by 2025, and high costs limit adoption in low-resource settings [32,33].

DISCUSSION

surgeon-in-the-loop artificial intelligence (AI) systems represent a pivotal advancement in robotic surgery, effectively bridging the gap between human surgical expertise and the unparalleled precision offered by machine algorithms. These hybrid systems integrate human oversight with automated processes, allowing surgeons to maintain control while leveraging AI's capabilities to enhance procedural outcomes. In robotic surgery, where minimally invasive techniques demand high levels of dexterity and accuracy, AI acts as an augmentative tool, processing vast amounts of intraoperative data in real-time to assist in tasks such as tissue manipulation, suturing, and navigation. This synergy not only minimizes human error—stemming from fatigue or variability in skill—but also amplifies the surgeon's decision-making through predictive analytics and haptic feedback mechanisms. By keeping the surgeon actively involved in the control loop, these systems ensure that AI recommendations are vetted by human judgment, fostering a collaborative environment that transforms traditional surgical workflows into more efficient, precise operations.

A key feature of these systems is their capacity for personalization, achieved through advanced machine learning techniques such as reinforcement learning (RL) and imitation learning. Reinforcement learning enables AI models to learn optimal surgical strategies by iteratively interacting with simulated or real environments, receiving rewards for actions that lead to successful outcomes, such as minimal tissue damage or reduced operative time. This adaptive learning process allows the system to tailor its behavior to individual surgeon preferences, patient anatomies, and specific procedural contexts. Complementing RL, imitation learning draws from expert demonstrations, where AI algorithms observe and replicate the nuanced techniques of seasoned surgeons, capturing subtle cues like force application or tool trajectory that are difficult to codify explicitly. Together, these methods create highly adaptive surgical tools that evolve with use, improving over time to better align with the unique demands of each case. Furthermore, AI-driven decision support systems provide real-time guidance, such as suggesting optimal incision points or predicting complications based on historical data patterns. Enhanced imaging technologies, integrated with AI, further bolster accuracy by employing computer vision algorithms to segment anatomical structures, detect anomalies, and overlay augmented reality visualizations during surgery. These enhancements collectively contribute to superior precision, reducing variability in outcomes and potentially lowering complication rates [34].

Optimizing resource allocation—such as shortening operative durations and minimizing the need for additional personnel—these systems streamline surgical processes, allowing healthcare facilities to handle higher caseloads with fewer resources. For instance, AI-assisted planning can expedite preoperative assessments, while intraoperative automation reduces the cognitive load on surgeons, enabling faster decision-making and fewer revisions. This efficiency translates to cost savings through decreased hospital stays, lower rates of readmissions, and optimized use of expensive robotic equipment. However, these benefits are tempered by a range of ethical risks that demand careful scrutiny. Algorithmic bias, arising from training datasets that may underrepresent diverse populations, could perpetuate disparities in surgical outcomes across demographic groups. Privacy concerns are equally pressing, as AI systems rely on sensitive patient data, including imaging and biometric information, raising the potential for breaches or unauthorized use. Additionally, the integration of AI challenges surgeon autonomy, as over-reliance on automated suggestions might erode professional judgment or lead to deskilling over time. Addressing these risks requires robust frameworks for data governance, bias auditing, and ethical oversight to ensure that technological advancements do not compromise patient rights or equity in care [35].

Looking ahead, future research in surgeon-in-the-loop AI should prioritize the development of explainable AI (XAI) methodologies to enhance transparency and build trust among clinicians and patients. XAI techniques, such as feature attribution maps or counterfactual explanations, can demystify the "black box" nature of complex models, allowing surgeons to understand the rationale behind AI recommendations and intervene when necessary. This transparency is crucial for regulatory approval and widespread adoption, as it mitigates concerns over accountability in adverse events. Concurrently, efforts should focus on achieving higher levels of autonomy in robotic systems while maintaining human supervision, progressing from current assistive roles toward semi-autonomous functions where AI handles more complex subtasks under surgeon guidance. Such advancements could involve hybrid control paradigms that dynamically adjust autonomy based on procedural complexity or surgeon confidence levels, ensuring safety without stifling innovation [36].

Efforts, surgeon-in-the-loop AI has the transformative power to democratize high-quality surgical care globally, making advanced procedures more accessible and affordable, and ultimately improving health outcomes on a worldwide scale [37].

CONCLUSIONS

Surgeon-in-the-loop AI systems are reshaping robotic surgery by augmenting precision, efficiency, and personalization. While advancements are promising, addressing technical, ethical, and regulatory challenges is critical for widespread adoption. Continued innovation and interdisciplinary efforts will unlock their potential, improving surgical outcomes and patient care.

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Cite this article as:

Pareek A, Kanwar P, Bansal R, et al. Surgeon-in-the-Loop AI Systems in Robotic Surgery: Enhancing Precision, Efficiency, and Personalisation – A Short Narrative Review. Curr Trends Med Clin Res. 2025 Sep;1(1):1-6. doi:10.5281/zenodo.16946082