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# *AI-Robot Synergy in Surgery: Mechanisms, Challenges, and Future Prospects*

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***Abstract.*** Recently, with the rapid development of robotics and the advancement of high-demand medical technologies, many robots have been applied in surgical operations. Conventional medical robots rely heavily on preoperative planning during surgery, require intraoperative assistance and control by physicians, and exhibit relatively low efficiency. In contrast, AI-integrated robots—equipped with autonomous decision-making capabilities and real-time environmental interaction through AI algorithms—have become a research focus. Based on recent high-impact literature, this paper reviews AI-collaborative robots' working mechanisms and clinical applications across three dimensions: preoperative perceptual decision-making, intraoperative precise execution, and postoperative learning optimization. It also analyzes the limitations of such robots, such as insufficient precision in multimodal data fusion. It prospects applying technologies like 6G and flexible robotic arms in these robots. The aim is to help AI-collaborative robots overcome clinical application bottlenecks and unlock more possibilities for future treatments.

***Keywords:*** Surgical Operations, AI-Robot, Preoperative Decision-Making, Intraoperative Execution, Postoperative Optimization

## 1. Introduction

With the progress of the times, surgical operations have gradually focused on new directions such as personalized precision medicine, minimally invasive techniques, and adaptive decision-making to address complex conditions like joint replacement and lesioned tissue resection. Surgical robots play a crucial role in surgical operations: they effectively enhance the stability and repeatability of surgical procedures. Their key advantages include improving physicians' operational flexibility—their robotic arms' free movement facilitates surgical operations in narrow spaces and alleviates physicians' fatigue during operations in special body positions. Meanwhile, with the support of functions such as sensors and haptic feedback, the precision of physicians' robotic arm operations is also guaranteed [1]. Currently, such robots are applied in systems ranging from the Da Vinci laparoscopic system to the MAKO platform for orthopedics.

However, single-function surgical robots still have clinical limitations. For instance, their over-reliance on preoperative planning makes it difficult to adjust promptly to intraoperative emergencies (e.g., unexpected massive bleeding, tissue displacement, or deformation). For example, Qin et al. found that the dual-robot system for spinal surgery often faces challenges from the limitations of

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preoperative planning; due to individual differences in spinal structures, preoperatively planned paths may sometimes be unimplementable [2]. Therefore, developing AI-collaborative robots that can independently perform surgical decision-making through preoperative learning and perception, execute precisely during surgery, and conduct secondary learning and optimization postoperatively can effectively address some shortcomings.

The importance of AI-collaborative robots in today's medical field is gradually increasing. Conventional surgical robots can effectively surpass human operational limits, while AI collaboration further improves surgical precision and stability. Additionally, integrating AI algorithms endows surgeries with functions such as multimodal image fusion, environmental perception and interaction, and anatomical model conversion, creating more possibilities for surgical procedures. In general, the significance of AI-collaborative robots lies in their ability to amplify physicians' technical capabilities and provide higher precision and stability for surgeries. Currently, academic research focuses on single technical modules of AI-collaborative robots, lacking an analysis of such robots' complete clinical process loop. This paper summarizes the mechanisms, related applications, challenges, and prospects of AI-collaborative robots in surgical operations from three dimensions (preoperative perceptual decision-making, intraoperative precise execution, and postoperative learning optimization), aiming to provide support for AI-collaborative robots to overcome technical bottlenecks and create more possibilities.

## 2. Principle of surgical application in AI-robot synergy

The core of AI-robot collaborative applications in surgery lies in leveraging AI's perception, decision-making, and learning capabilities to empower robots and enable them to perform exact surgical operations.

### 2.1. Preoperative perceptual decision-making of AI-robot synergy

#### 2.1.1. Medical image modal processing

As the most intuitive way for physicians to understand patients' individual pathological conditions, medical image modal processing is usually used to help physicians grasp anatomical structures, pathological locations, nerve functions, and metabolic processes of patients [3]. AI-collaborative robots typically integrate relevant images through AI algorithms to establish deep learning models, obtain structured basic data, and provide references for subsequent multimodal data modeling, improving the process's precision and efficiency. For example, in a study published in Nature Communications by the Fudan University Team, data from 4,557 patients across several hospitals showed that deep learning models combined with preoperative CT images to predict the benign/malignant nature and invasiveness of renal tumors achieved AUC values ranging from 0.853 to 0.898, which is significantly superior to conventional image interpretation methods [4].

#### 2.1.2. Anatomical model conversion

AI converts 2D medical images into 3D anatomical models, considering individual differences and aligning with the robot coordinate system (dynamic mapping between robotic movement and pathological sites) to improve precision. At the Affiliated Hospital of Qingdao University, 3D reconstructed models matched with the Da Vinci robot reduced the hepatectomy open surgery conversion rate to 1.9%, saving preoperative time and reducing blood loss [5].

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### 2.1.3. Environmental perception and interaction

Based on the above two steps, AI-collaborative robots initially establish anatomical models by fusing images and pathology. However, intraoperative tissue deformation, displacement, and mechanical movement can also introduce errors into model analysis. At this point, AI-collaborative robots' environmental perception and interaction help to optimize decisions further, and they can be divided into large-scale structural and local semantic layers. The large-scale layer focuses on operating room layout and instrument paths. Li et al. proposed a new surgical perception framework called “SuPer”, which combines model-based trackers and model-free trackers to generate large-scale surgical constraint point clouds in the surgical area, thereby supporting the robot in path planning and autonomous obstacle avoidance [6]. The local layer focuses more on refined operations; it achieves a refined perception of operations in key surgical areas by fusing a two-stream compact network and a bird’s-eye view. The combination of the large-scale structural layer and the local semantic layer helps AI-collaborative robots construct environmental models and plan surgical paths during surgery, effectively compensating for the defect of preoperative planning errors in conventional robotic surgery caused by patients’ specific pathological structures.

## 2.2. Intraoperative precise execution of AI-robot synergy

AI-collaborative robots can enter the formal surgical operation stage after establishing a patient-specific 3D anatomical model through preoperative decision-making and planning, and successfully achieving environmental perception and interaction. AI-collaborative robots have significant advantages during surgery: high operational precision, strong coordination in multitasking, and high surgical efficiency. These advantages are supported by links such as robotic arm control, real-time navigation, and force feedback fusion of AI-collaborative robots during surgery.

### 2.2.1. Robotic arm control

Robotic arm control integrates core technologies like hardware structure design and algorithm control. Regarding hardware, multi-degree-of-freedom (multi-DOF) force-controlled robotic arms have become a current research focus. During surgery, robotic arms are usually designed with 7–10 degrees of freedom; based on preoperative path planning, redundant degrees of freedom adjust postures through the combined movement of multiple joints to accurately and flexibly avoid obstacles and cooperate with physicians to ensure a natural “hand feel”A 2015 experiment on the 7-DOF LWR 4+ robot used a Null Space Optimization (NSO) strategy, reducing joint collision risk in narrow spaces while maintaining positioning precision. The core of this strategy lies in restricting the movement range of the robotic arm’s elbow and avoiding contact with intraoperative obstacles [7].

Regarding algorithm control, the integration of AI endows surgical robots with deep learning capabilities and optimizes the operation process through algorithms. Here, the focus is on introducing Model Predictive Control (MPC) and the Koopman operator. After the fusion of Improved Particle Swarm Optimization (IPSO) and MPC, the key parameters of MPC are optimized in real time, ensuring the precision of the robotic arm’s movement trajectory. In an innovative MPC-based incremental torque controller experiment, combining IPSO and MPC significantly reduced the mean squared error (MSE) of joint angles by 33.35% compared with conventional MPC [8].

Compared with conventional MPC, IPSO uses a linear inertia weight strategy to ensure that instruments move along preset paths (e.g., wound suturing paths, tumor puncture paths) and makes

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real-time corrections to reduce errors as organs move. Moreover, conventional MPC struggles to solve nonlinear prediction models quickly; however, in robotic surgery, the contact between robotic arms and organ tissues is usually nonlinear. Thus, introducing the Koopman operator— which maps nonlinear systems to a high-dimensional linear space ("lifted space")—has become a research focus. After linearization, MPC can complete rolling optimization within milliseconds to realize path re-planning. The role of the Koopman operator combined with MPC in surgery can be summarized as follows: MPC tracks the operation trajectory, while the Koopman operator remakes decisions and plans new paths for unreasonable trajectories caused by emergencies.

### 2.2.2. Real-time navigation

Real-time navigation of AI-collaborative robots during surgery serves as a bridge connecting preoperative planning and intraoperative precise execution. To address the limitation that conventional navigation only applies to static images, AI algorithms fuse relevant intraoperative photos (e.g., CT, laparoscopy) to form real-time navigation, accurately capturing the coordinate positions of patients' target areas. In a deep learning framework, dynamic registration from 2D to 3D is achieved by learning the Displacement Vector Field (DVF), with a calculation time of only 0.181 s—suitable for real-time navigation [9].

During surgery, noise, blood, or organ occlusion often affects intraoperative real-time images. Deep learning enabled by AI can also train models through data augmentation to obtain robust features resistant to interference. Multimodal image fusion contributes to the continuous update of intraoperative real-time navigation: it helps optimize surgical efficiency and reduce intraoperative calibration time.AI robots equipped with multimodal image fusion provide a dynamically updated navigation system that returns the real-time position of the target area, facilitating surgeons' operations instead of confirming the target position repeatedly.For example, the unsupervised deep learning deformable registration model based on U-Net (ConvU-Net-DIR) fuses preoperative and intraoperative MRI in real time, dynamically updating the tumor position to improve surgical efficiency. The model provides technical support for tumor recurrence monitoring and radiotherapy plan optimization [10].

## 2.3. Postoperative learning and optimization of AI-robot synergy

The postoperative learning and optimization of AI-collaborative robots rely on integrating multidimensional data (e.g., patients' rehabilitation status, intraoperative imaging) with machine learning, deep learning, and related algorithms to form a feedback loop from preoperative planning to intraoperative execution and postoperative optimization. The core lies in adaptive learning driven by intra- and postoperative data: by correlating recovery indicators (wound healing, organ function) with intraoperative metrics (robotic arm trajectory, wound length and depth), algorithms optimize surgical strategies. Hafeez et al. proposed a federated deep reinforcement learning framework; training reinforcement learning models across different medical institutions addresses the challenges of postoperative data privacy and model generalization across institutions. The FDRL framework constrained the deviation of surgical precision from the centralized benchmark model to within 1.5% and succeeded lowering the risk of privacy leakage by 60% [11].Similarly, Yamasaki et al. showed that analyzing force feedback data from suture experiments on ex vivo intestinal tubes improved suturing quality: after optimizing force feedback, maximum clamping force dropped from 3.4 N to 2.8 N [12]. These studies illustrate how integrating intra- and postoperative data with algorithmic frameworks enhances robotic adaptability and surgical outcomes.

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## 3. Current challenges in AI-robot synergy in surgery

AI-collaborative robots face challenges and shortcomings in their development, such as insufficient precision in multimodal data fusion, physical instrument path limitations, insufficient coordination between physicians and robots, and ethical controversies. How to improve systems and optimize these issues in future research has become a new research direction.

### 3.1. Insufficient precision in multimodal data fusion

Multimodal data fusion has become one of the main applications of AI-collaborative robots in the surgical field. However, multimodal data fusion also faces the problem of insufficient precision: there is a risk of mismatch when fusing data from multiple dimensions. Similarly, a similar problem exists: modules with significant characteristic differences may cause systematic visual defects when fused. When AI-collaborative robots' large language models (LLMs) make misjudgments in systematic vision, leading to inefficiency or even major issues such as medical accidents. For example, current multimodal LLMs (e.g., GPT-4V) have systematic errors in basic visual tasks (e.g., shape recognition, color classification);For instance, even the best-performing GPT-4V achieves an average accuracy which significantly lower than the accuracy of humans across the 9 visual patterns of MMVP, highlighting the critical visual limitations of current multimodal LLMs and the generated explanations have apparent hallucinations [13].

### 3.2. Instrument limitations and insufficient human-robot coordination

Hardware devices of AI-collaborative robots (e.g., robotic arms, end sensors) directly participate in the surgical process. However, in human anatomical structures with high specificity, the mechanical structure of robots may sometimes be restricted; clinically, the precision achievable by hardware equipment may not meet surgical requirements. For example, Hara et al. developed a DOF robot with a drilling precision of 1 mm and a cutting precision of 0.5 mm, which is insufficient to meet the submillimeter requirements of complex maxillofacial surgeries [14].

Meanwhile, physicians must collaborate clinically with robots to complete a series of operations. For example, when robots use low-resolution cameras for tissue operations, surgeons must also receive feedback and participate in the process [15]. A subsequent problem is insufficient coordination between physicians and robots. In AI-collaborative robot surgeries, the physician team usually consists of 6 members, among them, the assistant nurses and technicians must learn professional robot operation knowledge [16]. When the coordination between physicians and robots is insufficient, physicians must switch to manual mode, which can cause delays measured in milliseconds, leading to reduced surgical efficiency.

### 3.3. Ethical issues

AI-collaborative robots are different from conventional physician-performed surgeries, and the ethical issues they bring cannot be ignored. Ethical questions include accident responsibility, data infringement, and informed consent bias. Among these, some scholars have proposed that whether a robot qualifies as a criminal subject depends on the "singularity" boundary—i.e., whether the robot has complete consciousness and free will. The autonomous consciousness of surgical robots beyond the "singularity" will impact the human-centric nature of criminal law; in this case, the inaccuracy of physicians' intraoperative behaviors and the variability in their ability to foresee outcomes will increase [17].

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Despite the widespread clinical application of AI surgical robots, a survey of 86 respondents on the intention to use AI for tonsillectomy showed that only 42% were confident in the security of their data, and 51% would recommend this type of surgery [18].

## 4. Future prospects of AI-robot in surgery

With technological development, AI-collaborative robots have been applied in many surgical operations, significantly contributing to minimally invasive surgeries and partial organ resections. The bottlenecks and challenges mentioned above have become urgent issues that need to be addressed for such robots.

### 4.1. Technological innovation and clinical expansion of AI-collaborative robots

The breakthrough of AI-collaborative robots relies on deep reinforcement learning, large language models (LLMs), and advanced algorithms. These enable robots to establish adaptive models and perform complex reasoning. For example, Zargarzadeh et al. integrated multimodal LLMs into robotic surgery, allowing robots to autonomously assess bleeding type and surgical complexity during suction tasks, cutting suction time by 50% [19]. At the same time, ultra-low latency and high-speed data transmission from 5G networks provide essential support for instrument movement and multi-sensory feedback. With 6G, latency will be further reduced, maximizing AI potential and surgical safety. Already, 5.5G networks have lowered latency to milliseconds and stabilized instrument precision at the millimeter scale [20].

Conventional methods struggle in minimally invasive procedures within small lumens, but combining flexible robotic arms with autonomous navigation may overcome this limitation. Kim et al. introduced a wire-driven serpentine robotic arm whose direct-drive mechanism eliminates backlash and friction, improving interaction and control performance [21]. In the future, flexible robotic arms integrated with precise force feedback and AI navigation are expected to enable minimally invasive, fully autonomous surgeries, addressing current hardware precision bottlenecks.

### 4.2. Ethical supervision

To address ethical issues in clinical surgeries, the academic community generally introduces ethical supervision mechanisms to overcome these challenges. First, whether a patient accepts surgical treatment involving AI-collaborative robots requires a complete evaluation process covering three dimensions: robot, physician, and patient. Preoperatively, patients must be fully informed and understand the requirements of AI and robots during surgery and their potential risks. Physicians must receive strict training to meet surgical standards. AI must undergo extensive data training without infringement, establish models, and improve its applicability [22].

Meanwhile, various laws in China (e.g., Artificial Intelligence Law) are promoting regulations on relevant medical accidents based on relevant theories, and clearly stipulating that physicians bear unshirkable responsibilities for the operation, supervision, and training of robots; in the event of an accident, the responsible subject remains medical personnel [18]. The “OR Black Box” is an intelligent system integrating audio-visual collection, multi-device data integration, and AI analysis. By recording the complete process data of surgery, OR Black Box technology can accurately locate accidents if they occur, ensure surgical quality, and lay the foundation for future remote surgical collaboration of AI robots.

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## 5. Conclusion

This paper summarizes the primary mechanisms, applications, challenges, and prospects of AI-collaborative robots in surgery. In the section on mechanisms and applications, the clinical applications of AI-collaborative robots and their underlying mechanisms are reviewed across three modules: preoperative, intraoperative, and postoperative. Regarding preoperative perceptual decision-making, the primary methods of multimodal data fusion—including medical image modal processing, anatomical model conversion, and environmental perception and interaction—are introduced. Among these, AI-enabled technologies such as deep learning construct multi-module 3D anatomical models for surgery, supporting intraoperative precise operations. While AI-collaborative robots are developing rapidly, their challenges cannot be ignored. This paper elaborates on the limitations of hardware equipment, insufficient human-robot coordination, and potential ethical issues of robots during surgery. Finally, prospects for the future development direction of AI-collaborative robots are proposed, hoping to provide more possibilities for AI-collaborative robots at the technical level and further address their ethical challenges.

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